Geology of the Hugo Pegmatite Keystone, South Dakota

GEOLOGICAL SURVEY PROFESSIONAL PAPER 297-B

U. S. DEPARTMENT OF THE INTERIOR

March 3, 1849

Geology of the Hugo Pegmatite Keystone, South Dakota

By J. J. NORTON, L. R. PAGE, *and* D. A. BROBST

PEGMATITES AND OTHER PRECAMBRIAN ROCKS IN THE
SOUTHERN BLACK HILLS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 297-F

A detailed structural and petrologic
study of a pegmatite containing
seven zones and two replacement bodies

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

PEGMATITES AND OTHER PRECAMBRIAN ROCKS IN THE SOUTHERN BLACK HILLS

GEOLOGY OF THE HUGO PEGMATITE KEYSTONE, SOUTH DAKOTA

By J. J. Norton, L. R. Page, and D. A. Brobst

ABSTRACT

The Hugo pegmatite, 1 mile south of Keystone, S. Dak., is an unusually well developed zoned pegmatite offering abundant structural and petrographic information that is useful in inferring the behavior during crystallization. This pegmatite is also economically important as one of the largest potash feldspar mines in the southern Black Hills; in addition it has been a source of scrap and sheet mica, amblygonite, spodumene, beryl, and tantalite-columbite. It was mined as early as 1909 for amblygonite, and has been mined continuously since 1924 for potash feldspar.

The pegmatite is an irregular body consisting of two structurally independent segments separated from each other for most of their length by a thin rib of quartz-mica schist. Each segment strikes N. 70° E. and dips about 50° NW. The plunge of each segment is nearly 50° N.

The country rock is mainly quartz-mica schist and quartz-mica-staurolite schist, but sillimanite is sparsely distributed within 2 feet of the pegmatite. In places the schist has been altered at the contact by the introduction of albite, tourmaline, muscovite, and apatite.

Seven zones and two replacement bodies have been mapped in the pegmatite. Zones 1 and 2, the border and wall zones, consist of quartz, albite, and muscovite. Zone 3 is mostly perthite, quartz, and albite; perthite is concentrated in the upper part of the unit, and quartz and albite in the lower part. In zone 4 quartz and cleavelandite are the dominant minerals, but microcline and amblygonite are also notable constituents of this zone in the south segment of the pegmatite. Zone 5 consists of quartz, microcline, and spodumene. It is succeeded by a small hood-shaped unit of quartz-microcline pegmatite, zone 6, that lies above the cleavelandite-microcline-lithia mica core, zone 7. Two replacement units in which the dominant introduced minerals are cleavelandite, lithia mica, and microcline extend outward from the core and cut across zones 2 through 6. These contain enough relicts of the zones to trace zonal contacts through the replacement units.

Megascopic and microscopic studies of the textures indicate that although a paragenetic sequence can be established for each unit, there was extensive overlap in the crystallization of the primary minerals of the zones, and there was also overlap among the introduced minerals of the replacement bodies. Most of the albite formed early to intermediate in the sequence, and quartz formed late. Mica formed early in zones 1 and 2, and progressively later in zones 3 to 6; it formed late in zone 7 and in the replacement units. Potassic feldspar formed early in zone 3, somewhat later in zones 4 to 6, and early in zone 7 and in the replacement units. Spodumene and amblygonite were early minerals of the zones in which they have been found.

Evidence that this pegmatite formed by the intrusion of a magmatic liquid that crystallized from the contact inward consists chiefly of: (1) sharp contacts with the wallrock; (2) structural relations between zones and crosscutting fracture-filling and replacement units; (3) systematic and progressive changes in the character of certain minerals from outer to inner units; and (4) tapered crystals of beryl that are normal to the pegmatite contact. The temperature of crystallization, as deduced from the $NaO:K_2O$ ratios in muscovite, fluid inclusions, and the known stability fields of different minerals, was probably less than 650° C; in the core it may have been as low as 300° C.

The chemical composition of the pegmatite has been calculated from visually estimated modes and a detailed structural analysis of the pegmatite. The composition, in percent, is: SiO_2, 77.9; Al_2O_3, 12.2; Na_2O, 3.7; K_2O, 3.2; P_2O_5, 0.9; and other constituents, 2.1. Although the content of H_2O is estimated at 0.5 percent and fluorine at 0.1 percent, a higher content of these and perhaps other hyperfusibles is suggested by the low temperatures of crystallization.

The composition of the outer zones indicates that during most of the crystallization period of this pegmatite the rest liquid became progressively richer in SiO_2 and leaner in Al_2O_3, Na_2O, and K_2O. In late stages, however, the rest liquid gave rise to a fluid rich in Al_2O_3, Na_2O, K_2O, H_2O, and fluorine that formed the core and replacement units.

The principal industrial mineral at the Hugo pegmatite is potash feldspar. It has been recovered chiefly from the upper part of zone 3, but also from zones 4, 5, and 6. Scrap mica and beryl are most abundant in zone 2 along the footwall of the south segment. Spodumene and amblygonite are obtained from zone 5. Most of the recoverable potash feldspar has already been mined, but large reserves of scrap mica and beryl still remain.

INTRODUCTION

The Hugo pegmatite, at Keystone, S. Dak., has been one of the major mines in the southern Black Hills, and it has also been a fruitful source of geologic information. The structural relations of the zones and replacement bodies together with their petrographic and mineralogic characteristics provide a body of data that can be widely applied in interpreting the geology of zoned pegmatites.

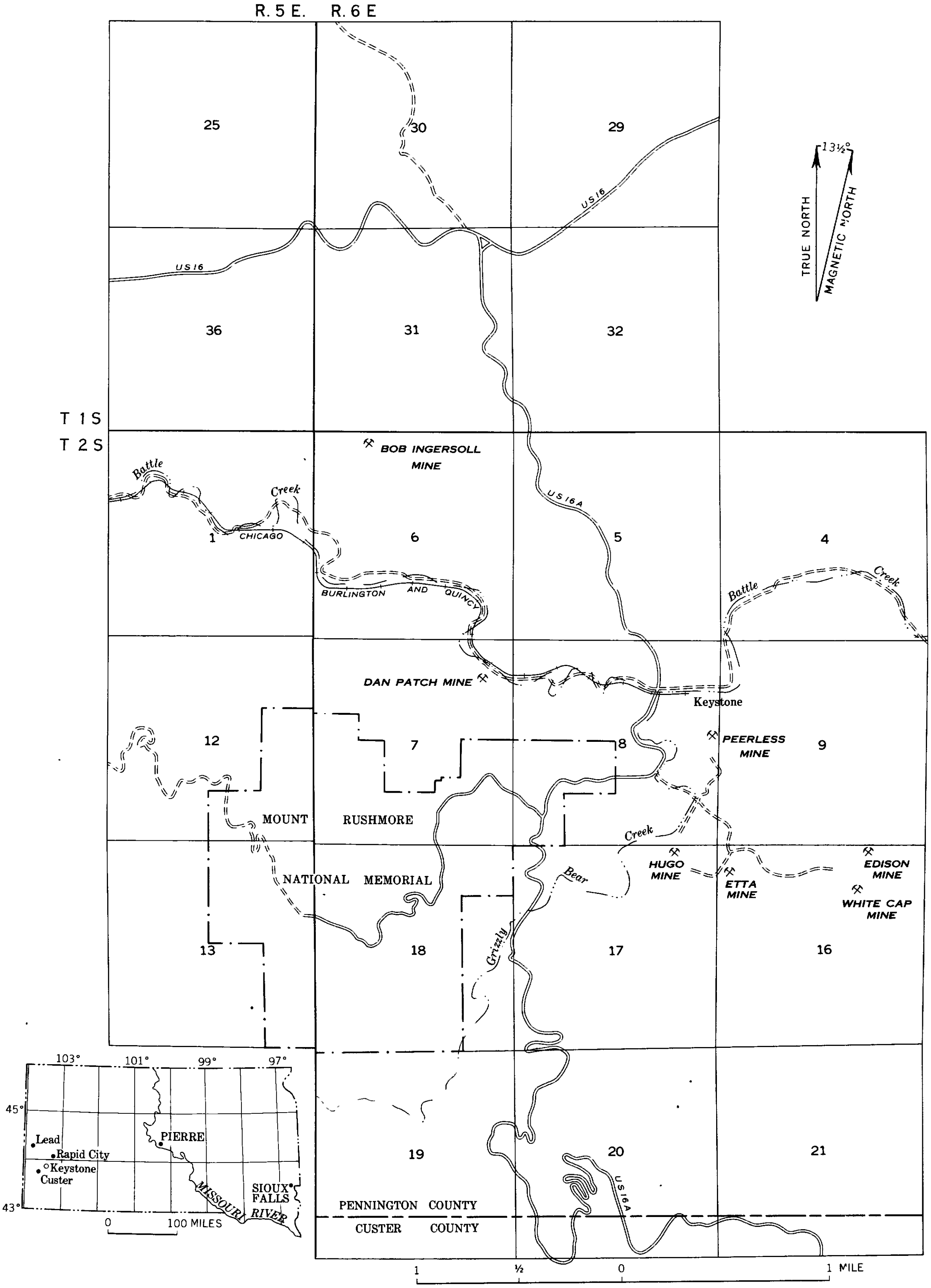

FIGURE 3.—Index map showing location of the Hugo pegmatite, Keystone, S. Dak.

This pegmatite is 1 mile south of Keystone, near the north border of NE¼ sec. 17, T. 2 S., R. 6 E. (fig. 3). It has been mined for potash feldspar,[1] scrap and sheet mica, amblygonite, spodumene, beryl, and tantalite-columbite, and probably was prospected for tin in the latter part of the 19th century. The most important mineral by far has been potash feldspar, and the other minerals have ordinarily been byproducts.

The earliest recorded mining was in 1909, when amblygonite was extracted from a pegmatite "a short distance east of the Peerless, where the mineral, accompanied by spodumene, is said to occur in large amount" (Hess, 1911, p. 652). This pegmatite could be only the Hugo. The mine was named after Hugo Reinbold, who was owner or operator of this property for many years. Ziegler (1914a, p. 201) notes that the pegmatite was previously named the "Christiansen."

Potash feldspar was produced in South Dakota for the first time in 1924 (Middleton, 1927, p. 20) when the Keystone Feldspar and Chemical Co. began operating the Hugo mine. The Consolidated Feldspar Corp. took over the mine in 1929, and in the same year built a feldspar-grinding plant in Keystone that was supplied chiefly by the Hugo mine. Mining was continued until 1957, when the grinding plant was destroyed by fire, and the future of the mine became uncertain. The Consolidated Feldspar Corp., which became a department of the International Minerals and Chemical Corp. in 1954, still leased the property from the Keystone Feldspar and Chemical Co., which in turn leased it from the heirs to the Reinbold estate.

Production figures for potash feldspar and scrap mica through 1946 are given in table 1. Production continued from 1947 through 1956, but exact figures have not been obtained. Page and others (1953, p. 135) estimate the amblygonite production at 1,300 to 1,500 tons throughout the life of the mine, and also state that 2,519.37 pounds of sheet mica and 10,421.81 pounds of untrimmed punch mica were sold to the Colonial Mica Corp. in 1943. Spodumene production probably has been more than 1,000 tons, and beryl more than 100 tons. Tantalite-columbite production may have been several thousand pounds.

The Hugo pegmatite has been described briefly in many publications. The more important references are: Ziegler (1913, especially p. 1055–1056; 1914b; 1914c, p. 275); Schwartz (1928, p. 61); Landes (1928, especially p. 527–529); Guiteras (1940, p. 24–25); and Page and others (1953, p. 135).

TABLE 1.—*Potash feldspar and scrap mica produced from the Hugo mine*

[Supplied by J. A. Schreiber, Keystone Feldspar and Chemical Co. Published by permission of the owners]

Year	Potash feldspar (tons)	Scrap mica (tons)
1924	1, 391	385
1925	3, 636	207
1926	4, 187	213
1927	3, 200	335
1928	3, 550	244
1929	2, 004	----------
1930	4, 440	----------
1931	8, 563	----------
1932	4, 397	87
1933	2, 250	----------
1934	7. 239	----------
1935	17, 166	----------
1936	23, 461	----------
1937	16, 262	41
1938	9, 222	97
1939	13, 176	70
1940	12, 498	104
1941	6, 966	27
1942	13, 213	44
1943	16, 671	176
1944	9, 380	94
1945	6, 388	----------
1946	6, 512	----------
Total	195, 772	2, 124

Fieldwork was done in the summer and fall of 1946 by J. J. Norton and L. R. Page, assisted for a short time by C. H. Chao. Microscopic petrography was done mainly by Norton and D. A. Brobst, but partly by Page and J. A. Redden.

The Hugo pegmatite and the adjacent area were mapped at a scale of 1:480 by planetable and telescopic alidade (pls. 8, 9). Some of the mapping near the outer edges of the area shown on plate 8 was by pace and compass. The underground workings were mapped at a scale of 1:240 by tape and Brunton compass (pl. 9).

The Hugo pegmatite contains an unusually complete set of internal structural units that are well exposed in open pits, glory holes, and underground workings. The main units are seven zones and two replacement bodies. These units were mapped with special care, and 178 hand specimens and 58 thin sections were studied in detail to determine the mineral relations and paragenesis. The knowledge gained from the study of this complicated pegmatite has clarified many problems concerning the internal structure, mineralogic relations, and genesis of zoned pegmatites.

The Consolidated Feldspar Corp. and its employees, especially J. W. Mitchell, have done their best to facilitate this work. J. A. Schreiber of the Keystone Feldspar and Chemical Co. has been similarly cooperative. Capable assistance has been provided by C. H. Chao,

---

[1] The nomenclature for potassium-rich feldspars in this report is as follows: (a) Potash feldspar is used, in accordance with industry practice, for the mineral product that is mined and sold for its content of potassium-rich feldspar; (b) perthite applies to material consisting of microcline with abundant perthitic intergrowths of albite; (c) microcline means microcline in the strict sense, carrying little or no perthitic albite; and (d) potassic feldspar is used as a broader term applying to perthite and microcline and also to whatever form these minerals had at the time of original crystallization, prior to inversion to lower temperature forms and exsolution of albite.

who did some of the surface mapping, and Wendell Walker and A. J. Denson, who made the photomicrographs. D. B. Stewart kindly advised the authors in correlating their field data with data that have been obtained in laboratory study of silicate systems.

GENERAL GEOLOGY

The oldest rocks of the southern Black Hills are metamorphic rocks consisting dominantly of quartz- and mica-rich schists that contain garnet, staurolite, and sillimanite. Amphibolite is abundant in many places, especially north of Keystone. Other metamorphic rocks have been recognized, but they are scarce.

The metamorphic rocks are cut by many granitic and pegmatitic intrusive bodies. These intrusive bodies appear over an area of about 250 square miles, but they are most abundant in a circular area about 8 miles in diameter surrounding Harney Peak. The rock at Harney Peak has been called granite in much of the literature, and the rock in outlying areas has been called pegmatite (Paige, 1925, p. 4). Throughout the southern Black Hills, however, the rock of these intrusive bodies characteristically has such coarse grain size and uneven texture that nearly all of it can properly be called pegmatite.

The Keystone district is on the northeast side of Harney Peak. The edge of the so-called Harney Peak granite is only 1½ miles southwest of the Hugo mine, and the outer border of the pegmatite-bearing area is about 1½ miles to the northeast. The area in between contains a great many pegmatites, mostly small but some as large as the Hugo. A few of the pegmatites in the Keystone district are zoned, but most are not. The largest pegmatite mines, all in zoned pegmatites, are shown on figure 3.

METAMORPHIC ROCKS

Nearly all the rock immediately surrounding the Hugo pegmatite consists of a moderately well foliated fine-grained quartz-mica schist. The minerals in the approximate order of their abundance are: quartz, plagioclase, biotite, muscovite, garnet, staurolite, and sillimanite. At the Hugo mine sillimanite has been recognized only within 2 feet of the pegmatite, but it is more abundant a few miles to the south.

Ellipsoidal lime-silicate nodules, as much as 15 inches long, are sparsely distributed in the schist, especially in massive beds. These nodules are metamorphosed concretions (Runner and Hamilton, 1934) containing actinolite, plagioclase, quartz, diopside, epidote, and garnet.

A mappable unit containing garnet schist, quartzite, and amphibole schist has been recognized to the east. The nearest outcrop is 500 feet N. 70° E. of the center of the Hugo pegmatite. From that outcrop it can be traced for 1,400 feet N. 67° E., and then for 2,500 feet S. 83° E. The thickness of this unit is ordinarily less than 20 feet, but the maximum is 100 feet.

This unit was not definitely recognized in the immediate vicinity of the Hugo mine. Its projection, however, would carry it through a point on the 4,446-foot level, 235 feet from the portal, where an unusual lime-silicate rock was found at the pegmatite contact. This rock consists chiefly of olive-brown diopside crystals having an average length of 2 inches. The diopside is partly replaced by dark-green amphibole that occurs both as individual crystals parallel to the diopside cleavages and as felted aggregates. Irregular masses of quartz that form most of the rest of the rock embay and vein the diopside and amphibole. Late carbonate veinlets cut all the other minerals. This rock may be an altered variety of either an amphibole schist bed or a lime-silicate nodule.

At places near the contact with pegmatite the quartz-mica schist grades into recrystallized rocks rich in tourmaline and plagioclase. Ordinarily the average grain size is less than 1 mm, but tourmaline and muscovite crystals are as much as 5 mm long. The rock is in part schistose and in part granulitic. The maximum thickness of these recrystallized rocks is about 4 feet. They are most common where the pegmatite contact cuts across the schistosity of the country rock.

The mineral composition of these recrystallized rocks varies greatly. Some tourmaline schists contain as much as 40 percent tourmaline, 40 percent quartz, 30 percent muscovite, 20 percent albite (possibly including oligoclase), and 1 percent apatite; on the other hand, one or more of these minerals may be entirely absent. Some granulites have as much as 80 percent muscovite, 65 percent albite (possibly including oligoclase), 40 percent tourmaline, 40 percent quartz, and 10 percent apatite, with small amounts of garnet, zircon, and tantalite-columbite. The minimum refractive index of albite cleavage fragments in each of four specimens of granulite was 1.528, indicating a composition very near An_0.

A typical specimen of feldspar-rich granulite examined in thin section has a sugary texture and an average grain size of 0.5 mm. It contains albite (60 percent), tourmaline (15 percent), quartz (10 percent), apatite (10 percent), and muscovite (5 percent). The thin section shows a dominantly granular texture formed by albite and quartz. Tourmaline is in greenish-black subhedral to euhedral crystals as much as 2 mm long, some of which are zoned and have yellow-brown absorption in the center and greenish-blue in the outer part. Apatite occurs both as fine-grained material interstitial to albite and quartz and as coarser subhedral crystals 1 to 2 mm long.

The Hugo pegmatite is near the axis of a syncline. Bedding of the quartz-mica schist in areas west and south of the area shown on the map of the Hugo pegmatite has a general strike of about N. 15° E., and a dip of 75° SE. East of the Hugo mine, the strike is N. 66° E., and the average dip is about 85° SE. Schistosity is very nearly parallel to bedding, but it commonly has a somewhat steeper dip. Local variations in bedding-schistosity relations and the presence of a few southward-plunging drag folds indicate that there are folds of moderate size on the limbs of this major fold. Many minor folds in an area extending half a mile south of the Hugo mine plunge about 45° N. 30° E. and have no evident relation to the major fold.

ROY AND MONTE CARLO PEGMATITES

The Roy and Monte Carlo pegmatites, shown to the east and west of the Hugo on plate 8, consist mostly of quartz-plagioclase-perthite pegmatite. Perthite crystals as much as 10 feet long form about 25 percent of the rock. They are set in a groundmass of quartz and albite having an average grain size of 2 inches. Accessory minerals include muscovite, tourmaline, apatite, biotite, beryl, and garnet.

At the Roy pegmatite, west of the Hugo, a 3- to 5-foot-thick wall zone and a very narrow border zone of quartz-plagioclase-muscovite pegmatite have also been mapped. The average grain size is about 1 inch. Accessory minerals include tourmaline, apatite, and beryl.

The two pegmatites shown on plate 8 east of the Hugo are parts of large zoned pegmatites on the Monte Carlo claims.

STRUCTURE

The Hugo pegmatite is an irregularly shaped intrusive body consisting of two structurally independent segments separated from each other for most of their length by a screen of quartz-mica schist. The structure has been interpreted as shown in the vertical and horizontal sections (pls. 9, 10), which are based on the distribution of rock units and on the strikes, dips, and plunges shown on the geologic maps (pl. 9).

The pegmatite as exposed on the surface has a roughly elliptical form, 580 feet long in a N. 40° W. direction, and 440 feet wide. The schist screen that separates the north and south segments of the pegmatite has an average strike of about N. 60° E., and a nearly vertical dip. Large rolls have the effect of dividing the south segment into partly independent lobes, as shown in cross section A–A′ (pl. 9). The thickest lobe has all seven of the zones formed in this pegmatite; lobes on either side lack the two innermost zones.

The horizontal and vertical sections indicate that the two major segments strike about N. 70° E., and dip about 50° NW. The plunge of an axial line through each segment is about 50° N., as shown in plate 10 by the outline of the pegmatite at three different levels.

The actual strikes, dips, and plunges recorded on the maps show many variations from these average figures, as the contact swings around the sides of these two thickly lenticular bodies. Nevertheless, the readings indicate a pattern of northeastward strikes, northwestward dips, and plunges that commonly trend between north-northwest and northeast. The dominant rolls, shown at different levels on plate 10, have an average plunge of about 40° N. 15° E. Where the dip is locally to the south, as it is in places at the surface on the west side of the north segment and at the northeast corner of the south segment, the plunge of these rolls is also to the south. A second set of rolls exposed along the east contact of the south segment has a nearly vertical plunge. A third direction of plunge, about 12° N. 75° E., is represented only by a roll in the hanging wall of the south segment. This roll is shown 60 feet above the surface in cross section *A–A′* (pl. 9) and is exposed, as indicated by the geologic map (pl. 9), at three places east of cross section *A–A′*.

The northwestward dip of the pegmatite indicates a discordance with the generally southeastward regional dips of bedding and schistosity in the country rock. Within a few feet of the pegmatite, however, the schistosity turns until it is parallel to the contact; this is interpreted as the induced schistosity of Page and others (1953, p. 16). The rolls that plunge 40° N. 15° E. may reflect control by the set of minor folds that, south of the Hugo mine, plunge 45° N. 30° E.

The pegmatite is significantly displaced by only two small faults. One of these, shown in cross section *A–A′*, is a reverse fault that has an average strike of N. 70° E., a dip of 55° SE., and a displacement of 4 feet measured in the plane of the fault. The other, shown in cross section *B–B′*, is a normal fault that strikes N. 48° W., dips about 85° SW., and has a displacement of 5 feet.

PEGMATITE UNITS

Seven zones, two replacement units, and two types of fracture-filling units have been mapped in the Hugo pegmatite. The north segment contains only the outer four zones; the south segment contains all zones and both replacement units. Detailed mineralogic and petrographic data for the different units are shown in tables 2 through 11, and visually estimated modes for all units are shown in table 19. Paragenetic diagrams for the individual units are shown in figure 13. The rock names are expressed in the form "quartz-albite-muscovite pegmatite," in which the first mineral is the most abundant and the last is the least abundant of the essential minerals.

The successive units of the pegmatite change progressively in composition from the outermost zone to the core. The grain size increases from fine-grained pegmatite in zone 1 to rock consisting of very coarse crystals in zone 6 and large aggregates of minerals in zone 7.[2] Contacts between units are gradational, both in composition and texture. Zones 1 and 2, the border and wall zones, consist of fine- to medium-grained pegmatite in which the dominant minerals are quartz, albite, and muscovite. Large crystals of perthite first occur in zone 3, where muscovite becomes less abundant. The albite has 3 to 4 percent anorthite in zone 1, but less than 1 percent anorthite in other units. In zones 1 to 3 albite generally has a blocky to irregular shape, but in zone 4 it assumes the platy form of cleavelandite, which is characteristic of all succeeding units. Quartz is the only other plentiful mineral of zone 4, but amblygonite first becomes conspicuous in this zone. Potassic feldspar in zone 4 has so little perthitic structure that it is called microcline rather than perthite. Quartz is the dominant mineral in the extremely coarse grained rocks of zones 5 and 6. Spodumene is an essential mineral in zone 5, and microcline without much perthitic albite is an essential mineral in both zones.

Zone 7, the core, differs greatly from the silica-rich rock of zones 5 and 6. The dominant minerals are cleavelandite, microcline, and lithia mica.[3] Microcline occurs in medium- to coarse-grained crystals that are much smaller than the very coarse potassic feldspar crystals of zones 3 through 6. Fine-grained crystals of cleavelandite and lithia mica form large aggregates that give the rock the very irregular texture shown in figure 44.

Two replacement units that are mineralogically somewhat similar to zone 7 extend outward from the core across the zones almost to the pegmatite contact. Relict minerals and aggregates of minerals inherited from the zones are surrounded and replaced, partly pseudomorphically, by introduced minerals—chiefly cleavelandite, lithia mica, and microcline. Enough minerals, textures, and structures of the zones are preserved to trace zonal contacts through the replacement bodies, and these contacts are shown on the geologic map (pl. 9). The replacement units are irregular in form, have no evident structural control, and their depth cannot be predicated accurately.

The only fracture-filling unit of significant size cuts zones 1, 2, and 3 of the north segment, just northwest of the glory holes. It consists of quartz-cleavelandite pegmatite that is mineralogically the same as zone 4, and probably is an offshoot from zone 4.

The only other fracture-filling unit large enough to map consists of quartz pegmatite, 10 feet long and 3 feet thick, that cuts zone 2 in the northeast part of the north segment.. Additional tabular bodies that probably are fracture fillings, although none are more than 2 inches thick or 8 feet long, consist largely of albite and muscovite.

Textural relations indicating paragenesis of the minerals in each unit have been studied in detail because they have been used in the past (Hess, 1925; and Landes, 1928) to establish a sequence of stages in the crystallization of this and other pegmatites. Discussion of these textures in the following pages shows that there was extensive overlap in the paragenesis of each of the pegmatite units, and that views expressed by previous authors need some modification.

Paragenesis diagrams in figures 13 and 66 have been constructed in two somewhat different ways. Figure 13 is based solely on textures, and thus shows only the paragenesis at any single (but hypothetical) place within a pegmatite unit. Later sections of this report, however, will show that this pegmatite was probably formed from a magmalike liquid that crystallized from the wall inward. One may postulate that, at any stage during crystallization of the zones, the liquid was separated from completely solidified rock by material consisting of liquid plus a meshwork of crystals. On the basis of this concept, figure 66 has been constructed to show the paragenesis in terms of time of precipitation of minerals from the liquid as the pegmatite formed from the wall inward. Figure 13, on the other hand, shows only the sequence of formation of the minerals as the material at any one place changed from liquid, to liquid plus crystals, and finally to crystals only. The strictly textural treatment of paragenesis in figure 13 is a preliminary step in developing the more interpretive presentation in figure 66.

Textural relations are unfortunately subject to different interpretations by different investigators, as emphatic reminders by those who reviewed this report prior to its publication have demonstrated. Even the question of whether a given texture is primary may

---

[2] The following grain-size classification (adapted from Cameron and others, 1949, p. 16) is used in this report: very fine grained, less than ¼ inch; fine grained, ¼ to 1 inch; medium grained, 1 to 4 inches; coarse grained, 4 to 12 inches; and very coarse grained, more than 12 inches.

[3] The term "lithia mica" will be used in this report for all mica of zone 7 and for the introduced mica of the replacement units. It is a field name for a greenish-gray mica similar in habit to lepidolite but containing less lithium. The mineralogic character of this mica is not well enough known to give it a specific name.

be a subject for argument, because changes in the mineral phases to adjust to lower temperatures and pressures after the pegmatite first crystallized may have altered the primary textural relations. Nevertheless, any disagreement that could arise would have no great effect on the prime objective of the paragenetic studies, which is to provide background for discussing previous opinions regarding the genesis of pegmatites.

The interpretations used at the Hugo are summarized below.

Interpretations of relations observed at the Hugo pegmatite

Relation	*Interpretation*
Mineral A is cut by veinlets or embayments consisting of mineral B.	Mineral A formed first.
Mineral A is in aggregates of subhedral to euhedral crystals. Interstices of these aggregates are filled by mineral B.	Do.
Mineral A has crystal faces in contact with anhedral grains of mineral B. Mineral A does not contain optically continuous inclusions of mineral B. There is no structural evidence that the rock is a replacement unit in which mineral A formed during the replacement stage.	Do.
Large crystals of mineral A have an approximately euhedral form but with rounded edges in contact with finer-grained crystals of a groundmass consisting of minerals B and C.	Do.
Mineral A forms inclusions in mineral B. These inclusions are optically continuous with each other or with grains of mineral A that lie outside of mineral B. There are no sharp embayments of mineral A in mineral B to suggest that the inclusions are merely embayments in three dimensions. The inclusions show no evident control by structures of mineral B, nor is there evidence that the inclusions exsolved from mineral B.	Mineral A formed first or at the same time as mineral B.
Mineral B has inclusions of Mineral A that are preferentially distributed along cleavage, twinning, or similar structures of mineral B.	Mineral B formed first.
Pseudomorphs of mineral A consist of aggregates of several other minerals.	Mineral A formed first.
Some grains of mineral A show strain features and others do not. Or there may be unstrained grains of mineral B, which is known to be subject to the development of strain features because it has them elsewhere in the rock.	Strained grains formed first.
Skeletal crystals of mineral A contain aggregates of groundmass minerals.	Mineral A is at least partly contemporaneous with the other minerals.
A euhedral crystal of mineral A has inclusions of mineral B in rows parallel to crystal faces and probably following ghost crystal faces.	Mineral A partly preceded and partly followed mineral B.
Minerals A and B are graphically or subgraphically intergrown, or there are vermicular inclusions of one mineral in the other.	Contemporaneous crystallization.

Many of the mineral contacts, having a curving or somewhat irregular form, are of the sort that is customarily called mutual boundaries (Bastin and others, 1931, p. 604). Although many such boundaries may be a consequence of simultaneous crystallization, they provide no firm evidence of it, and it seems best to follow Bastin and others (1931, p. 604–605) in regarding this texture as not diagnostic of age relations. Where mutual boundaries are especially abundant, however, this fact has been recorded.

Paragenesis has been established largely by megascopic textural relations that are not likely to have been affected by postconsolidation processes, but useful supplementary data have been provided by microscopic textures. Where, for example, plates of cleavelandite that are megascopically euhedral project into quartz, either the cleavelandite formed first and the quartz crystallized around it, or the cleavelandite formed later and had sufficient force of crystallization to take on a euhedral form. At the Hugo the former argument is more often correct because it can be shown microscopically that the quartz commonly embays the cleavelandite.

Another use of combined megascopic and microscopic evidence is illustrated by the relations between cleavelandite and lithia mica in the core and replacement bodies. In thin section the lithia mica so commonly cuts across cleavelandite that, without other data, all of the lithia mica might be assumed to have crystallized after all of the cleavelandite. On the other hand, large veinlike aggregates of cleavelandite shown in figure 44 cut across lithia mica masses, and thus indicate that much of the cleavelandite crystallized later than the lithia mica.

ZONE 1: ALBITE-QUARTZ-MUSCOVITE PEGMATITE

DESCRIPTION

Zone 1, the border zone, consists of very fine grained to fine-grained albite-quartz-muscovite pegmatite (table 2). It forms an envelope from 3 to 6 inches thick that surrounds the entire pegmatite. The zone is so thin, however, that it can be shown separately on the geologic map only on dipslopes. It has a sharp contact with quartz-mica schist except in the few places where the two are separated by granulite.

The dominant mineral is albite. Other abundant minerals are quartz, muscovite, and tourmaline. Minor accessory minerals are apatite, an unidentified iron-manganese phosphate, and an unusual mica of low index of refraction that may be zinnwaldite.

TABLE 2.—*Mineralogy and petrography of zone 1, albite-quartz-muscovite pegmatite*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch]

Albite
- Size and shape: Mostly VF, some F; irregular, but approximately equidimensional: partly granular (fig. 4).
- Refractive indices: $\alpha'=1.530$ to 1.534. Outer parts of larger grains commonly have lower index than inner parts; maximum range of α' in a single crystal is from 1.530 to 1.534.
- Textural relations: Albite has inclusions of rounded to euhedral tourmaline and apatite; some of the tourmaline contains graphic to vermicular quartz. Muscovite inclusions are embayed, especially along their cleavage. Albite has mostly mutual contacts with quartz, and also is graphically intergrown with quartz. Albite also embays quartz, and less commonly is embayed by quartz.
- Additional data: Strain shadows prominent.

Quartz
- Size and shape: VF and F; irregular, but approximately equidimensional.
- Textural relations: Veinlets of quartz cut muscovite and also follow muscovite-albite contacts. Rims of quartz are on albite grains at contacts with apatite. Quartz embays tourmaline and muscovite (fig. 7). It has inclusions of rounded to euhedral albite; some albite inclusions are optically continuous with nearby embayed grains of albite fig. 7). Graphic to vermicular quartz is included in tourmaline; this same tourmaline also has inclusions of albite and crystal faces against both albite and quartz (fig. 6). Quartz is graphically intergrown with muscovite (fig. 5) and with albite. Quartz grains have sutured contacts with each other.
- Additional data: Strain shadows less pronounced than in albite.

Muscovite
- Size and shape: F; subhedral. Also a small quantity of VF, sericitic mica. Zinnwaldite(?) in one specimen.
- Refractive indices: The zinnwaldite(?) has β slightly below 1.57.

TABLE 2.—*Mineralogy and petrograph of zone 1, albite-quartz-muscovite pegmatite*—Continued

Muscovite—Continued
- Textural relations: Muscovite has inclusions of rounded to euhedral tourmaline and apatite. Some muscovite has crystal faces against albite, but more commonly muscovite is embayed by or interstitial to albite. A small tablet of muscovite in figure 7 is included in quartz that embays coarser muscovite. Aggregates of very fine grained muscovite (0.02 mm) are along albite grain boundaries.
- Additional data: Zinnwaldite(?) has $2V$ of 30° and light-brown pleochroism.

Tourmaline
- Size and shape: F; subhedral to euhedral. Size increases markedly from contact inward.
- Textural relations: Tourmaline occurs as skeletal crystals containing many inclusions, mostly of graphic to vermicular quartz but also of albite and apatite (fig. 6). These tourmaline crystals are commonly subhedral: on some sides they have crystal faces against albite and quartz, and on other sides they have highly irregular boundaries against these same minerals; albite is somewhat more abundant on sides with crystal faces than along the irregular sides. Rounded to euhedral skeletal crystals of tourmaline containing quartz are included in albite. Needlelike inclusions, 0.06 mm long, included in albite are probably tourmaline.
- Color: Black (variety, schorlite). Pleochroic from light blue to deep blue.

Apatite
- Size and shape: Apatite occurs as rounded grains and as needles (0.03 mm long) included in albite and muscovite, and as larger (but still VF) anhedral grains.
- Refractive indices: $\omega=1.63$.
- Textural relations: Apatite occurs as anhedral grains interstitial to albite. Apatite is wrapped around albite grains, some of which are separated from the apatite by a rim of quartz. It also forms rounded to euhedral inclusions in albite, muscovite, and tourmaline (fig. 6).
- Color: Green.

Fe–Mn phosphate
- Refractive indices: $\gamma=1.69$.
- Textural relations: Fe–Mn phosphate was observed only in the outer part of an apatite grain, where it probably is an alteration product of apatite.
- Color: Clove brown.
- Additional data: Biaxial(?); parallel extinction; length slow. Pleochroic, pink to colorless.

The average grain size is about a quarter of an inch, but individual crystals and aggregates of a single mineral are as much as 1 inch long. At the contact with the schist the rock is very fine grained, but the grain size increases inward as the rock assumes the characteristics of the wall zone. The texture is largely granular (fig. 4) and most of the minerals show no preferred orientation, although some muscovite and tourmaline crystals at the outer edge of the zone are perpendicular to the schist contact. In a few places muscovite flakes are arranged parallel to the contact.

The albite has 3 to 4 percent anorthite in zone 1, but less than 1 percent in all other units, according to the analyses in table 13. As the difference in composition is so slight, the difference in the index of refraction is also small. Nevertheless, figure 68 shows that albite from zone 1 tends to be of higher index than that from inner units. Single grains and aggregates of albite commonly have material of higher index in the center than on the edge, but there is no zoning in the sense that distinct symmetrically distributed zonal boundaries can be recognized in thin section.

PARAGENESIS

The textural relations (table 2) that can be used to determine paragenesis indicate that the minerals of this unit crystallized largely contemporaneously. Figures 5 and 6 show intergrowths of the principal minerals of this zone that probably could have formed only by crystallization of the minerals during very nearly the same period of time. On the other hand, there is textural evidence for a sequence in which the principal period of crystallization of each mineral is in the order: (1) tourmaline, (2) muscovite, (3) quartz, and (4) albite (fig. 13).

Tourmaline crystals not only have well-defined crystal faces against albite and quartz of the matrix, but also are intimately intergrown with and embayed by these same minerals. Such crystals commonly have a skeletal structure caused by the great abundance of graphic to vermicular inclusions of quartz and albite (fig. 6). Along euhedral borders of tourmaline, these inclusions are ordinarily not in optical continuity with grains of the matrix. Some skeletal tourmaline crystals containing abundant quartz appear as inclusions in albite. These inclusions, together with the euhedral and embayed borders, indicate that at least part of the tourmaline crystallized before the other minerals. Nevertheless, the intimate intergrowths permit little doubt that tourmaline was largely contemporaneous with quartz and albite.

Muscovite was also generally early, but it probably formed after the tourmaline inclusions that it contains. Muscovite is embayed by both albite and quartz (fig. 7), and has crystal faces against them.

Quartz is graphically intergrown with both albite and muscovite (fig. 5), just as it is with tourmaline, and it must have overlapped with all of these minerals. Quartz contains small inclusions of rounded to euhedral albite, some of which are optically continuous with nearby embayed grains of albite (fig. 7), showing that quartz followed part of the albite. Usually, however, the borders show no evidence that one mineral is later than the other, or else albite embays quartz. Probably most of the albite crystallized either at the same time or somewhat later than the adjacent quartz. The small quantity of quartz that forms veinlets or is distributed along contacts of other minerals was very late.

Both albite and quartz have strain shadows, but albite was more susceptible to deformation than quartz. The absence of strain features in earlier muscovite may mean the muscovite took up the deformation along its cleavage as the crystalline material was stressed.

Apatite has an extensive range in age. Small grains, rounded to euhedral in shape, appear as inclusions in muscovite, albite, and tourmaline. On the other hand, many larger grains formed so late that they are interstitial to the grains of albite aggregates. Some apatite surrounds albite grains, and at several such places the albite has a rim of quartz at its contact with apatite.

A small quantity of very fine grained muscovite, presumably deuteric, occurs as aggregates along the borders of albite grains. The possibility that such mica here or elsewhere in the pegmatite may be paragonite, containing sodium derived from albite, has not been investigated.

ZONE 2: QUARTZ-ALBITE-MUSCOVITE PEGMATITE

DESCRIPTION

Zone 2, the wall zone, consists of quartz-albite-muscovite pegmatite (table 3). It is 8 to 10 feet thick on the footwall of the south segment, and ordinarily between 2 and 5 feet thick elsewhere.

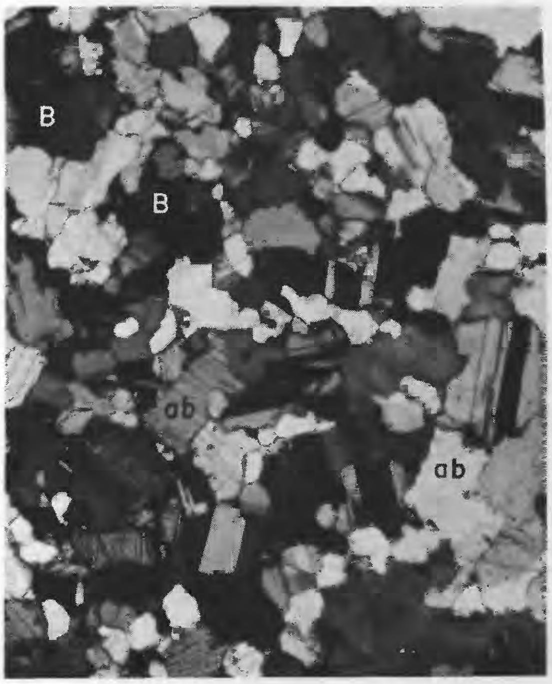

FIGURE 4.—Photomicrograph of granular aggregate of albite. Zone 1 at the south border of the south segment. Crossed nicols. ab, albite; B, balsam in hole in slide. × 52.

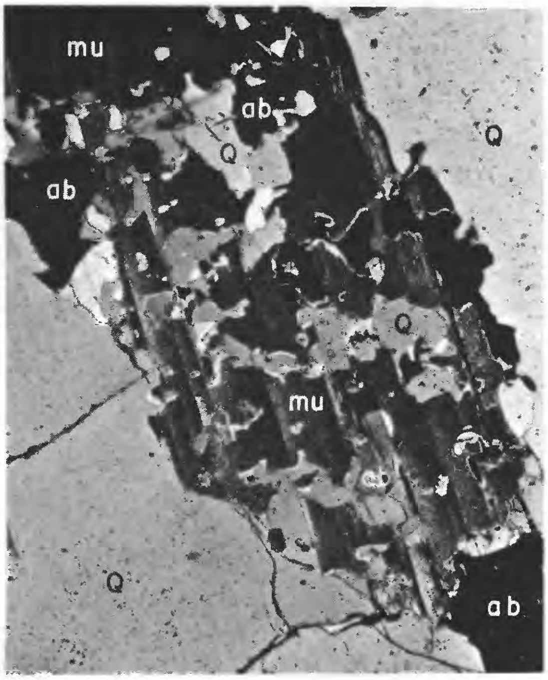

FIGURE 5.—Muscovite graphically intergrown with quartz. The quartz has inclusions of albite. Zone 1 on the footwall of the north segment, in the west drift on the 4,446-foot level. × 32.

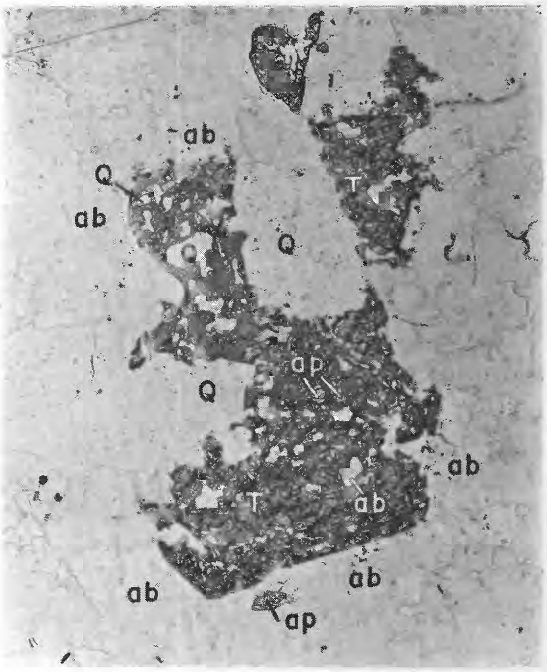

FIGURE 6.—Tourmaline with graphic inclusions of quartz and albite. The contacts of tourmaline with the albite-quartz matrix are mostly irregular, but are partly crystal faces. Apatite appears as inclusions in the tourmaline and as anhedral grains surrounded by albite. Zone 1 on the footwall of the north segment, in the west drift on the 4,446-foot level. × 18.5.

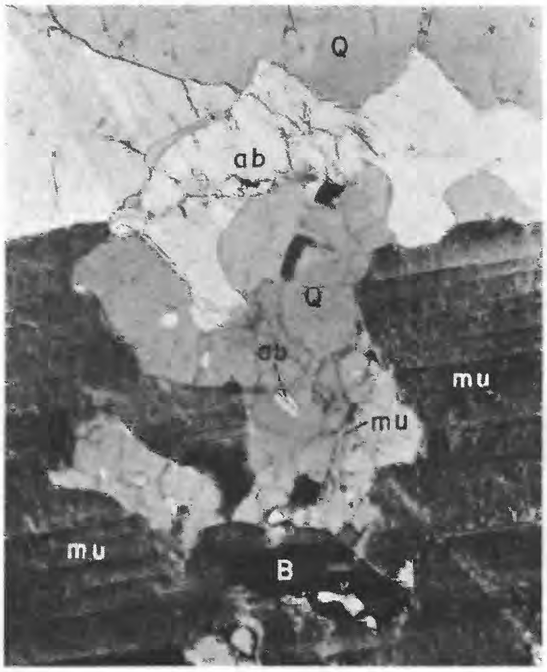

FIGURE 7.—Coarse muscovite cut by an embayment that consists mainly of quartz. A small tablet of muscovite surrounded by quartz appears in the embayment. The quartz also embays albite and has optically continuous inclusions of albite. Zone 1 on the footwall of the south segment near the south end of the drift on the 4,446-foot level. X 97.

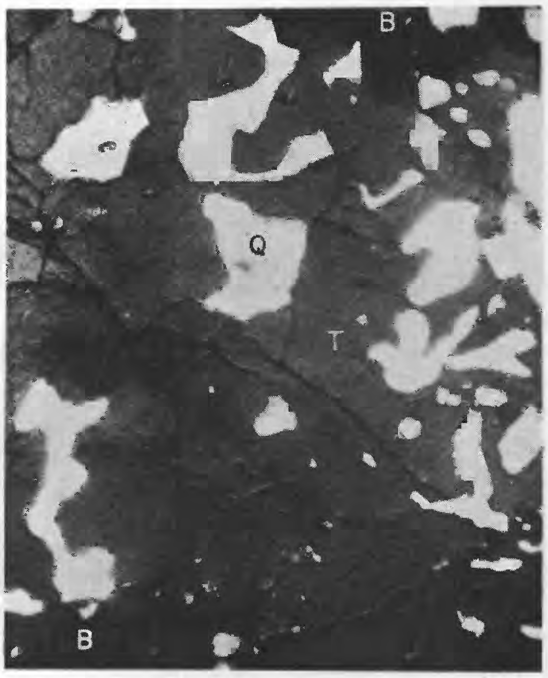

FIGURE 8.—Tourmaline with graphic inclusions of quartz. Zone 2 at the south border of the south segment. × 97.

FIGURES 5–12.—PHOTOMICROGRAPHS OF ZONES 1 AND 2. ALL ARE UNDER CROSSED NICOLS EXCEPT C, WHICH IS UNDER PLANE-

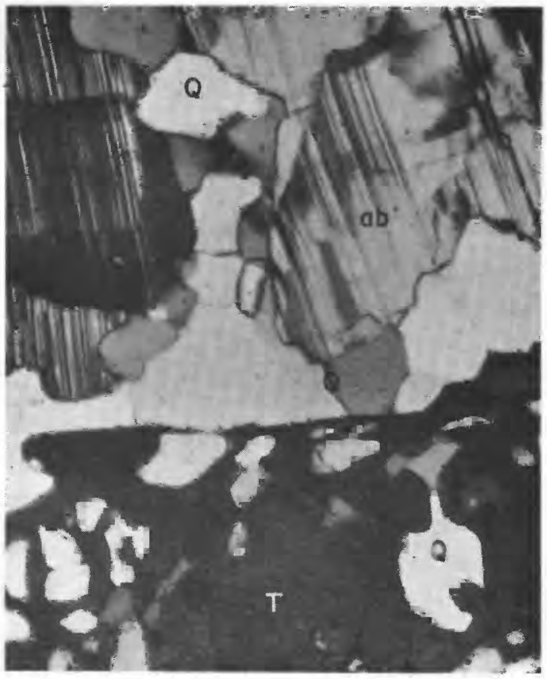

FIGURE 9.—A veinlet of quartz that follows a crystal face of tourmaline and cuts across adjacent albite. The tourmaline has graphic inclusions of quartz. Zone 2 at the south border of the south segment. × 110.

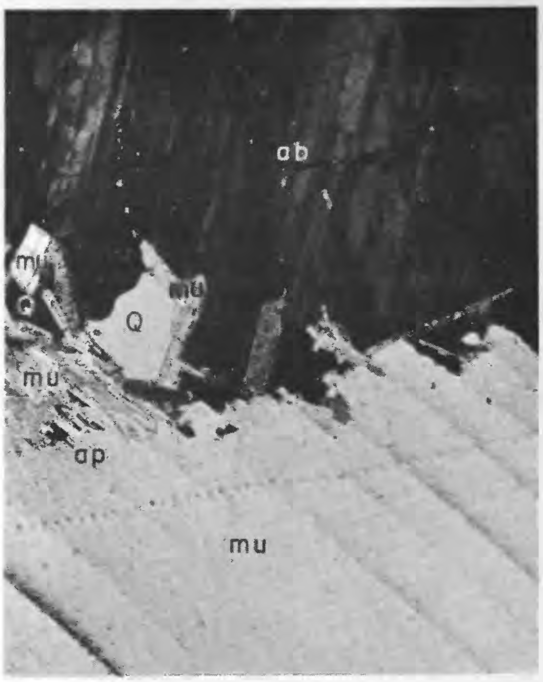

FIGURE 10.—Coarse muscovite embayed along its cleavage by albite. Finer grained muscovite with quartz and apatite is distributed along the contact between the albite and coarse muscovite. Some of the fine-grained muscovite is oriented parallel to albite twinning planes. Zone 2 on the footwall of the north segment, in the west drift on the 4,446-foot level. × 32.

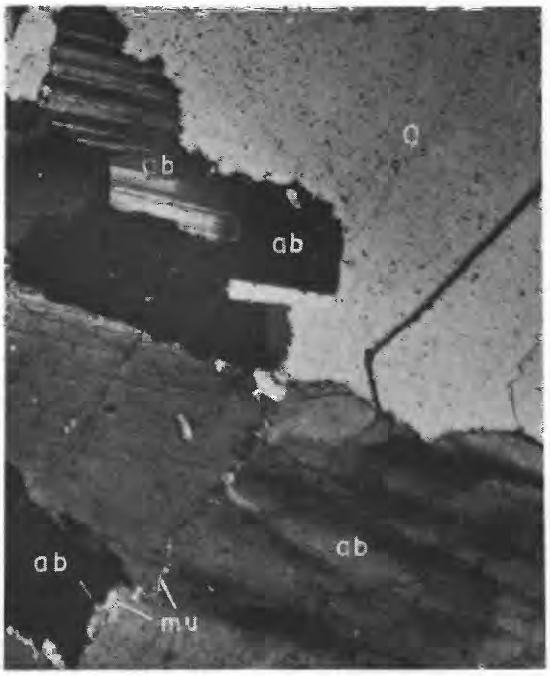

FIGURE 11.—Albite that is embayed by quartz and has crystal borders against quartz. Fine-grained muscovite is along contacts between albite grains. Zone 2 on the footwall of the north segment, in the west drift on the 4,446-foot level. × 40.

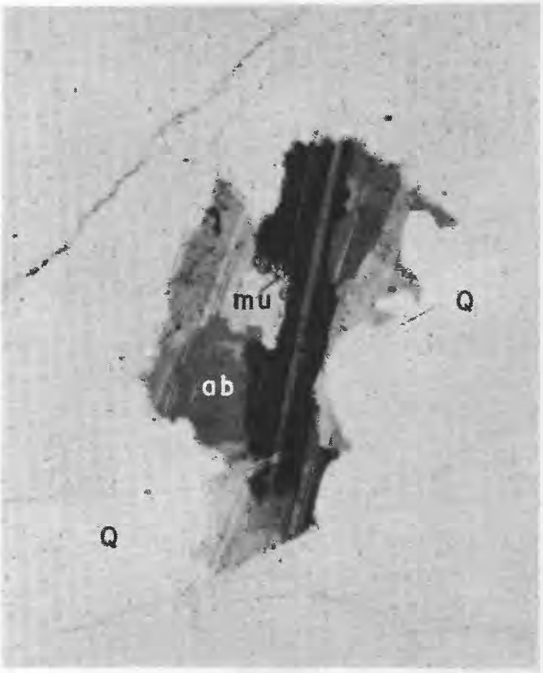

FIGURE 12.—Embayed inclusion of albite in quartz. Fine-grained muscovite is along a contact between albite grains. Zone 2 on the footwall of the north segment, in the west drift on the 4,446-foot level. × 32.

POLARIZED LIGHT. Q, QUARTZ; ab, ALBITE; mu, MUSCOVITE; t, TOURMALINE; ap, APATITE; B, BALSAM IN HOLE IN SLIDE.

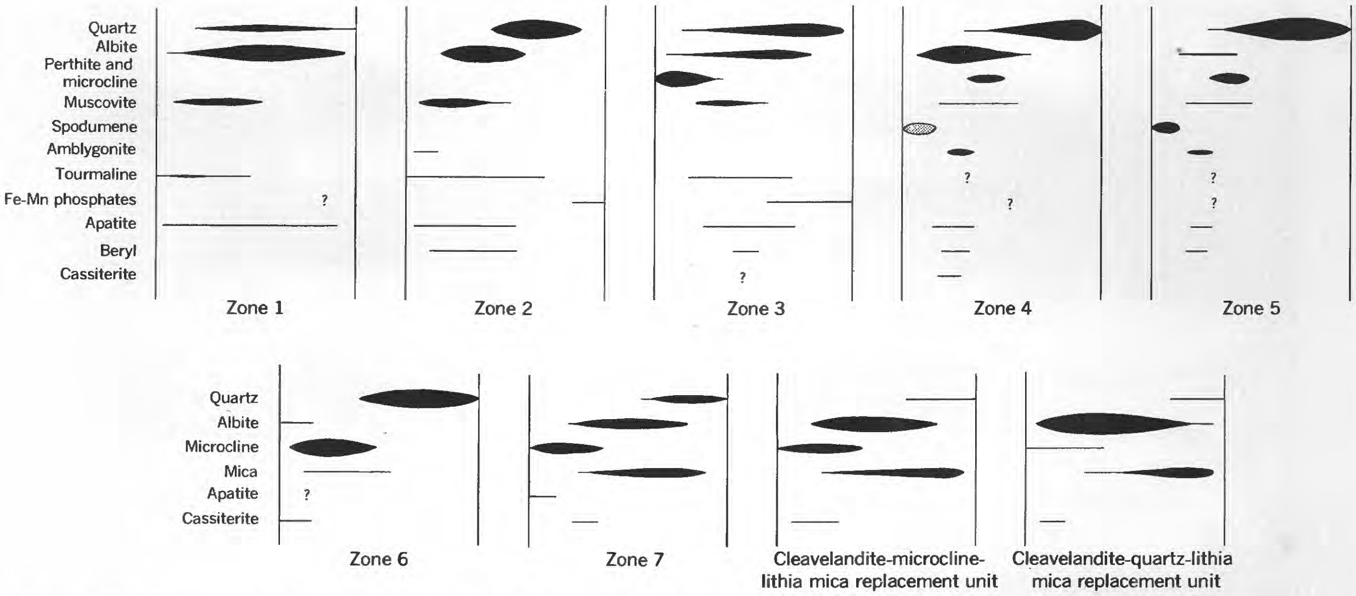

FIGURE 13.—Paragenesis of the units in the Hugo pegmatite, based on textures described in tables 2–4 and 6–11. Deuteric materials are omitted. Relict minerals are excluded from the diagrams of the replacements units. Black areas are proportional to the abundance of the minerals within each unit. Question marks for incompletely known minerals are in the most probable position of these minerals in the paragenetic sequence. All the spodumene of zone 4 was resorbed and its place taken by other minerals of the zone.

This zone consists chiefly of a fine- to medium-grained groundmass of quartz and albite surrounding larger crystals of muscovite and tourmaline. Less abundant minerals include beryl, apatite, iron-manganese phosphates, and amblygonite. The proportions of component minerals, especially muscovite and beryl, differ greatly from place to place. Along the north side of each segment this zone contains only small quantities of muscovite or beryl, but on the south side it contains as much as 50 percent muscovite and 1 percent beryl.

In places zone 2 can be subdivided into as many as four smaller units on the basis of the relative abundance of quartz, albite, muscovite, and tourmaline. Some surface exposures on the footwall of each segment of the pegmatite contain more than 50 percent black tourmaline in the outer 2 feet (fig. 14). This grades into a layer that is rich in large books of muscovite. The muscovite-rich layer grades into one characterized by abundant blue-black tourmaline and small books and flakes of muscovite. The iron-manganese phosphate minerals, such as triphylite-lithiophilite and their alteration products, occur along the inner edge of the zone, especially where zone 3 is absent. On the 4,549-foot level the wall zone, from the border zone inward, consists of (a) 1 to 2 feet of rock containing 50 percent tourmaline in crystals as much as 18 inches in diameter, (b) 2 feet containing 30 percent muscovite in books as much as 2 feet long, and (c) 4 feet containing muscovite in books less than 6 inches in maximum dimension.

The quartz and albite of the groundmass are the most abundant minerals. Outer parts of albite crystals tend to be lower in index than inner parts, but as in zone 1, plagioclase zoning is not at all apparent in thin section. The albite includes blocky grains and the platy variety known as cleavelandite, both of which are intergrown with other minerals. The cleavelandite is in radial aggregates. The quantity of cleavelandite generally increases and blocky albite decreases inward across the zone; cleavelandite is most common near contacts with replacement units or inner zones in which cleavelandite is the dominant plagioclase. The refractive index of the plagioclase tends to go down as the proportion of cleavelandite becomes greater.

Muscovite, beryl, and black tourmaline form the largest crystals of the wall zone; some are as much as 3 feet in diameter. Muscovite occurs in large wedge-shaped books that are soft, heavily air stained, and contain herringbone structure. Beryl commonly forms tapered, euhedral crystals in which the small end is toward the outside of the zone. Many of these tapered crystals are composed of shells of beryl that alternate with shells of groundmass minerals. Other crystals are euhedral to anhedral, and some contain virtually no inclusions. Beryl of a high index of refraction seems to be associated with albite of high index, and beryl of low index with albite of low index (table 3). However, in the pegmatite as a whole, the index of beryl generally increases as that of albite decreases (fig. 68).

TABLE 3.—*Mineralogy and petrography of zone 2, quartz-albite-muscovite pegmatite*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Quartz

Size and shape: VF to M; rarely more than 2 inches; anhedral to subhedral.

Megascopic textural relations: Quartz is intergrown with albite to form the matrix surrounding large muscovite crystals.

Microscopic textural relations: Quartz embays albite (figs. 11, 12). It forms veinlets in the blue tourmaline of the Fe-Mn phosphate aggregates, and is graphically intergrown with similar tourmaline (figs. 8, 9). Quartz separating albite and blue tourmaline forms embayments in the albite and is in contact with a crystal face of tourmaline (fig. 9). Quartz commonly has mutual contacts with albite and muscovite. Quartz grains have sutured contacts with each other.

Additional data: Has strain shadows.

Albite

Size and shape: Mostly F and M, but ranges from sugary to as much as 2 inches. Blocky to platy; the proportion of blocky material decreases and platy material (cleavelandite) increases from the outer to the inner part of the zone. Cleavelandite forms radial aggregates.

Refractive indices: $\alpha'=1.528$ to 1.534. Outer parts of grains commonly have lower index than inner part. Index also tends to decrease from outer to inner part of zone. Low index albite (especially with α' of 1.528) may have been introduced during the development of the replacement bodies.

Megascopic textural relations: Described under quartz.

Microscopic textural relations: Albite embays large muscovite grains along their cleavage (fig. 10). It has mutual contacts with muscovite and quartz. It also has crystal faces against quartz and is embayed by quartz (figs. 9, 11, and 12), and forms inclusions in quartz that is graphically intergrown with tourmaline. It also embays quartz.

Additional data: Some of the albite is deformed and has undulating extinction.

Muscovite

Size and shape: Mostly C but also VC on footwall of south segment; M elsewhere. The largest crystals are 2 feet in diameter. Flat to wedge "A"; anhedral to subhedral.

Refractice indices: $\beta=1.58$–1.59.

Megascopic textural relations: Large crystals of muscovite are surrounded by albite and quartz; some of muscovite has crystal faces against albite and quartz. Muscovite has inclusions of tourmaline, albite, quartz, and apatite.

Microscopic textural relations: Coarse muscovite has mutual contacts with coarse quartz, and rare crystal faces against albite. Muscovite grains 0.3 mm long are associated with quartz and apatite along a contact between large grains of albite and muscovite; the coarse muscovite is embayed by the albite, but some of the finer muscovite follows albite twinning (fig. 10). Very fine grained muscovite (0.01 mm) occurs along grain boundaries and as fracture fillings, especially in association with albite (figs. 11, 12).

Color: Pale ruby. Heavy airstain gives silvery appearance.

Additional data: Soft; very flexible.

TABLE 3.—*Mineralogy and petrography of zone 2, quartz-albite-muscovite pegmatite*—Continued

Tourmaline

Size and shape: Black tourmaline is mostly M to C, but some crystals are 1.5 feet wide; anhedral to euhedral. Blue-black and blue tourmaline are in needles, VF and F.

Refractive indices: Blue-black tourmaline has somewhat lower indices of refraction than black tourmaline.

Megascopic textural relations: Grossly euhedral form is common in black, blue-black, and blue tourmaline. All varieties have crystal faces against muscovite, albite, and quartz. Black tourmaline has inclusions of muscovite, albite, and quartz, subgraphic intergrowths with quartz, and fractures filled by muscovite, albite, and quartz.

Microscopic textural relations: Blue tourmaline from phosphate aggregates contains graphic quartz (figs. 8, 9). Black tourmaline has embayed inclusions of albite, some of which are optically continuous; it also has euhedral inclusions of apatite. Crystal faces are in contact with muscovite, albite, and quartz. Very fine needlelike inclusions (0.04 mm long), mostly in albite but also in quartz, are probably tourmaline.

Additional data: Black tourmaline is most abundant in the outer 2 feet of the zone (fig. 14). Blue-black tourmaline is characteristic of the inner part of the zone; commonly the inner edge of the zone has a 2-inch layer in which these crystals are abundant. Blue tourmaline is associated with Fe–Mn phosphates.

Beryl

Size and shape: Mostly M to C, but some crystals are 3 feet in diameter; anhedral to euhedral. Commonly oriented at right angles to the contact. Some crystals are tapered, such that the large end is toward the inner part of the pegmatite.

Refractive indices: $\omega=1.578$ to 1.588. Beryl with $\omega=1.578$ is associated with albite having $\alpha'=1.528$; beryl of $\omega=1.588$ is with albite of $\alpha'=1.534$.

Megascopic textural relations: Beryl shows strong tendency to have euhedral form. Crystal faces are in contact with muscovite, albite, and quartz. Crystal faces are commonly pitted and rough, or coated with yellow-green mica. Beryl has euhedral and rounded inclusions of apatite and tourmaline. Skeletal crystals consist of shells of beryl alternating with shells of groundmass minerals, especially albite, quartz, and muscovite.

Color: Predominantly yellowish white; also pale green, white, or colorless.

Additional data: Beryl is most abundant along footwall.

Apatite

Size and shape: F to M; largest crystals are 2 inches long; subhedral to euhedral.

Refractive indices: $\omega=1.64$ to 1.65.

Megascopic textural relations: Apatite has embayed inclusions of muscovite. Skeletal crystals consist of thin shells of apatite alternating with thin shells containing albite, quartz, muscovite, and beryl. In some places minerals of the groundmass are continuous with shells of the same composition.

Microscopic textural relations: Aggregates of apatite(?) form veinlets and embayments in albite. Similar material forms rims around Fe-Mn phosphate aggregates and veinlets in minerals adjacent to these aggregates. Euhedral apatite occurs as inclusions in blue tourmaline and albite.

Color: Blue, blue gray, and blue green.

TABLE 3.—*Mineralogy and petrography of zone 2, quartz-albite-muscovite pegmatite*—Continued

Fe–Mn phosphates (triphylite-lithiophilite, heterosite-purpurite, and dufrenite have been tentatively identified)
  Size and shape: F and M. Nodular aggregates as much as 2 feet in diameter are rich in phosphates, but also contain quartz, albite, muscovite, blue tourmaline, and other minerals.
  Megascopic textural relations: Fe–Mn phosphates are associated chiefly with albite and tourmaline. They are too greatly stained by iron and manganese oxides for adequate textural data to be obtained.
  Microscopic textural relations: Fe–Mn phosphates embay and fill fractures in albite, tourmaline, quartz, and apatite.
  Additional data: These phosphates occur chiefly near contact of zone 2 with zone 4. (See table 5 for data obtained by M. L. Lindberg.)
Amblygonite (montebrasite)
  Size and shape: M; rounded.
  Megascopic textural relations: Rounded borders of amblygonite crystals are in contact with albite, quartz, and muscovite.

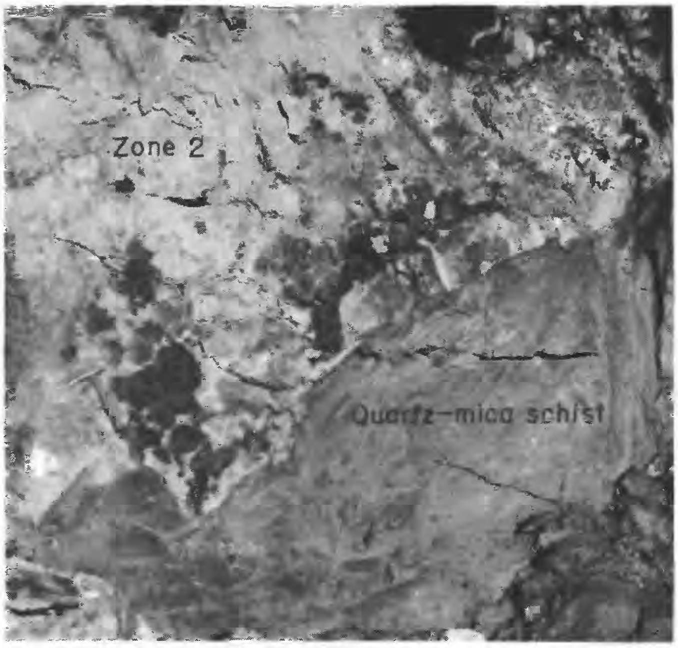

FIGURE 14.—Layer rich in black tourmaline in the outer part of zone 2, along the south border of the Hugo pegmatite.

Tourmaline crystals decrease in size and abundance from the outer to the inner part of the wall zone. Large black crystals are a major constituent of the outer 1 to 2 feet of the zone, and smaller crystals of black tourmaline are scattered through all of the outer part of the zone. As the quantity of black tourmaline decreases, fine-grained crystals of blue-black tourmaline become more abundant. Blue-black tourmaline is especially characteristic of the inner part of the zone; in places, the inner edge of the wall zone is marked by a 2-inch layer in which these crystals are concentrated.

Nodular aggregates containing iron-manganese phosphate minerals, although most abundant in zone 3, also occur along the inner contact of zone 2 where zone 3 is absent. These aggregates are greatly altered and so heavily stained by manganese and iron oxides that the minerals and textures are difficult or impossible to recognize. Although lithiophilite-triphylite may have been the most abundant primary phosphate, heterosite is probably dominant in present exposures, according to M. L. Lindberg (oral communication, 1955), who based her opinion on field examination as well as laboratory work with typical specimens. Greenish-gray to blue triphylite and olive-green dufrenite have been tentatively identified. Albite and blue tourmaline are the most abundant minerals closely associated with the phosphates.

PARAGENESIS

The textural relations in zone 2, as in zone 1, indicate that the dominant feature of the paragenesis is the virtually contemporaneous nature of the minerals. The overlapping sequence indicated in figure 13 is similar to the sequence in zone 1: (1) tourmaline, (2) amblygonite, (3) muscovite, (4) apatite, (5) beryl, (6) albite, (7) quartz, and (8) iron-manganese phosphates. Many grains of tourmaline and beryl and a few of muscovite have crystal faces that can be recognized megascopically, and the quartz and albite of the groundmass are chiefly anhedral. These gross relations, suggesting that the quartz and albite formed later than the other minerals, are partly supported by microscopic data, but other relations recognized both megascopically and microscopically are evidence for overlap in the times of crystallization.

Perhaps the firmest evidence for overlap is provided by skeletal crystals of beryl and apatite. These crystals consist of thin shells of beryl or apatite alternating with thin shells containing albite, quartz, and muscovite. In places, quartz and albite of the groundmass are continuous with shells of these same minerals. Possibly the shells of beryl and apatite grew first, resembling the skeletal ice crystals photographed by Schaefer (1946, fig. 2), and the spaces were filled shortly thereafter by the other minerals, but there can be little doubt that the apatite and beryl were virtually contemporaneous with muscovite, albite, and quartz.

Skeletal crystals of beryl have been described and illustrated many times in pegmatite literature, and they commonly have been interpreted as indicating virtually simultaneous crystallization of beryl and the associated minerals. The published descriptions indicate that skeletal beryl of the Black Hills is similar to that of other areas. In the Black Hills, such beryl is mainly in outer zones. Tapered crystals are perpendicular to the pegmatite contact, and the small end is nearest the contact. The skeletal intergrowths appear in the middle and at the large end of the crystal; the small end consists only of beryl. The most satisfactory explanation of this arrangement is that the beryl grew from a favorably oriented seed near the small end, and as it grew, it surrounded and became intergrown with other minerals forming at the same time. Page and others (1953, p. 45) published a drawing of such a crystal from the Florence pegmatite and also drawings of a prismatic crystal of skeletal beryl from the Helen pegmatite in the Black Hills.

The earliest thorough discussion of this texture was in an article by Shaub (1937) that contains several good photographs of beryl from New England. Shaub concluded not only that the crystallization of the beryl and intergrown albite was virtually contemporaneous, but also that this texture was not in harmony with the replacement theories of pegmatite genesis that held wide favor at that time. Johnston (1945, p. 1032–1034) presented excellent drawings of three skeletal crystals from Brazil, where beryl is chiefly in core-margin zones, and arrived at the same conclusion as Shaub.

More recently, this texture has been observed and similarly interpreted by Davies (1957, p. 20) in the Winnipeg River area of southeastern Manitoba. He provided a succinct account of it that could apply to other areas:

> It is not uncommon to find a shell of beryl, showing hexagonal outline, surrounding a core of albite. Small 'veinlets' of beryl cut the albite core, and many of these 'veinlets', conversely, are penetrated by albite. Quartz, also, fills fractures in some beryl crystals. Mineral relationships, in general, indicate that the beryl, quartz, and albite crystallized more or less at the same time.

Heinrich (1948, p. 557–559) offered a contrary view by stating that skeletal beryl is found only in replacement units in Eight Mile Park, Colo., and that albite and quartz replace selected zones in the beryl. Although Heinrich regarded all of the beryl and albite as of hydrothermal origin, his drawings of skeletal beryl are similar to those published elsewhere, and this beryl is concentrated in core-margin units that other geologists might describe as zones instead of replacement bodies (Heinrich, 1948, p. 441–442, 558, 569–584).

Tourmaline in zone 2 of the Hugo pegmatite is in many ways like the beryl. It provides evidence for overlap in that its commonly euhedral form indicates an early age, yet it contains inclusions of muscovite, albite, quartz, and apatite. Furthermore, it has subgraphic and even graphic intergrowths with quartz (figs. 8, 9). The blue tourmaline of the phosphate aggregates contains embayed, optically continuous inclusions of albite.

Large grains of muscovite are shown by figure 10 to be embayed along their cleavage by albite, and they evidently formed at a fairly early stage. Smaller grains are shown in the same illustration in association with quartz along the contact between larger grains of muscovite and albite. Some of these small muscovite grains are oriented paralell to the albite twinning planes, and must have formed later than the albite.

Albite generally preceded quartz. It has crystal faces against quartz, and it commonly is embayed or veined by quartz (figs. 9, 11, 12). Some overlap is indicated by embayments in quartz and by many mutual contacts and intergrowths with quartz and muscovite; part of the intergrowths are included in skeletal crystals of beryl and apatite.

Amblygonite occurs as crystals having rounded borders in contact with albite, quartz, and muscovite. Like the amblygonite of inner zones, it probably formed early.

The iron-manganese phosphates are so heavily stained and altered that the age of the primary phosphate minerals cannot be determined readily. Many of the fracture fillings and embayments of phosphate minerals in albite, tourmaline, quartz, and apatite may have formed during relatively recent alteration. On the other hand, only the most dubious evidence indicates that any of these phosphates preceded the associated minerals, and it may be tentatively concluded that the primary phosphates formed late in the paragenesis.

Very fine grained aggregates of muscovite found chiefly along albite grain boundaries and as veinlets in albite probably are deuteric products (figs. 11, 12). Other veinlets consisting of very fine grained aggregates that probably are mostly apatite may also have been deuteric. Similar aggregates form rims on the iron-manganese phosphate patches; they may have formed during the alteration of the phosphates, and must have followed the primary phosphate minerals.

ZONE 3: PERTHITE-QUARTZ-ALBITE PEGMATITE, QUARTZ-PERTHITE-ALBITE PEGMATITE, ALBITE-QUARTZ-PHOSPHATE PEGMATITE, AND QUARTZ-ALBITE PEGMATITE

DESCRIPTION

Zone 3 has been subdivided on the maps and sections (pls. 9, 10) into three parts: zone 3a, perthite-quartz-albite pegmatite; zone 3b, quartz-perthite-albite pegmatite; and zone 3c, quartz-albite pegmatite (table 4). The boundaries between these units are drawn on the basis of perthite content, which is greatest near the top of the pegmatite and decreases downward and inward.

Zone 3a contains 50 percent or more perthite, zone 3b from 5 to 50 percent, and zone 3c less than 5 percent.

Many pods of albite-quartz-phosphate pegmatite distributed through zone 3 are shown separately on the geologic map (pl. 9). These are most abundant near the inner edge of zone 3b. One of these pods is 50 feet long and 20 feet thick, but most of them are less than 10 feet long and 5 feet thick, and many are too small to show on the map.

Zone 3a has been recognized only in the upper part of the south segment (pls. 9, 10), where it has a maximum exposed thickness of about 20 feet. The geologic sections show that it probably formed an asymmetric hood at the top and along the hanging wall of the pegmatite, but most of this hood has been removed by mining.

TABLE 4.—*Mineralogy and petrography of zone 3a (perthite-quartz-albite pegmatite); zone 3b (quartz-perthite-albite pegmatite); and zone 3c (quartz-albite pegmatite)*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Quartz

Size and shape: VF to M; maximum size about 2 inches; mostly anhedral, but some subhedral.

Megascopic textural relations: Intimately intergrown with albite. Much of the albite has a veinlike form in quartz, but its contacts with quartz are commonly mutual.

Microscopic textural relations: Quartz embays albite (figs. 17, 18), muscovite, and beryl. Some embayments in albite are localized along cleavage. Quartz that embays albite may also be optically continuous with inclusions of quartz in the albite. Quartz has embayed inclusions of muscovite. Tourmaline and quartz form graphic intergrowths; in places the quartz in and near these intergrowths has albite inclusions, some of which are optically continuous (fig. 19). Quartz is subgraphically intergrown with albite (fig. 22). Many contacts of quartz with albite are mutual and not diagnostic of age (fig. 21). Where inclusions of quartz are in both microcline and adjacent albite, they may be optically continuous with each other (fig. 20).

Albite

Size and shape: VF to M, but mostly F; maximum size about 2 inches. Albite occurs as irregular patches and streaks consisting of single grains or aggregates between quartz grains. Most of the albite in blocky or subplaty, but some is in plates as much as 2 inches long.

Refractive indices: α'=1.529 to 1.532.

Megascopic textural relations: Described under quartz.

Microscopic textural relations: Albite embays microcline (fig. 20) and has optically continuous inclusions of microcline. It also embays beryl and muscovite. Laths of albite may have a crystal face against quartz on one side and be embayed by quartz on other sides (fig. 18).

Additional data: Part of albite has undulating extinction.

Perthite

Size and shape: VC. Largest crystal observed was 35 by 15 by 6 feet, but much larger crystals were exposed in the early years of mining (G. M. Schwartz, oral communication, 1948). Crystals are rounded and crystal faces are rare, although the shape is approximately that of euhedral crystals.

TABLE 4.—*Mineralogy and petrography of zone 3a (perthite-quartz-albite pegmatite); zone 3b (quartz-perthite-albite pegmatite); and zone 3c (quartz-albite pegmatite)*—Con.

Perthite—Continued

Megascopic textural relations: Perthite crystals have rounded borders and embayments in contact with the matrix of quartz, albite, and muscovite. Embayments are not localized along cleavages or other structures of microcline. Inclusions consist of albite, muscovite, quartz, tourmaline, and skeletal apatite, especially near edges of the perthite crystals. Albite inclusions are lath-shaped, but rounded and embayed; they have no preferred orientation. Perthitic albite is in lenses and irregular patches that are uniformly distributed through the perthite; the albite seems to have corroded the microcline, but there is no evidence that it was introduced from outside the crystals.

Microscopic textural relations: Microcline has embayed inclusions of albite and quartz, some of which are optically continuous (fig. 16). Irregular patches and streaks of perthitic albite are shown in figure 15. Very small muscovite inclusions are more abundant in the albite than in the microcline.

Color: Buff, white, and gray.

Additional data: Norm has 72.5 percent microcline, 27.4 percent albite, and 0.1 percent anorthite (Figazy, 1949, tables 1 and 4; norm recalculated).

Muscovite

Size and shape: Mostly F and M. Occurs as books and flakes that are ordinarily less than 2 inches across; books more than 6 inches across are rare.

Refractive indices: β=1.59

Megascopic textural relations: Muscovite is intimately associated with the intergrown quartz and albite of the groundmass.

Microscopic textural relations: Muscovite has crystal faces against albite. It is embayed by albite and quartz, and by graphically intergrown quartz and tourmaline. Muscovite inclusions occur in microcline, albite, quartz, beryl, and tourmaline. Aggregates consisting mainly of very fine grained muscovite (0.03 mm), in places containing quartz, are along grain boundaries, especially of albite. Similar aggregates form veinlets in beryl.

Additional data: 2V 40°.

Fe–Mn phosphates (mostly heterosite-purpurite and triphylite-lithiophilite)

Size and shape: F and M; anhedral.

Megascopic textural relations: Fe–Mn phosphates are intergrown with albite, quartz, tourmaline, and muscovite. The phosphates are veined by tourmaline. Gray-green triphylite is surrounded by brown, black, and dark-green alteration products. Phosphate nodules have rounded borders against albite.

Microscopic textural relations: Fe–Mn phosphates embay and vein albite, quartz, tourmaline, and apatite. An unknown mineral, possibly goyazite, appears as very small inclusions in albite; it has rectangular outlines, zonal growths, N about 1.62, birefringence about 0.010, uniaxial positive.

Additional data: The phosphate aggregates are heavily stained by manganese and iron oxides, and by late phosphate minerals. (See table 5 for data obtained by M. L. Lindberg.)

TABLE 4.—*Mineralogy and petrography of zone 3a (perthite-quartz-albite pegmatite); zone 3b (quartz-perthite-albite pegmatite); and zone 3c (quartz-albite pegmatite)*—Con.

Tourmaline
Size and shape: VF and F; rarely more than one-half inch long; anhedral to euhedral.
Refractive indices: Thin sections contain tourmaline in which ϵ is less than the ω of apatite.
Megascopic textural relations: Tourmaline is included in muscovite, albite, quartz, and beryl. Blue tourmaline is closely associated with Fe–Mn phosphates.
Microscopic textural relations: Tourmaline has graphic intergrowths with quartz, some of which contains albite inclusions; it also has crystal faces against quartz and albite. Anhedral tourmaline is along the rim of a larger grain of apatite that is approximately euhedral. A veinlet containing tourmaline crystals 0.02 mm in diameter cuts apatite. Very fine grained needles (0.04 mm long) included in quartz and albite are probably tourmaline.
Color: Blue to black; mostly bright blue in Fe–Mn phosphate aggregates.

Apatite
Size and shape: Mostly F and M; anhedral to euhedral.
Refractive indices: ω=1.63 to 1.64.
Megascopic textural relations: Apatite occurs both in the quartz-albite groundmass and in the Fe–Mn phosphate aggregates. Albite is the most abundant included material in skeletal crystals of apatite.
Microscopic textural relations: Apatite has inclusions of albite that are surrounded by a rim of quartz. Part of the apatite is in altered aggregates that vein and embay albite, quartz, and tourmaline, but also have rounded to euhedral borders against these minerals. Rounded to euhedral inclusions of apatite are in albite and quartz. Very fine grained apatite forms veinlets in or along the borders of other minerals, especially albite.
Color: Blue and blue-green.

Beryl
Size and shape: M to VC; anhedral to euhedral.
Refractive indices: ω=1.577 to 1.590, but mostly 1.584 to 1.586.
Megascopic textural relations: Skeletal crystals of beryl contain inclusions of albite, quartz, muscovite, apatite, and tourmaline. The outer and inner surfaces of the beryl are embayed by these minerals. Beryl is in part sericitized, especially along crystal faces.
Microscopic textural relations: Beryl embays tourmaline and has embayed inclusions of albite (fig. 23), quartz, and apatite. Some inclusions of quartz are optically continuous with each other. Straight crystal borders, which probably are crystal faces of beryl, are in contact with intergrown quartz and tourmaline and also quartz and albite (fig. 22).
Color: Green to white.

Zone 3a grades downward and inward into zone 3b. In the north segment, zone 3b is the uppermost subdivision recognized. Thicknesses as great as 65 feet are exposed, and the asymmetric hood structure is well defined (pl. 9).

The quartz-albite pegmatite of zone 3c is exposed only in the underground workings (pl. 9), where it lies beneath the perthite-rich units. Its greatest known thickness is about 30 feet, but as section B-B′ shows, it may be thicker in deep, unexposed parts of the pegmatite.

Zone 3 contains very large perthite crystals in a matrix of fine- to medium-grained pegmatite consisting chiefly of quartz and albite. Other common minerals are muscovite, iron-manganese phosphates, and tourmaline. Minor accessory minerals include apatite, beryl, and a few crystals of cassiterite, tantalite-columbite, and possibly stannite.

Perthite occurs as somewhat elongate rounded masses that rarely have crystal faces, but nevertheless have nearly the shape of euhedral microcline crystals. The largest crystal observed contained an estimated 250 tons of perthite. G. M. Schwartz (oral communication, 1948) saw much larger crystals exposed during the early history of the Hugo mine.

Perthitic albite is uniformly distributed throughout the crystals. It appears mainly as thin lenses that are easily visible megascopically, but in detail it forms many veinlets and irregular patches (fig. 15). A normative calculation of an analysis published by Higazy (1949, table 1) shows 27.4 percent albite in perthite from this zone. Inasmuch as there is 10.4 percent normative albite in microcline of zone 6, which has very little modal albite, the perthite of zone 3 probably contains 5 to 10 percent albite in solid solution in the microcline and about 20 percent visible albite.

Poikilitically included albite in the perthite shows little evidence of a preferred orientation. Black and blue tourmaline, muscovite, quartz, and skeletal crystals of apatite are also included in perthite, especially near the edges of crystals.

The matrix surrounding these large perthite crystals consists predominantly of quartz and albite. The albite occurs as irregular patches, streaks, veinlike masses, and blocky to subplaty crystals around and between quartz grains. Muscovite, tourmaline, and apatite are accessory minerals in the matrix. They occur as single crystals, inclusions, and intergrowths with other minerals.

Beryl is only a minor mineral of zone 3, but crystals weighing more than a ton have been mined. A skeletal crystal of beryl collected from zone 3c in the west drift on the 4,446-foot level contained quartz, albite, muscovite, apatite, and tourmaline.

Heavily stained aggregates containing iron-manganese phosphates are a prominent constituent of the inner part of perthite-rich pegmatite in zone 3. The dominant phosphates are heterosite-purpurite and triphylite-lithiophilite, which may be the only primary mineral. M. L. Lindberg has also identified triplite and childrenite (table 5). The triphylite grains tar-

TABLE 5.—*Mineralogy of certain minor*

[Data obtained by M. L. Lindberg,

Specimen No.	Description of specimen	MINERALS	
		Name	Description
Zone 2			
JJN 76–46	Phosphates associated with cleavelandite, quartz, and muscovite. Bears limonite stains and other alteration products.	Apatite	Vitreous; blue-green
		Unknown	Brown phosphate altering to heterosite-purpurite.
		Heterosite-purpurite	Alteration product of the unknown brown phosphate.
Albite-quartz-phosphate			
JJN 65–46	Phosphates associated with albite, quartz, and blue tourmaline.	Triphylite	Grayish-green
		Heterosite-purpurite	
JJN 110–46	Phosphates associated with cleavelandite and small quantities of muscovite, apatite, and other minerals. Cleavelandite has yellowish-green alteration products. Phosphates and cleavelandite are crudely layered.	Unknown	Dark-green
		Aggregates of unknown minerals.	Yellowish-green alteration products associated with albite.
		Tourmaline	Blue
		Triphylite	Grayish-green
		Triplite	
		Heterosite-purpurite	
		Unknown	Green
JJN 111–46	Contains crudely developed layers of white albite, albite with green stains, and phosphates and blue to black tourmaline. Also contains gray quartz, muscovite, and alteration products of different minerals.	Unknown carbonate minerals.	
		Childrenite	Buff; cellular
		Unknown	Green alteration product of childrenite
		Unknown	Brown
Zone 4			
JJN 87–46	Buff to greenish fine-grained material resembling altered spodumene. Consists mostly of sericitic muscovite; also contains quartz. From one of the blade-shaped aggregates of zone 4.	Muscovite	Sericitic
JJN 103–46	Pale-pink, chalky to fibrous aggregate that coats ambylgonite. Enclosed in cleavelandite.	Mixture of muscovite and cleavelandite.	The muscovite is partly platy and partly very fine grained.
JJN 109–46	Buff clayey coating on amblygonite. From between amblygonite and cleavelandite.	Halloysite	Associated with cleavelandite, muscovite, and calcite.
		Unknown	Brown. $G>2.88$

minerals of the Hugo pegmatite

U.S. Geological Survey]

MINERALS—continued		
Optical data	Comparison with material from other sources	Additional data
(wall zone)		
ω, 1.645; ϵ, 1.642		
N, 1.75 to 1.83, variable		
N, 1.83 to 1.94, variable X, greenish; Y, light-purple; Z, dark-purple		
pegmatite of zone 3		
α, 1.683; β, 1.688; γ, 1.693		
α, 1.817; β, near 1.85; γ, 1.882 Absorption-orange brown; faintly pleochroic, $X>Z$. Several cleavages.	This mineral and the heterosite-purpurite of specimen JJN 110–46 have X-ray patterns similar to known heterosite and purpurite from other localities, but the cell size is somewhat larger.	
α, 1.778; β is between 1.787 and 1.808; γ, 1.815 X, green; Z, straw-colored; strong absorption.		
N mostly near 1.66, but as high as 1.77. Anisotropic; very fine grained.		
ω, 1.650; ϵ, 1.628		
α, 1.687; β, 1.6875; γ, 1.693 Biaxial positive. Small to medium 2V.		
α, 1.653; β, 1.660; γ, 1.672		
	See specimen JJN 65–46	
α, 1.778; β, near 1.803; γ, 1.815 X, blue-green; Z, straw-colored. Chestnut-brown interference color in thin pieces.		Probably the same as the dark green unknown mineral of specimen JJN 65–46.
$\omega>1.80$		
α, 1.649; β, 1.669; γ, 1.680 Absorption, pale apple-green; $r<v$; biaxial negative; medium 2V.		
α, 1.79; β, 1.82; γ, 1.83 X, blue-green; Y and Z, olive-green to brownish-green.		May belong to the same group of minerals as the unknown green mineral in specimens JJN 65 and 110–46.
Variable indices: $\alpha>1.86$; $\gamma>1.88$ X, green; Z, brown; strong absorption.		
Zone 4		
Indices a little lower than in normal muscovite	Resembles alteration product of spodumene from the Etta pegmatite, described by Schwartz and Leonard (1926, p. 261) as similar to killinite derived from spodumene (Brush and Dana, 1880, p. 274–275).	
Isotropic		
N, 1.544 for most grains, but there is some variability.		
$N>2.00$; high birefringence; wavy extinction		

TABLE 5.—*Mineralogy of certain minor*

[Data obtained by M. L. Lindberg,

Specimen No.	Description of specimen	MINERALS	
		Name	Description
		Zone 4—Continued	
JJN 5-47	Greenish-yellow, fine-grained, earthy aggregate	Muscovite	Sericitic
JJN 6-47	Black metallic mineral with green and yellow alteration products. Specimen also has earthy masses of dark grayish-brown to olive-green minerals pseudomorphous after triphylite. Other minerals are quartz, microcline, albite, muscovite, and tantalite.	Stannite	
		Unknown	Green; vitreous Alteration products of stannite.
		Unknown	Dull-yellow
		Unknown	Alteration product of triphylite
JJN 4-47	Cleavelandite, yellowish-white muscovite, quartz, and blue apatite with yellow and gray alteration products.	Apatite	Occurs as blue crystals. Also as fine-grained material in white, crumbly, fine-grained muscovite.
		Calcite	
		Tantalite	
JJN 119-46	Dark-brown mineral included in amblygonite	Alluaudite (?)	Dark-brown
		Zone 5	
JJN 104-46	Dark-brown mineral surrounded by cleavelandite and quartz, probably at the edge of a spodumene crystal.	Alluaudite (?)	Dark-brown
JJN 114-46	Alteration products on the surface of an amblygonite crystal.	Halloysite	Pink surface stains; intimately mixed with amblygonite.
		Unknown	Brown
			Cleavelandite-quartz-lithia
JJN 107-46	Tantalite associated with cleavelandite, quartz, and lithia mica.	Tantalite	

minerals of the Hugo pegmatite—Continued

U.S. Geological Survey]

	MINERALS—continued	
Optical data	Comparison with material from other sources	Additional data
	Zone 4—Continued	
------	------	
------	Both unknown minerals have an X-ray pattern similar to cassiterite and to material labeled cuprocassiterite.	Identified by X-ray pattern.

α, 1.765; β, 1.825; γ, 1.833 X, yellowish-green to colorless; Y and Z, brown to olive-green. Biaxial negative; small 2V. Material similar in appearance from another part of the specimen has: α, 1.77; β, near 1.80; γ, 1.82; polysynthetic twinning.	Mason (1942, p. 337) describes arrojadite formed from triphylite. His optical data are: α, 1.754; γ, probably about 1.785; X, pale gray-green; Z, dark-green. Arrojadite from Serra Branca, Picuhy, Parahyba, Brazil (USNM specimen 96111) has: α, 1.665; β, 1.670; γ, 1.674; biaxial negative, very large 2V; weak dispersion, r > v. Type headdenite from Harvard, equivalent to arrojadite and having the same X-ray pattern, also has all indices less than 1.70. The Hugo material may be equivalent to Mason's mineral, but not to the material from the US National Museum or Harvard.	
------	------	
------	------	
------	------	
Nearly opaque	Material through which light could be passed has optics and also weak X-ray pattern similar to allaudite described below from Varuträsk, Sweden.	
	Zone 5	
α, 1.772; γ, between 1.779 and 1.783 X, orange; Y, purplish; Z, olive green. Partly nonpleochroic, orange-brown absorption, biaxial negative, small 2V, and with slightly higher indices of refraction than the pleochroic material. Between crossed nicols, either orange-brown or green, or orange-brown with a green border.	Alluaudite from Varuträsk, Sweden (USNM specimen 103, 194) has: α, 1.765; β, between 1.778 and 1.787; γ, 1.796; nonpleochroic; absorption orange-brown; not as dark in thick pieces as the Hugo material. X-ray pattern indicates this and the Hugo mineral are the same.	
Isotropic	------	
N, variable, mostly 1.544, but some as high as 1.554.		
β and γ between 1.88 and 2.00; α may be less than 1.88.	------	
mica replacement body		
------	------	Specific gravity of 6.265 indicates a content of about 40 percent Ta_2O_5.

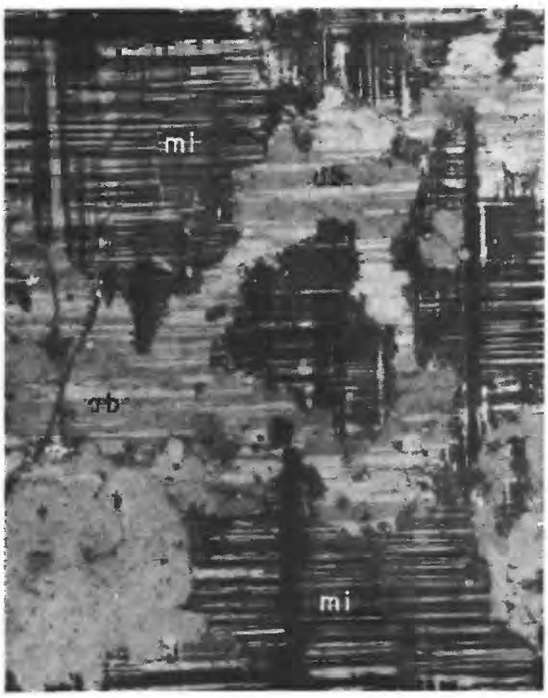

FIGURE 15.—Photomicrograph of perthite, consisting of irregular patches and streaks of albite (ab) in microcline (mi). Zone 3a near the east side of the south segment. Crossed nicols. × 50.

nish quickly after exposure, and form alteration products that are mostly brown, black, and dark green. The phosphates are closely associated with bright-blue tourmaline.

PARAGENESIS

The chief difference in paragenesis between zone 3 and the outer zones is that potassic feldspar, which first appears in zone 3, generally preceded adjacent minerals of the groundmass. The edges of perthite crystals are rounded and embayed, and the corrosion textures thus formed are not localized along cleavage planes or other structures of microcline. The texture and mineralogy of the groundmass is the same in embayments as elsewhere in the unit. On the other hand, laths of albite included in perthite are embayed by microcline. Perthite crystals also have inclusions of muscovite, quartz (fig. 16), tourmaline, and apatite, indicating that these minerals, as well as albite, began to form before potassic feldspar completed crystallization.

The paragenesis of the matrix is similar to the paragenesis of the minerals in zone 2. Skeletal crystals and subgraphic to graphic intergrowths indicate extensive overlap among muscovite, albite, quartz, tourmaline, apatite, and beryl.

Muscovite was generally early, and it was followed by albite and then by the greater part of the quartz. Muscovite is extensively embayed by albite and quartz, and it has crystal faces against albite. Similarly, albite is embayed by quartz, has crystal faces against quartz, and forms optically continuous inclusions in quartz (figs. 17–19). Although much of the microscopic evidence favors a late age for the quartz, the megascopically veinlike form of albite aggregates in quartz suggests the contrary. Furthermore, some of the albite has optically continuous inclusions of quartz (fig. 20). In one thin section the optical continuity extends to quartz inclusions in adjacent microcline, and the quartz must have preceded both the feldspars. These contractory relations show that, although much of the quartz followed albite, there was extensive overlap in the paragenesis. The many mutual contacts between quartz and albite (fig. 21) and the close association between the two minerals, even to a point such that they are intimately intergrown (fig. 22), are also in accord with the conclusion that they were largely contemporaneous.

Tourmaline, apatite, and beryl are so intimately intergrown with quartz, albite, and muscovite that overlapping paragenesis must be inferred. All of these accessory minerals commonly have crystal faces, especially against albite and quartz, and they probably formed at a relatively early stage. Embayments in quartz and albite (fig. 23) indicate that part of the beryl and apatite formed later. Tourmaline is graphically intergrown with quartz, and some of this quartz has optically continuous inclusions of previously formed albite.

The iron-manganese phosphates form many embayments and veinlets in albite, quartz, tourmaline, and apatite. Although these textures indicate a late age, it is by no means clear that any of them are primary, rather than caused by very late alteration and redistribution of the phosphatic materials. The phosphates are associated with abundant albite and blue tourmaline, and they are cut by veinlets of the tourmaline. Thus at least part of the phosphates formed before the other minerals had finished crystallizing.

Zone 3, like zone 2, contains deuteric aggregates consisting mainly of very fine grained muscovite or apatite.

The perthitic albite in microcline (fig. 15) undoubtedly formed after the original precipitation of the potassic feldspar crystals. The albite shows no evidence of having been introduced from the edges of host crystals. It is so evenly distributed through the microcline that it seems unlikely it could have formed in any way except by exsolution as the pegmatite cooled (Bowen and Tuttle, 1950, p. 510). Very fine grained inclusions of muscovite are especially abundant in perthitic albite, and their origin may be related to the exsolution process. The age relations between perthitic albite and the minerals in the matrix surrounding perthite could not be determined.

ZONE 4: QUARTZ-CLEAVELANDITE-MICROCLINE-AMBLYGONITE PEGMATITE AND QUARTZ-CLEAVELANDITE PEGMATITE

DESCRIPTION

Zone 4 has been mapped as quartz-cleavelandite pegmatite in the north segment and on the 4,446-foot level in the south segment, where coarse quartz and large rosettes of cleavelandite are the only abundant constituents (table 6). At higher levels in the south segment, however, this unit takes on a very different aspect. It has many blade-shaped aggregates that almost certainly are pseudomorphs after spodumene, but now consist mainly of quartz, microcline, cleavelandite, and amblygonite. To call attention to the distinctive nature of this rock, and to stress the conspicuous presence of microcline and amblygonite, this part of the zone has been called quartz-cleavelandite-microcline-amblygonite pegmatite.

TABLE 6.—*Mineralogy and petrography of zone 4, quartz-cleavelandite-microcline-amblygonite pegmatite in the south segment and quartz-cleavelandite pegmatite in the north segment*

[Minerals are listed in order of abundance. Modes are in table 19. Thin sections are from south segment only. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Quartz

Size and shape: Mostly C and VC; anhedral, massive; partly VF and sugary.

Megascopic textural relations: Massive quartz forms the matrix surrounding all other minerals of this zone. Quartz also appears in the blade-shaped aggregates described under cleavelandite.

Microscopic textural relations: Quartz forms veinlets and embayments in microcline; one veinlet has muscovite grains along its border that project into adjacent microcline along the twinning. Quartz also embays cleavelandite, muscovite, and amblygonite. Quartz containing vermicular inclusions of albite forms veinlets and embayments in adjacent grains of albite and muscovite, and has optically continuous inclusions of muscovite. Quartz is graphically intergrown with microcline. There are a few sutured contacts between quartz grains.

TABLE 6.—*Mineralogy and petrography of zone 4, quartz-cleavelandite-microcline-amblygonite pegmatite in the south segment and quartz-cleavelandite pegmatite in the north segment*—Continued

Cleavelandite (including a small quantity of nonplaty albite)

Size and shape: Platy crystals are VF to M, but mostly M; they occur in aggregates that are M to VC. Also partly nonplaty, VF to F; less commonly VF to sugary. Cleavelandite aggregates as much as 1 foot thick surround spodumene casts that are as much as 6 feet long, 1 foot wide, and 3 inches thick (fig. 25). Other aggregates of cleavelandite as much as 8 feet long and 6 inches thick may be small fracture-filling units.

Refractive indices: $\alpha'=1.528$ to 1.532. Sugary albite has lower index than coarse-grained material.

Megascopic textural relations: In the north segment and the lower part of the south segment, cleavelandite is in rosette-shaped aggregates surrounded mainly by quartz. Cleavelandite laths project into the quartz and are embayed by quartz. In the upper part of the south segment, cleavelandite forms sheaths around blade-shaped aggregates that are probably casts of spodumene, although they now lack spodumene and contain all other minerals of this zone. These aggregates have the shape and distribution of spodumene crystals in zone 5, which are also surrounded by cleavelandite sheaths. The cleavelandite aggregates have flat sides against these blades, and a rosette form against the matrix; individual plates of cleavelandite are at right angles to the edge of the blade. Cleavelandite aggregates that may be fracture fillings have yellow mica in their center. Sugary albite occurs in aggregates that are interstitial to coarser grained cleavelandite.

Microscopic textural relations: Cleavelandite has radiating form (fig. 26). Cleavelandite laths have crystal faces against quartz and muscovite, and are embayed by these minerals. Mutual contacts with microcline and muscovite are common.

Microcline (and perthite)

Size and shape: Microcline in blades is F to M, and assumes the thin tabular form of the blades. Microcline in matrix is in subhedral crystals as much as 15 feet long.

Megascopic textural relations: Perthitic albite in microcline is more abundant in the outer part of the zone than in the inner part. Microcline has inclusions of euhedral beryl and anhedral quartz. It commonly has mutual boundaries with amblygonite and quartz, but in part embays amblygonite and is embayed by quartz. It also has crystal faces against quartz.

Microscopic textural relations: Microcline has embayed inclusions of cleavelandite and muscovite. Cleavelandite inclusions contain muscovite inclusions within them. Microcline also has irregular inclusions of muscovite with rims of quartz that veins and embays the microcline (fig. 29); the thickness of the quartz rims varies in proportion to the size of the muscovite grain. Microcline is graphically intergrown with quartz. Many contacts with cleavelandite and muscovite are mutual. Aggregates containing cleavelandite, quartz, and muscovite are interstitial to large microcline grains. Inclusions of apatite in microcline are rounded to euhedral.

Additional data: More coarsely twinned than in zone 3. Gridiron twinning is recognizable megascopically in nonperthitic microcline.

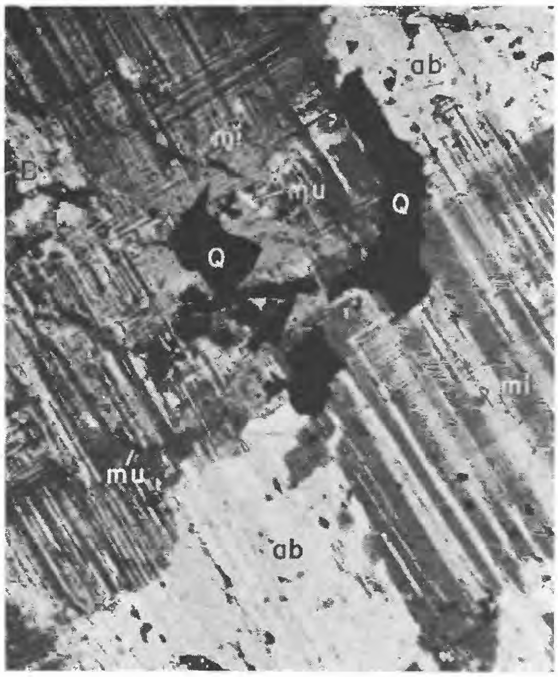

FIGURE 16.—Optically continuous inclusions of quartz in microcline. The microcline also contains perthitic albite, and both feldspars have very small inclusions of muscovite. Zone 3a near the east side of the south segment. × 32.

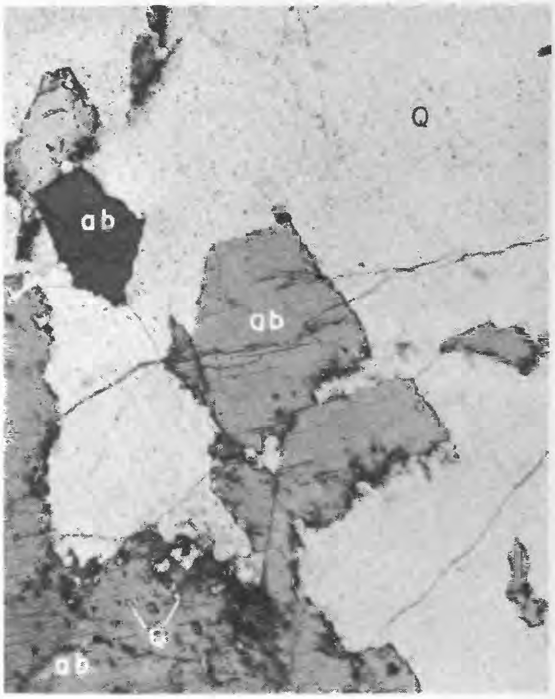

FIGURE 17.—Albite embayed by quartz and forming optically continuous inclusions in quartz. Small blebs of quartz appear in the albite. From zone 3b in the northwest part of the south segment. × 32.

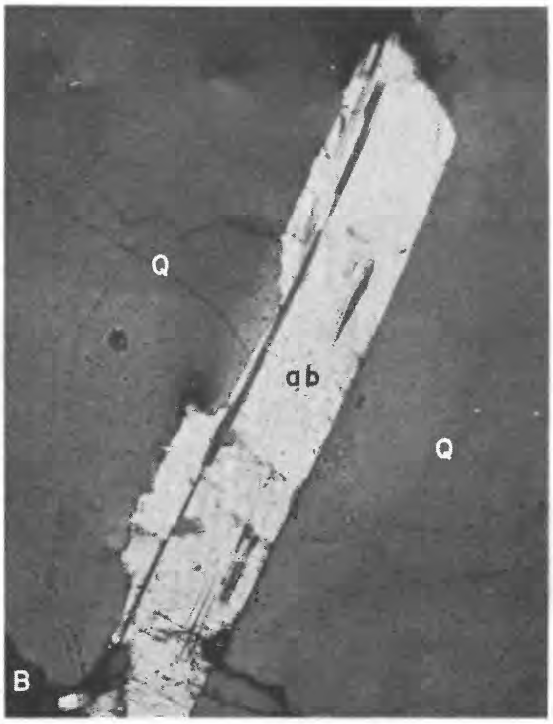

FIGURE 18.—Lath of albite that on one side has a crystal face against quartz and on the other side is embayed by quartz. Zone 3c on the 4,549-foot level. × 47.

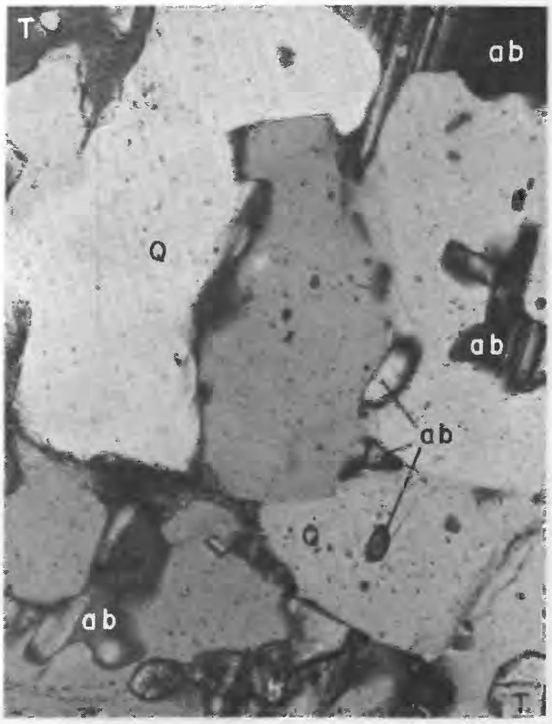

FIGURE 19.—Optically continuous remnants of albite in quartz. The quartz is graphically intergrown with nearby tourmaline, parts of which appear at the lower right and upper left. From zone 3b southeast of the portal of the 4,549-foot level. × 115.

FIGURES 16–23.—PHOTOMICROGRAPHS OF ZONE 3. ALL ARE UNDER CROSSED NICOLS. Q,

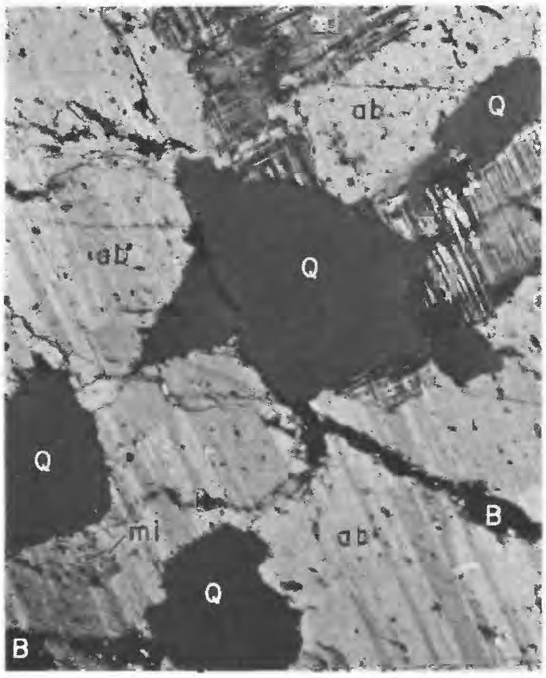

FIGURE 20.—Optically continuous grains of quartz surrounded by microcline and albite at the border of a perthite crystal. A small grain of microcline included in the albite at the lower left is optically continuous with the main body of microcline. Zone 3a near the east side of the south segment. × 32.

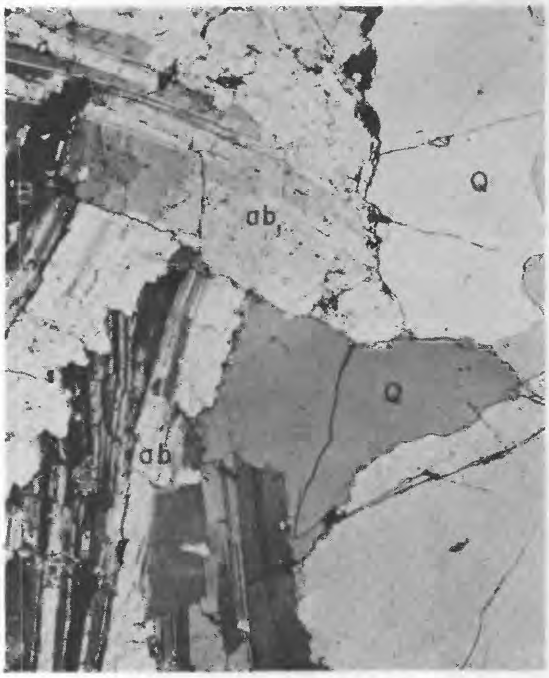

FIGURE 21.—Quartz and albite with mutual contacts. Zone 3c on the 4,549-foot level. × 18.5.

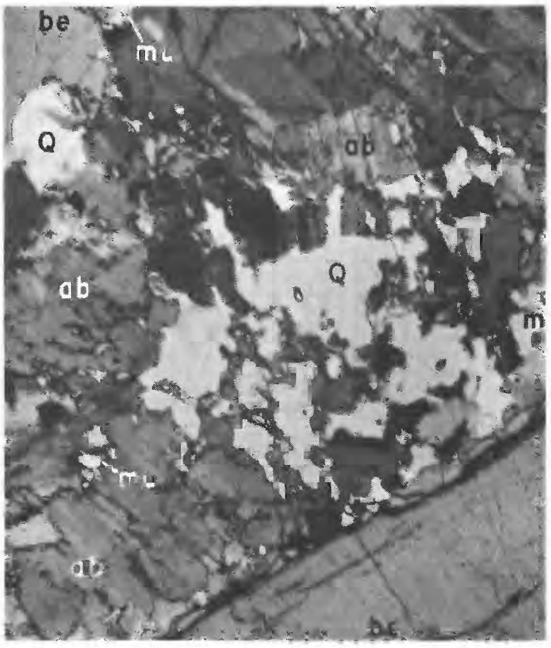

FIGURE 22.—Intergrown quartz and albite within a skeletal beryl crystal. The quartz and albite have an irregular contact with the host beryl at the upper left, but are against a straight crystal border at the bottom. Fine-grained quartz is distributed along this straight contact and forms embayments in albite. Small grains of muscovite are mainly in albite, but also appear in contact with beryl. From a beryl stockpile, probably mined from zone 3b of the south segment. × 37.

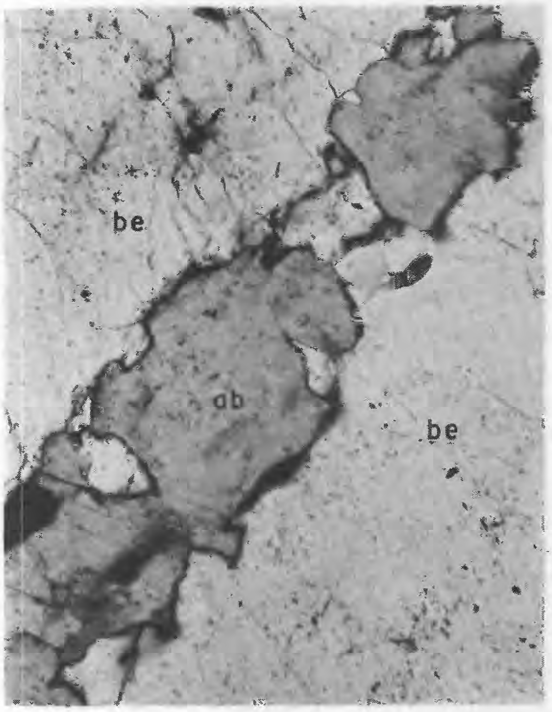

FIGURE 23.—Embayed albite included in beryl. Zone 3c in the west drift on the 4,446-foot level. × 97.

QUARTZ ; ab, ALBITE ; mi, MICROCLINE ; mu, MUSCOVITE ; t, TOURMALINE ; be, BERYL ; B, BALSAM.

TABLE 6.—*Mineralogy and petrography of zone 4, quartz-cleavelandite-microcline-amblygonite pegmatite in the south segment and quartz-cleavelandite pegmatite in the north segment*—Continued

Amblygonite (montebrasite)

- Size and shape: F to M in blades; M to VC elsewhere. Straight borders at edges of blades; rounded elsewhere.
- Refractive indices: α=1.60; γ=1.63. Indices indicate about 85 percent montebrasite and 15 percent amblygonite according to Winchell and Winchell (1951, p. 224).
- Megascopic textural relations: Textural relations of amblygonite are obscured by a very fine grained pink to buff coating, as much as three-eighth inch thick, consisting chiefly of clay and micaceous minerals, but also containing quartz, apatite, and albite. Amblygonite has rounded and embayed borders against quartz, microcline, fine-grained cleavelandite, and yellow mica. Amblygonite at the ends of some blades extends into the groundmass, and has crystal faces against quartz of the groundmass. One crystal extending across the side of a blade into the matrix has a thin seam of fine grained muscovite marking the border of the blade. Amblygonite in blades embays coarse grained cleavelandite enclosing the blades. Inclusions in amblygonite consist of quartz, Fe–Mn phosphates (triplite(?)), muscovite, and euhedral tabular beryl crystals.
- Microscopic textural relations: The predominate constituents of the altered borders of amblygonite are an isotropic material, which probably is halloysite, and mica, partly muscovite and partly lepidolite(?). The altered material also contains apatite, some of which is too fine grained to be positively identified. Commonly the alteration halo is zoned, such that halloysite is abundant adjacent to amblygonite and mica is abundant farther away. The alteration products form embayments and veinlets in amblygonite, microcline, and quartz. Some of the lepidolite(?) has a rim of muscovite at contacts with microcline. Amblygonite has inclusions of quartz and mica, at least some of which is lepidolite(?). Crystal faces of amblygonite are against muscovite, microcline, and quartz. A veinlet containing quartz, albite, muscovite, and lepidolite(?) cuts amblygonite.
- Additional data: 2V large; twinned (fig. 28).

Muscovite (including a small quantity of lepidolite(?))

- Size and shape: Mostly VF to F; some M.
- Refractive indices: β=1.58 to 1.59. Some of the mica near amblygonite grains has α less than 1.54 and birefringence less than that of muscovite; it may be lepidolite.
- Megascopic textural relations: Yellow muscovite is concentrated at the borders of blades. It extends across the entire thickness in parts of a few blades.
- Microscopic textural relations: Muscovite interstitial to aggregates of cleavelandite is mostly irregular in form. Some grains have crystal faces against cleavelandite; others are elongate parallel to cleavelandite twins; still others embay cleavelandite (fig. 27). A muscovite aggregate follows a contact between amblygonite and euhedral apatite and embays the amblygonite (fig. 28). The same muscovite aggregate continues along a contact between the amblygonite and quartz where the border of the amblygonite is a crystal face. The euhedral apatite has a row of muscovite inclusions parallel to a crystal face. Muscovite has crystal faces against microcline. Very fine grained muscovite (0.02 mm), like that shown in figure 27, is chiefly at borders of cleavelandite grains.

TABLE 6.—*Mineralogy and petrography of zone 4, quartz-cleavelandite-microcline-amblygonite pegmatite in the south segment and quartz-cleavelandite pegmatite in the north segment*—Continued

Muscovite (including a small quantity of lepidolite(?))—Con.

- Additional data: 2V 45°.

Beryl

- Size and shape: F to M. The blades contain tabular crystals as much as one-half inch thick, flattened parallel to the c axis, and anhedral masses as much as 2 inches across. Also euhedral crystals in blades and in matrix.
- Megascopic textural relations: Beryl occurs largely as euhedral to rounded crystals, mostly in contact with quartz, microcline, and amblygonite.
- Color: White to pale-yellow or pinkish.

Apatite

- Size and shape: VF to F; anhedral to euhedral.
- Refractive indices: ω=1.63.
- Megascopic textural relations: Apatite is common at outer contacts of cleavelandite surrounding blades. Much of the apatite has rounded borders and is embayed by the more abundant minerals.
- Microscopic textural relations: Apatite has inclusions of lath-shaped cleavelandite and embayed muscovite. It has crystal faces against amblygonite, quartz, and muscovite (fig. 28). Apatite is interstitial to cleavelandite laths. It also appears as rounded to euhedral inclusions, 0.03 mm in diameter, in quartz and cleavelandite.
- Color: Blue to greenish-blue.
- Additional data: One zoned grain recognized: outer two-thirds of grain is not in optical continuity with the core.

Tourmaline

- Size and shape: VF to F.
- Microscopic textural relations: Needlelike inclusions of tourmaline(?) in quartz are 0.06 mm long.
- Color: Blue.

Fe–Mn phosphates

- Microscopic textural relations: Fe–Mn phosphates vein and embay albite and muscovite. An aggregate of alteration products has straight borders that may have been crystal faces of a primary phosphate mineral; these borders are in contact with amblygonite. Goyazite(?), like that in zone 3, appears mostly as inclusions in cleavelandite near amblygonite crystals.

Cassiterite

- Size and shape: VF; subhedral.
- Microscopic textural relations. Cassiterite has crystal faces against microcline, muscovite, cleavelandite, and quartz.

Spodumene

- Size and shape: Spodumene is represented only by blade-shaped casts or pseudomorphs (figs. 24–25) that now contain no recognizable spodumene, but consist instead of all the other minerals of the zone. A few blades contain small quantities of micaceous and clay minerals similar to alteration products of spodumene in zone 5. Blades are as much as 6 feet long, 1 foot wide, and 3 inches thick.

TABLE 6.—*Mineralogy and petrography of zone 4, quartz-cleavelandite-microcline-amblygonite pegmatite in the south segment and quartz-cleavelandite pegmatite in the north segment*—Continued

Spodumene—Continued

Megascopic textural relations: Casts or blades are pseudomorphically filled by all other minerals of the zone, and are surrounded by cleavelandite sheaths, as are the spodumene crystals of zone 5. Amblygonite, microcline, and beryl are more abundant and quartz is less abundant in the pseudomorphs than in the matrix. The shapes of these minerals are in part controlled by the outlines of the blades, but a few crystals extend from the blades into the matrix. Otherwise the textures in the blades are the same as in the matrix, but on a smaller scale.

Quartz-cleavelandite pegmatite of zone 4 forming the core of the north segment is exposed for a distance of 90 feet, and the thickness is as much as 10 feet. A quartz-cleavelandite fracture filling near the northwest corner of the pegmatite outcrop is presumably an offshoot from the core. Both the core and the fracture-filling unit consist of large masses of quartz and equally large aggregates of platy cleavelandite. Microcline and muscovite are the only other constituents occurring in significant quantities.

In the south segment, zone 4 forms a virtually complete shell around the inner units. At the surface it is absent for only a few feet near the south end of the pegmatite outcrop. The average thickness is about 10 feet, and the greatest thickness is not more than about 20 feet.

The most striking characteristic of zone 4 in the south segment is that about 10 percent of the zone consists of blade-shaped mineral aggregates as much as 6 feet long, 1 foot wide, and 3 inches thick that are scattered throughout the rock without any apparent preferred orientation (figs. 24, 25). These aggregates have the shape and distribution of spodumene crystals in zone 5 (fig. 35), and, like the spodumene, they are encased in aggregates of cleavelandite that radiates outward from the surfaces of the "blades" (as the aggregates will be called hereafter). The blades consist almost entirely of minerals that also form the groundmass. Remnants of the spodumene itself have not been found in these bladed aggregates, but sericitic material resembling altered spodumene of other pegmatites has been collected (specimen JJN 87–46, table 5). The predominant minerals in the blades are quartz, microcline, cleavelandite, and amblygonite; other minerals include muscovite, beryl, and apatite. Amblygonite, microcline, and beryl are somewhat more abundant, and quartz is less abundant, in the blades than in the matrix.

A few elongate bodies consisting mostly of coarse-grained cleavelandite lack evidence that this cleavelandite ever surrounded a spodumene crystal. These bodies may be small fracture-filling units as much as 8 feet long and 6 inches thick. Yellow muscovite also occurs in them, especially in the center.

The coarse plates of cleavelandite that are so characteristic of zone 4 are in large rosette-shaped aggregates that have a radiating form. The rounded sides of these masses are for the most part in contact with quartz, and the cleavelandite plates project into the quartz.

Radiating structure is also characteristic of finer grained cleavelandite, which occurs both in the blades and in the matrix. This material, however, may consist of many small radiating masses that occur together to form a single large aggregate, as in figure 26.

Zone 4 also contains sugary albite associated with minute grains of cassiterite, especially in the adit on the 4,549-foot level. This albite is interstitial to coarser cleavelandite, and it commonly has somewhat lower refractive indices.

Microcline, in part perthitic, occurs both within the blades, where the crystals tend to adopt the thinly tabular form of the blade, and as subhedral crystals as much as 15 feet long in the matrix. Perthitic microcline is more abundant in the outer than in the inner part of the zone. Twinning in most of the microcline is somewhat coarser than in zone 3, and much of it can be seen megascopically.

The amblygonite has indices of refraction that indicate it is near the montebrasite end of the series (table 6). Crystals in blades ordinarily have flat sides at the edges of the blade, but at the ends of blades, where they extend outward into the matrix, they have crystal faces against the surrounding quartz. One crystal was found that cuts across the side of a blade; the edge of the blade is marked by a thin seam of fine-grained muscovite within the amblygonite. The borders of amblygonite are rounded and embayed. They are coated by a thin pink to buff powdery aggregate of very fine grained material consisting chiefly of halloysite (table 5) and mica. Some of the mica is muscovite, but much of it has such very low indices of refraction (in part less than 1.54) that it may be lepidolite.

A large part of the mica of this zone is yellow muscovite concentrated at the borders of blades, but coarser grained white to ruby muscovite is disseminated through the groundmass. Veinlets of very fine grained muscovite are chiefly along grain boundaries, especially those of cleavelandite (fig. 27), but they also cut the primary minerals of the zone.

Beryl is most abundant in the blades, where it commonly occurs as tabular crystals. It is also in the quartz-cleavelandite fracture filling in the northwest

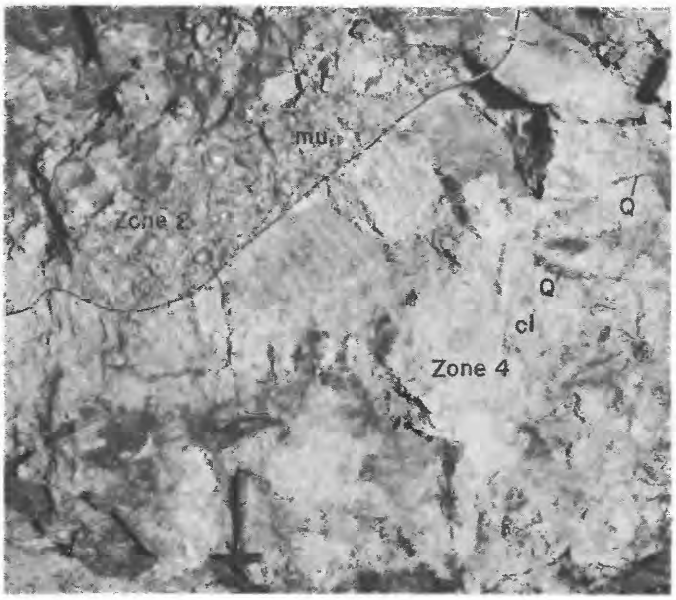

FIGURE 24.—Exposure of zones 2 and 4 southwest of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). Zone 4 contains gray quartz (Q) in blade-shaped aggregates, probably pseudomorphous after spodumene, surounded by white cleavelandite (cl). Zone 2 is rich in muscovite (mu) near the contact with zone 4.

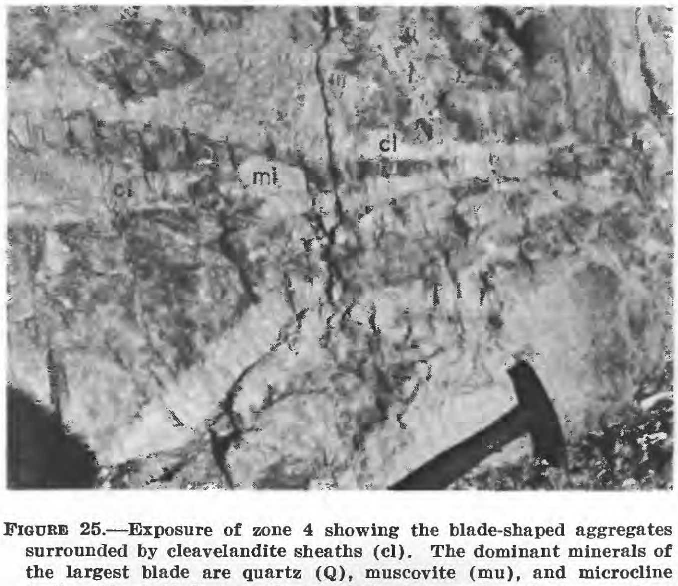

FIGURE 25.—Exposure of zone 4 showing the blade-shaped aggregates surrounded by cleavelandite sheaths (cl). The dominant minerals of the largest blade are quartz (Q), muscovite (mu), and microcline (mi). About 80 feet northwest of the intersection of cross sections *A–A′* and *B–B′* (pl. 9).

part of the north segment. Elsewhere in zone 4 it is rare.

Apatite and tourmaline are the only other accessory minerals that occur in significant quantities. Additional minerals, all very rare, include cassiterite, stannite, tantalite, alluaudite(?), calcite, and triphylite pseudomorphically altered to an unidentified mineral (table 5).

PARAGENESIS

The blade-shaped aggregates having the same characteristics as the spodumene of zone 5 indicate that a network of spodumene crystals formed in advanced of the other minerals during crystallization of this zone. These crystals were then surrounded by sheaths of cleavelandite, just as in zone 5. Cleavelandite plates that project outward into quartz of the groundmass have crystal faces against quartz and are also embayed by the quartz. Many small areas in this zone show a clear-cut sequence, with little overlap, of (1) spodumene, (2) cleavelandite, and (3) quartz.

The spodumene in this zone, unlike that in zone 5, was entirely replaced by other minerals. Perhaps it was replaced directly by these minerals, but more likely it was resorbed by the rest liquid and the space that it had occupied held open by the cleavelandite sheaths until other minerals were precipitated in the normal course of crystallization. Resorption by the liquid is the more probable because the pseudomorphs contain all the other minerals of the zone, rather than consisting preferentially of some single mineral, such as mica or amblygonite, which might be expected as a replacement product of spodumene. The pseudomorphs contain a relatively high proportion of minerals of intermediate age, such as amblygonite, microcline, and beryl (fig. 13), and one may infer that the resorption of spodumene and the substitution of other minerals took place before most of the quartz crystallized.

Amblygonite was probably the first of the major minerals to form after the spodumene and the cleavelandite sheaths had crystallized. It has crystal faces against microcline, muscovite, and quartz, and it is veined and embayed by these minerals. No firm evidence was found that any of the microcline preceded amblygonite. Muscovite associated with cleavelandite aggregates shows contradictory textural relations that indicate the two minerals were largely contemporaneous; muscovite has crystal faces against some cleavelandite, and it also embays cleavelandite (fig. 27). Muscovite associated with early cleavelandite probably preceded amblygonite. The paragenesis of mica inclusions in amblygonite is dubious, because much of it is of such low index of refraction that it may be lepidolite, probably formed by alteration of the amblygonite.

The last of the essential minerals to crystallize was quartz, which filled the interstitial spaces between the earlier crystals. Cleavelandite, amblygonite, and microcline all have crystal faces against quartz and are embayed by quartz. On the other hand, a small amount of overlap with these minerals is indicated by inclusions of quartz in amblygonite, vermicular intergrowths of albite, and graphic intergrowths with microcline.

Apatite, beryl, and cassiterite have crystal faces against most of the major minerals, and thus formed at a fairly early stage. A row of muscovite inclusions parallel to a crystal face of apatite in figure 28 probably formed while the apatite was crystallizing; other muscovite at the border of the apatite formed later.

The very fine grained muscovite like that in figure 27 was probably deuteric, and the same may be said of the halloysite and mica at the borders of amblygonite crystals. The muscovite with quartz rims included in microcline (fig. 29), and also the lepidolite(?) inclusions in amblygonite may have formed at a very late stage.

ZONE 5: QUARTZ-MICROCLINE-SPODUMENE PEGMATITE

DESCRIPTION

Zone 5 has a network of large tabular spodumene crystals, partly encased in sheaths of cleavelandite (fig. 35), and much larger microcline and amblygonite crystals. These minerals are surrounded by a groundmass of massive quartz (table 7). Where exposed on the 4,446-foot level (pl. 9), this zone contains only quartz; all other minerals are absent in this small exposure.

Zone 5 almost completely surrounds the inner zones, but it may lens out beneath the core. As section *A–A′* (pl. 9) shows, the zone is thickest in three lobes that reflect rolls in the outer contact of the pegmatite. The average thickness, measured from the contact with zone 4 to the contact with zone 6, is about 30 feet.

Tabular spodumene crystals, 3 to 10 feet long, form a network in which the spodumene has no favored orientation. Many of these crystals are surrounded by aggregates of cleavelandite in which the individual plates are normal to the borders of the spodumene crystals. Euhedral plates of cleavelandite project into the quartz. Much of the spodumene is altered to clay and micaceous minerals.

Both microcline and amblygonite occur as very large crystals which, although somewhat rounded, are nearly euhedral. The microcline has only a small quantity of perthitic albite, but it does contain minute corroded inclusions of cleavelandite (fig. 30). Microcline twinning can be seen with the unaided eye.

The amblygonite crystals are of extraordinary size. Ziegler (1913, p. 1056) reported amblygonite with dimensions of 15 by 22 by 40 feet. A single crystal of this size would weigh more than 1,000 tons. The average volume of the crystals exposed in 1946 was about 50 cubic feet, which would weigh about 5 tons. Nearly all surfaces of amblygonite are coated by pink to buff aggregates of very fine grained halloysite, mica, and probably apatite (fig. 31). Some of the mica has such a low relief that it may be lepidolite rather than muscovite.

The massive quartz of the groundmass consists at least partly of very fine grained anhedral crystals with sutured borders, as shown in figure 34. It may also contain crystals several feet wide.

PARAGENESIS

The distribution of nearly euhedral spodumene crystals in a network in which the other minerals fill the interstices indicates that the spodumene formed first. The spodumene when then surrounded by sheaths of cleavelandite, as in zone 4. The commonly rounded, but in part subhedral, crystals of microcline and amblygonite are embayed and veined by quartz. They generally preceded quartz in the paragenesis, but optically continuous inclusions of quartz in amblygonite indicate some overlap. Age relations between amblygonite and microcline are less certain because these two minerals are rarely in contact with each other; the only observed textures recorded in table 7 suggest that amblygonite preceded microcline.

Cleavelandite presents the clearest evidence of overlap in this zone. At the outer border of the sheaths surrounding spodumene crystals, lath-shaped cleavelandite projects into quartz and microcline. Quartz and microcline embay the cleavelandite and have a well-developed interstitial relation to the cleavelandite laths, strongly suggesting that the cleavelandite formed first (fig. 32). The small inclusions of cleavelandite in microcline are embayed. On the other hand, albite is associated with quartz in veinlets that cut microcline (fig. 33). It may be concluded that cleavelandite began to crystallize just after spodumene and continued to form until just after quartz began to fill the interstices.

The alteration effects observed in this zone probably were largely deuteric, but may have developed partly while primary crystallization was still in progress. The most evident of these effects is the alteration of spodumene to clay and micaceous minerals. The alteration is greatest where spodumene is adjacent to microcline, less where enclosed by cleavelandite, and least where accompanied only by quartz. A somewhat similar relation has been observed in many other spodumene-bearing pegmatites, as at the Etta, where the spodumene is more commonly altered in feldspar-rich outer intermediate zones than in a quartz-spodumene inner zone. In the Hugo and elsewhere the minerals of the matrix are not significantly affected. These relations suggest

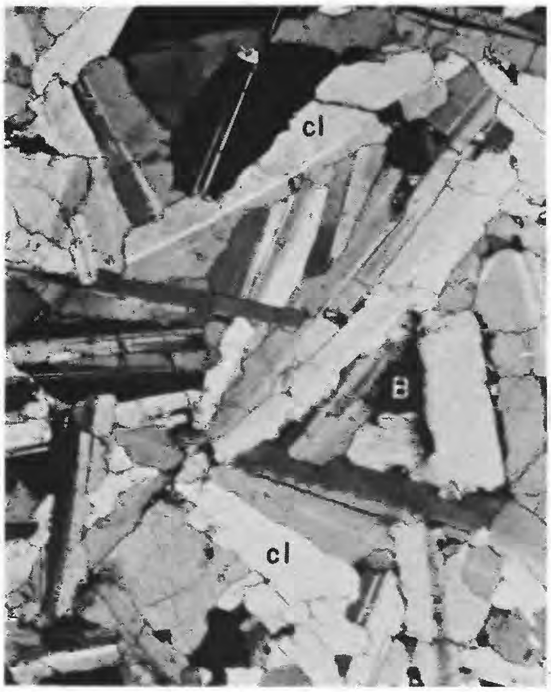

FIGURE 26.—Aggregate of cleavelandite showing radiating structure. Zone 4 on the 4,549-foot level. ×32.

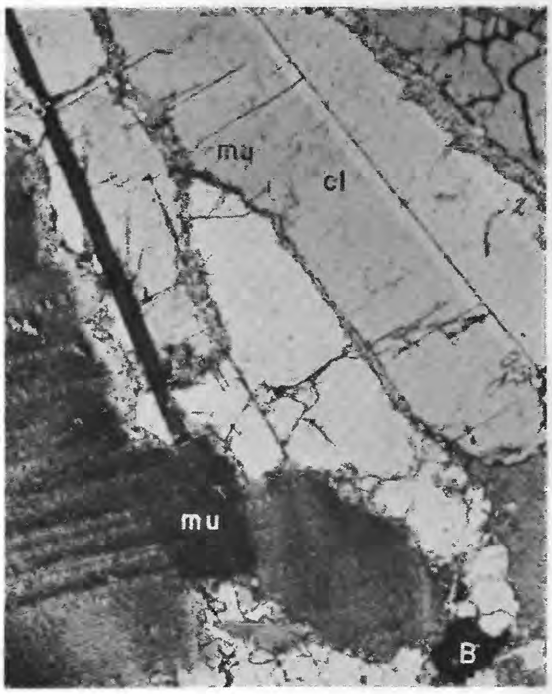

FIGURE 27.—Coarse muscovite cutting across cleavelandite plates. Aggregates of very fine-grained muscovite are between cleavelandite plates and between cleavelandite and coarse muscovite. Zone 4 on the 4,549-foot level. × 32.

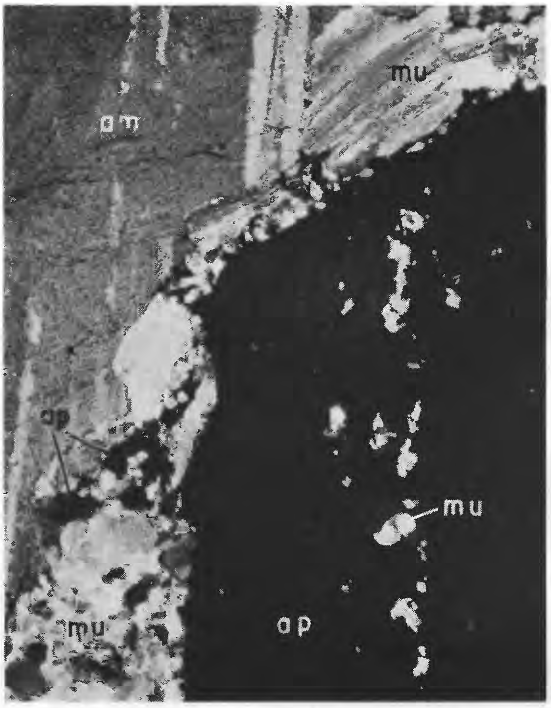

FIGURE 28.—Nearly euhedral apatite separated from amblygonite by an aggregate consisting mainly of muscovite but also containing apatite. A row of muscovite inclusions is parallel to a crystal face of apatite. Zone 4 at the portal of the 4,549-foot level. × 32.

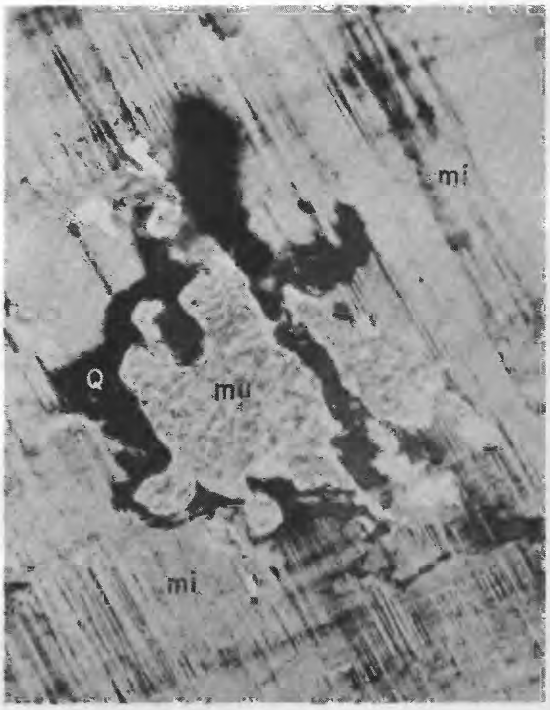

FIGURE 29.—Microcline containing an inclusion of muscovite rimmed by quartz. Zone 4 on the 4,549-foot level. × 97.

FIGURES 26–33.—PHOTOMICROGRAPHS OF ZONES 4 AND 5. ALL ARE UNDER CROSSED NICOLS. Q, QUARTZ; cl, CLEAVELANDITE;

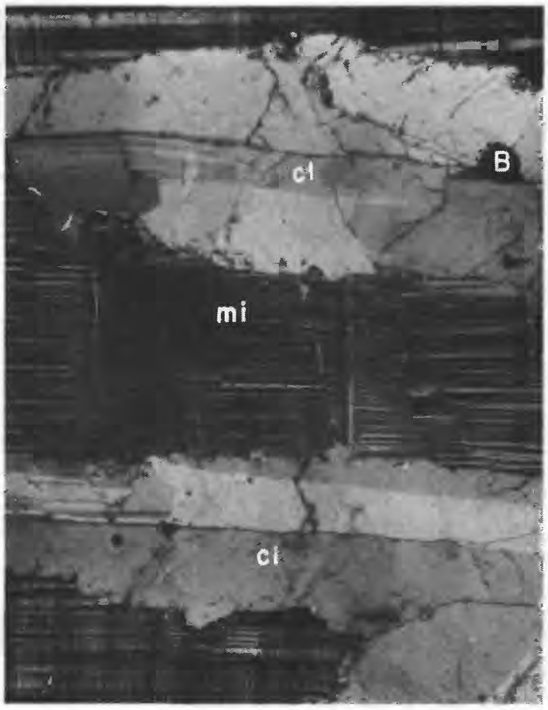

FIGURE 30.—Distorted cleavelandite included in a large crystal of microcline. Zone 5, 40 feet southeast of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 27.

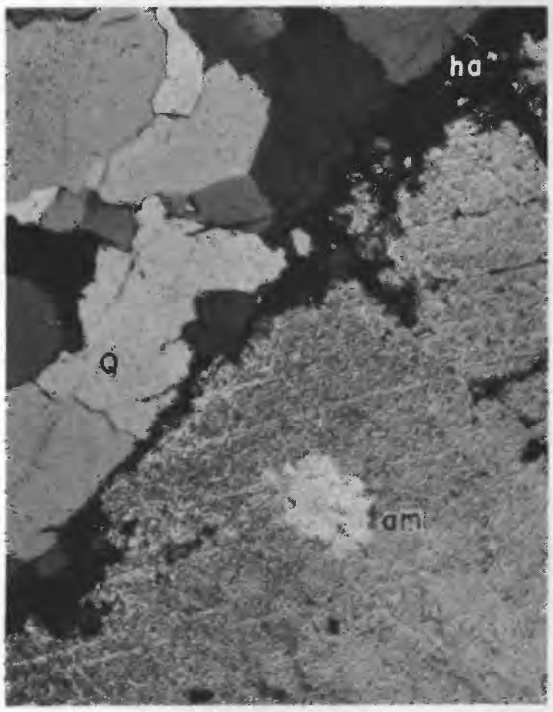

FIGURE 31.—Amblygonite with an altered rim that probably consists mainly of halloysite. The matrix is quartz. Zone 5, 80 feet north of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 40.

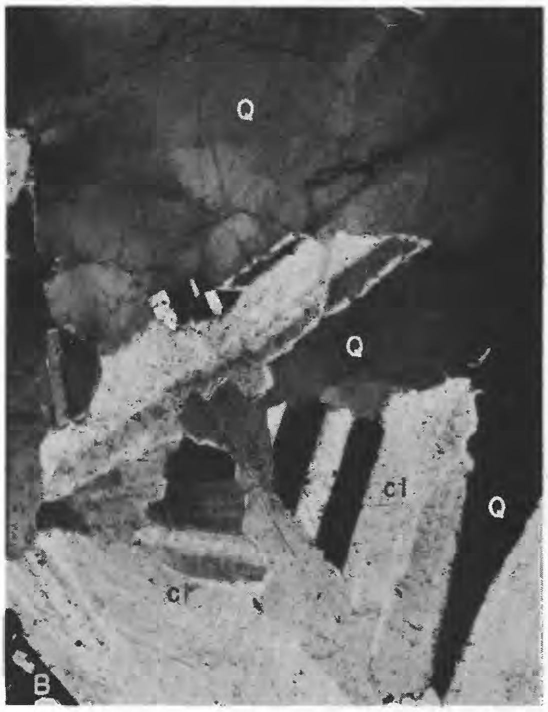

FIGURE 32.—Contact between quartz and a cleavelandite aggregate. Quartz is interstitial to cleavelandite laths. Zone 5, 60 feet southeast of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 18.5.

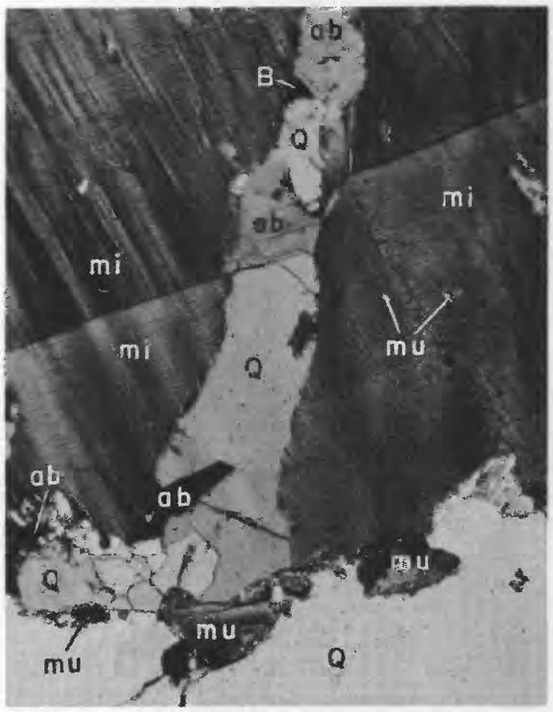

FIGURE 33.—Quartz and albite in a veinlet cutting microcline. The microcline is separated from adjacent coarse quartz by finer grained quartz, albite, and muscovite. Zone 5, 40 feet southeast of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 32.

ab, ALBITE; mi, MICROCLINE; am, AMBLYGONITE; mu, MUSCOVITE; ap, APATITE; ha, HALLOYSITE; B, BALSAM.

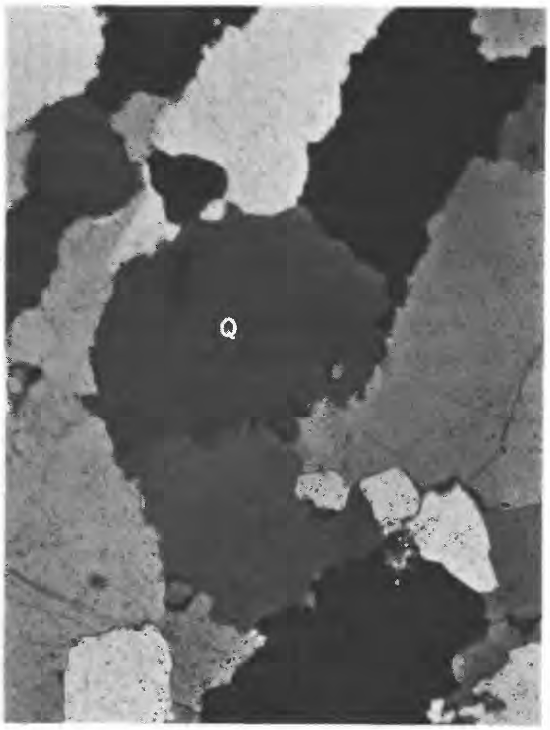

FIGURE 34.—Photomicrograph of aggregate of quartz (Q) with sutured grain boundaries. Zone 5, 80 feet north of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). Crossed nicols. × 32.

FIGURE 35.—Tabular crystals of spodumene (S) in quartz (Q), microcline (mi), and cleavelandite (cl). Zone 5 south of the contact with zone 7. Platy cleavelandite surrounds spodumene crystals. Gray areas (marked mu) are muscovite-rich borders of casts from which spodumene crystals have been removed.

TABLE 7.—*Mineralogy and petrography of zone 5, quartz-microcline-spodumene pegmatite*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Quartz

Size and shape: Virtually pure quartz occurs as irregular masses as much as 30 feet in maximum dimension.

Megascopic textural relations: Quartz forms the matrix of this unit, filling the interstices between well-formed crystals of microcline, spodumene (sheathed by cleavelandite), and amblygonite. It also forms veinlets and embayments in spodumene, cleavelandite, amblygonite, and microcline.

Microscopic textural relations: Quartz embays cleavelandite, muscovite, and amblygonite; has embayed inclusions of muscovite and cleavelandite; and has inclusions of tourmaline(?) needles. The grains in aggregates of quartz have sutured boundaries and interlocking texture (fig. 34).

Microcline

Size and shape: VC; rounded to subhedral crystals as much as 10 feet long.

Megascopic textural relations: Microcline is interstitial to the network of spodumene crystals and their cleavelandite sheaths. Inclusions of lath-shaped cleavelandite have an average length of ¼ inch. Microcline has rounded borders and crystal faces against quartz, and is veined and embayed by quartz.

Microscopic textural relations: Microcline embays cleavelandite and has embayed inclusions of lath-shaped cleavelandite, some of which are fractured and bent (fig. 30). It also has embayed inclusions of muscovite and rounded inclusions of optically continuous muscovite. Microcline is cut by veinlets containing albite and quartz (fig. 33), and carries veinlets and patches of perthitic albite.

Additional data: Twinning is visible megascopically.

Spodumene

Size and shape: Tabular crystals 3 to 10 feet long, 6 to 18 inches wide, and 1 to 4 inches thick (fig. 35).

Megascopic textural relations: Spodumene crystals form a network in which the interstices are filled by all the other minerals of the zone (fig. 35). Spodumene crystals are partly to wholly altered to clay and micaceous minerals; alteration begins along cleavages and fractures; it is greatest where spodumene crystals are in contact with microcline, less where crystals are in contact with cleavelandite, and least where in contact with quartz.

Cleavelandite

Size and shape: Individual plates are VF to C, but mostly M. The cleavelandite occurs chiefly in aggregates as much as 5 inches thick surrounding spodumene crystals (fig. 35).

Refractive indices: α'=1.529 to 1.530.

Megascopic textural relations: Cleavelandite sheaths around spodumene crystals are mostly between spodumene and quartz, but some are between spodumene and microcline. Cleavelandite plates are normal to edge of spodumene crystals (fig. 35). These plates project into quartz and microcline.

TABLE 7.—*Mineralogy and petrography of zone 5, quartz-microcline spodumene pegmatite*—Continued

Cleavelandite—Continued

Microscopic textural relations: At contacts with quartz and microcline the cleavelandite laths are approximately euhedral in form; the quartz and microcline embay the laths and fill interstices between them (fig. 32). Cleavelandite has rounded inclusions of muscovite.

Amblygonite (montebrasite)

Size and shape: VC. Rounded crystals as much as 25 feet long and 6 by 8 feet in cross section were observed; Zeigler (1913, p. 1056) reported a crystal 15 by 22 by 40 feet.

Refractive indices: α and β near 1.61; $\gamma=1.63$. Indices indicate about 85 percent montebrasite and 15 percent amblygonite according to Winchell and Winchell (1951, p. 224).

Megascopic textural relations: Amblygonite is associated with quartz and microcline in the interstices of the spodumene network. Rounded borders of observed amblygonite crystals are mostly in contact with quartz, but also in contact with microcline; the amblygonite is embayed by these minerals. There also are crystal faces in contact with quartz. Amblygonite is coated by a pink to buff, chalky to waxy aggregate of clay and micaceous minerals.

Microscopic textural relations: Amblygonite has embayed and rounded inclusions of albite and quartz, optically continuous inclusions of quartz, and irregular inclusions of mica that may be lepidolite. It is veined and embayed by aggregates consisting chiefly of isotropic material, probably halloysite (fig. 31). These aggregates also contain mica, some having such low indices that it may be lepidolite, and a high-relief mineral that may be apatite.

Muscovite

Size and shape. VF to F: largest grains are one-half inch across.

Refractive indices: Mica associated with amblygonite has lower indices than normal muscovite, and may be lepidolite.

Megascopic textural relations: Muscovite is mostly at edges of spodumene crystals, in association with cleavelandite, blue tourmaline, and clay. It also occurs along borders of cleavelandite, where it is oriented parallel to contacts between cleavelandite and adjacent minerals.

Microscopic textural relations: The larger grains of muscovite are interstitial to cleavelandite; smaller grains are included in cleavelandite, amblygonite, microcline. and quartz. Very fine grained muscovite is along grain boundaries of cleavelandite, microcline, quartz, and coarser muscovite.

Apatite

Size and shape: VF to M; anhedral to euhedral.

Megascopic textural relations: Apatite is commonly at edges of cleavelandite aggregates where these aggregates are in contact with spodumene or quartz. It has crystal faces against quartz.

Color: Blue.

Beryl

Size and shape: F to M; anhedral.

Refractive indices: $\omega=1.590$.

Megascopic textural relations: Beryl is associated with cleavelandite and quartz. It is embayed by cleavelandite.

Color: White.

TABLE 7.—*Mineralogy and petrography of zone 5, quartz-microcline spodumene pegmatite*—Continued

Fe–Mn phosphates

Size and shape: VF to F; rounded.

Megascopic textural relations: Fe–Mn phosphate was observed at edge of a spodumene crystal, where it is separated from the spodumene by muscovite flakes, and surrounded on other sides by quartz and cleavelandite.

that the alteration took place during primary crystallization of the zone, before the formation of most of the quartz. The alteration of amblygonite, though somewhat similar, is unlike the spodumene alteration in that it is confined almost entirely to the outer surfaces of crystals, and it is more likely to have been deuteric. Very fine grained aggregates of muscovite that are along the contacts of several minerals were probably deuteric.

ZONE 6: QUARTZ-MICROCLINE PEGMATITE

DESCRIPTION

Zone 6 consists of extremely coarse-grained quartz-microcline pegmatite that is at least as much as 70 feet thick above the core and probably lenses out entirely beneath the core (pl. 9). The rock consists of microcline crystals, as much as 20 feet long, set in a matrix of massive quartz (table 8). The microcline is in subhedral to nearly euhedral crystals, commonly with somewhat rounded borders.

TABLE 8.—*Mineralogy and petrography of zone 6, quartz-microcline pegmatite*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Quartz

Size and shape: VC; massive.

Megascopic textural relations: Quartz forms the matrix surrounding large crystals of microcline, which is the only other abundant constituent of the zone.

Microscopic textural relations: Quartz forms veinlets in microcline. It also follows a contact between microcline and apatite and embays the apatite (fig. 36).

Microcline

Size and shape: VC; subhedral to euhedral. As much as 20 feet long.

Megascopic textural relations: Microcline has crystal faces or rounded borders in contact with quartz. The amount of perthitic albite is small. The microcline has rounded apatite inclusions.

Microscopic textural relations: Microcline has embayed inclusions of albite. Veinlike streaks consisting of nearly untwinned microcline cut across normal twinned microcline.

Additional data: Twinning visible megascopically. Norm, recalculated from Higazy (1949, tables 1 and 4), has 89.5 percent microcline, 10.4 percent albite, and 0.1 percent anorthite.

TABLE 8.—*Mineralogy and petrography of zone 6, quartz-microcline pegmatite*—Continued

Apatite
- Size and shape: VF to VC; anhedral masses are as much as 2 feet in diameter.
- Refractive indices: ω=1.63 to 1.65.
- Megascopic textural relations: Apatite occurs as large rounded masses surrounded by quartz. It also forms rounded inclusions in microcline.
- Microscopic textural relations: The only observed apatite crystal is that shown in figure 36, which is separated from microcline by later quartz and very fine grained muscovite. Where the apatite and microcline are directly in contact, the relations are not clear, but there are indications that microcline embays apatite.
- Color: Blue.

Muscovite
- Size and shape: VF.
- Microscopic textural relations: Sparse inclusions of very fine grained muscovite are in microcline, albite, and quartz. Some of these are oriented parallel to microcline twinning planes. Others are unoriented and greatly embayed by microcline. Very fine grained muscovite is along grain contacts separating microcline, apatite, and quartz.

Pink Mica
- Size and shape: Only one 2-inch aggregate of very fine grained mica observed.
- Refractive indices: α=1.57; β=1.59; γ=1.60.
- Megascopic textural relations: The pink mica is associated with quartz and cleavelandite that are interstitial to microcline.
- Microscopic textural relations: The pink mica forms optically continuous inclusions in quartz, is embayed by quartz, and is intimately intergrown with quartz (fig. 37).
- Color: Pink to purple.
- Additional data: $2V$ 30° to 45°. Pleochroic, colorless to pale pinkish-gray.

Albite
- Size and shape: VF.
- Refractive indices: α'=1.528 to 1.529.
- Microscopic textural relations: Embayed inclusions occur in microcline.

Blue apatite is the only important accessory mineral. It occurs chiefly as large rounded masses surrounded by quartz, but also appears as small inclusions in microcline. An apatite crystal illustrated in figure 36 is separated from microcline by quartz and very fine grained mica. Albite has been found only as lath-shaped inclusions and perthitic material included in the microcline. One small specimen was collected containing pink mica that has 0.41 percent Li_2O (table 15). This mica was associated with cleavelandite and quartz interstitial to microcline.

PARAGENESIS

The large crystals of microcline crystallized either entirely or virtually entirely before the quartz of the matrix. Quartz forms veins and embayments in microcline, and there was little if any overlap with microcline.

Other minerals occur in such very small quantities that their position in the paragenesis is not important, and furthermore the data are probably incomplete. Cleavelandite appears as embayed inclusions in microcline and thus formed early. Apatite clearly preceded quartz in figure 36, and inclusions suggest that it may also have preceded microcline. Mica has a fairly wide range in age. Embayed muscovite inclusions in microcline probably formed early, but muscovite oriented parallel to microcline twinning or distributed along grain boundaries was late. The pink mica formed either before or at the same time as quartz (fig. 37), but it may have followed microcline.

ZONE 7: CLEAVELANDITE-MICROCLINE-LITHIA MICA PEGMATITE

DESCRIPTION

The core, zone 7, consists of a small body of cleavelandite-microcline-lithia mica pegmatite (table 9). The main exposure is on a southward-facing cliff in the upper part of the opencut, east of the intersection of cross sections *A–A′* and *B–B′*. The unit is probably lenticular (section *B–B′* pl. 9), and its maximum dimension is not more than about 100 feet.

Zone 7 is striking in the irregularity of its texture, as shown in figure 44. It has anhedral to subhedral crystals of microcline containing many inclusions of lithia mica. These are surrounded by aggregates as much as 3 feet wide consisting of cleavelandite, lithia mica, or quartz. Other minerals are rare.

TABLE 9.—*Mineralogy and petrography of zone 7, cleavelandite-microcline-lithia mica pegmatite*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Cleavelandite
- Size and shape: Cleavelandite occurs as VF to F, subhedral laths in aggregates that are mostly M to VC. Some sugary albite.
- Refractive indices: α'=1.528 to 1.529.
- Megascopic textural relations: Cleavelandite aggregates are closely associated with lithia mica. They commonly form veins that cut lithia mica aggregates (fig. 44), and much less commonly cut microcline and quartz. Cleavelandite laths tend to be subparallel to the borders of these veins.
- Microscopic textural relations: Some inclusions of lithia mica are embayed by the enclosing cleavelandite, but more commonly the two minerals have mutual contacts. Cleavelandite embays microcline. Distorted cleavelandite is in contact with undistorted quartz. Cleavelandite also has crystal faces against quartz, is embayed by quartz, and has mutual contacts with quartz.

TABLE 9.—*Mineralogy and petrography of zone 7, cleavelandite-microcline-lithia mica pegmatite*—Continued

Microcline

Size and shape: M to C; anhedral to subhedral.

Megascopic textural relations: Microcline invariably has a great quantity of poikilitic inclusions of lithia mica. It also has vermicular inclusions of quartz. Crystal faces are against aggregates of lithia mica (fig. 44) and against quartz. Microcline is veined and embayed by cleavelandite, lithia mica, and quartz.

Microscopic textural relations: Quartz containing many inclusions of lithia mica embays microcline and has optically continuous inclusions of microcline (fig. 38). Microcline is embayed by cleavelandite and rarely embays cleavelandite.

Lithia mica

Size and shape: Individual grains are VF; aggregates are F to VC.

Refractive indices: $\beta=1.59$.

Megascopic textural relations: Irregular aggregates of lithia mica are associated mainly with cleavelandite (fig. 44). These are cut by veinlike aggregates of cleavelandite, but in detail the lithia mica veins and embays cleavelandite. It also embays and veins microcline and rarely quartz.

Microscopic textural relations: Relatively coarse grained mica (0.3 mm) is surrounded by interstitial finer grained mica (0.06 mm). Still finer grained mica (0.02 mm) is distributed along borders of other minerals, especially cleavelandite. Aggregates of mica cut across optically continuous quartz (fig. 40). Mica embays cleavelandite (figs. 39, 43) and quartz, and is included in quartz that embays microcline. Inclusions of lithia mica are abundant not only in microcline but also in quartz (figs. 38, 42) and cleavelandite, which may carry more of these inclusions than does the adjacent microcline. There is no clear evidence that the inclusions are controlled by structures of the host mineral: most inclusions have mutual borders with the host mineral, but a few of the larger inclusions are embayed (figs. 38, 41).

Color: Greenish-gray.

Quartz

Size and shape: VF to VC; anhedral.

Megascopic textural relations: Mostly irregular in form, and interstitial to the crystals or aggregates of other minerals.

Microscopic textural relations: Quartz commonly has mutual relations with lithia mica, but embays the coarser inclusions of lithia mica (fig. 41) and is embayed and veined by finer grained lithia mica. Relations with cleavelandite and microcline are described above.

Cassiterite

Size and shape: VF to F; anhedral.

Megascopic textural relations: Cassiterite is associated mainly with sugary albite; it has crystal faces against the albite. Cassiterite has ragged edges at contacts with lithia mica.

Apatite

Size and shape: VF to F; anhedral.

Megascopic textural relations: Apatite occurs in contact with microcline, lithia mica, cleavelandite, and quartz. It forms inclusions in cleavelandite, has rare crystal faces against cleavelandite, has ragged contacts with lithia mica, and is veined by quartz.

Color: Greenish-blue.

Tantalite-columbite

Size and shape: VF to F; subhedral.

Megascopic textural relations: Tantalite-columbite has crystal faces against quartz and is veined by quartz.

Microscopic textural relations: Tantalite-columbite has crystal faces against cleavelandite and lithia mica (fig. 43), and also ragged contacts with lithia mica. Inclusions of lithia mica in some places have a subparallel alinement that suggests structural control by the tantalite-columbite.

PARAGENESIS

Microcline formed generally before the other major minerals in zone 7. It was succeeded by cleavelandite and lithia mica, which crystallized largely simultaneously. Most of the quartz crystallized after the other minerals.

Microcline has crystal faces in contact with lithia mica and quartz, and it is veined and embayed by all the other major minerals. Figure 38 shows an example in which all that remains of the microcline is optically continuous patches. Lithia mica inclusions are more abundant in the quartz than in the microcline of the thin sections. These inclusions accompany the quartz where it cuts microcline; thus the lithia mica probably also formed after the microcline.

Lithia mica as seen under the microscope consists of relatively coarse grains (average diameter, 0.3 mm) surrounded by interstitial aggregates of finer grains (average diameter, 0.06 mm). In addition still finer grained mica (average diameter, 0.02 mm) occurs along contacts of cleavelandite.

All varieties of mica embay cleavelandite in one place or another (figs. 39, 43), but the coarser mica also occurs as embayed inclusions in cleavelandite. More commonly, however, the inclusions in cleavelandite provide no clear evidence that they either preceded or followed the cleavelandite, and they may have been contemporaneous. The well-developed veins of cleavelandite that cross lithia mica aggregates (fig. 44) clearly indicate that much of the cleavelandite formed

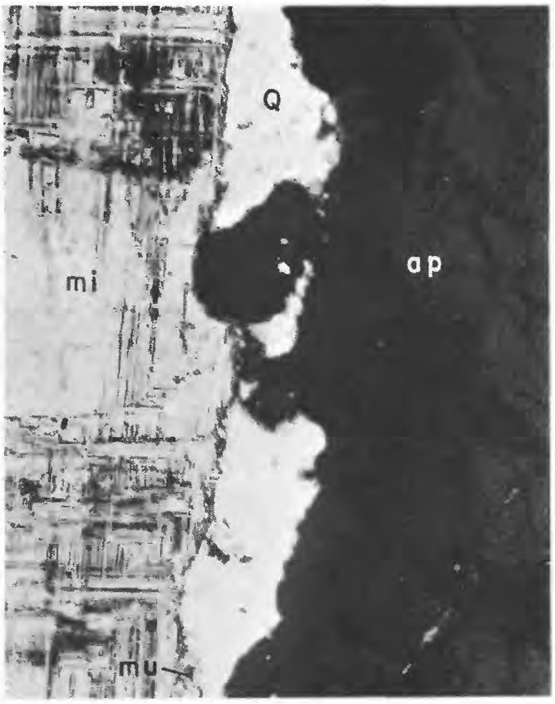

FIGURE 36.—Quartz along a contact between apatite and microcline. The quartz embays apatite. Small muscovite grains are along the edge of the quartz, especially on the side against microcline. Zone 6, 50 feet north of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 97.

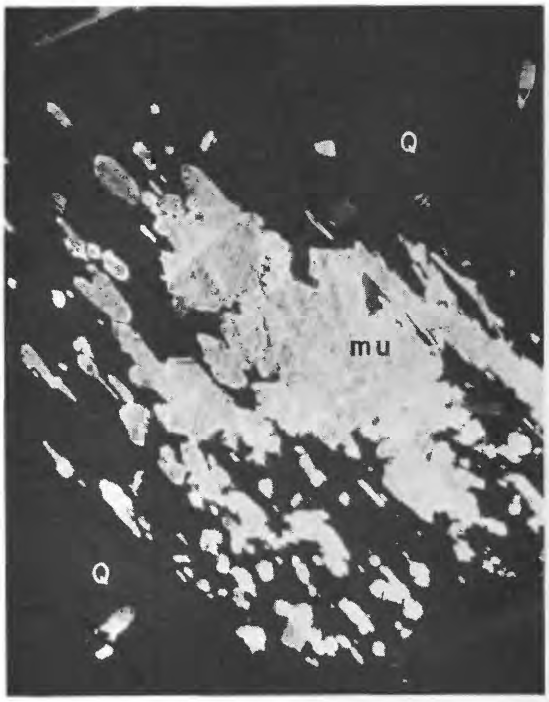

FIGURE 37.—Irregular, optically continuous pink mica surrounded by quartz. Zone 6, 20 feet north of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). ×32.

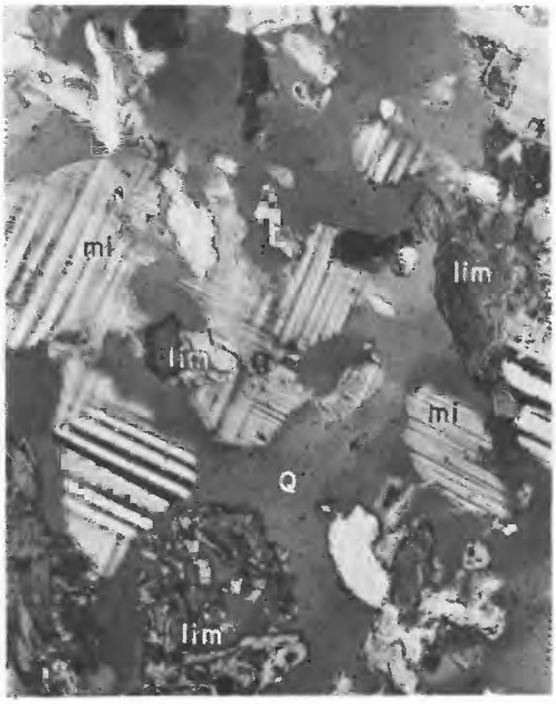

FIGURE 38.—Optically continuous patches of microcline surrounded by a large grain of quartz containing inclusions of lithia mica. Quartz embays part of the lithia mica. From the southwest part of zone 7. × 97.

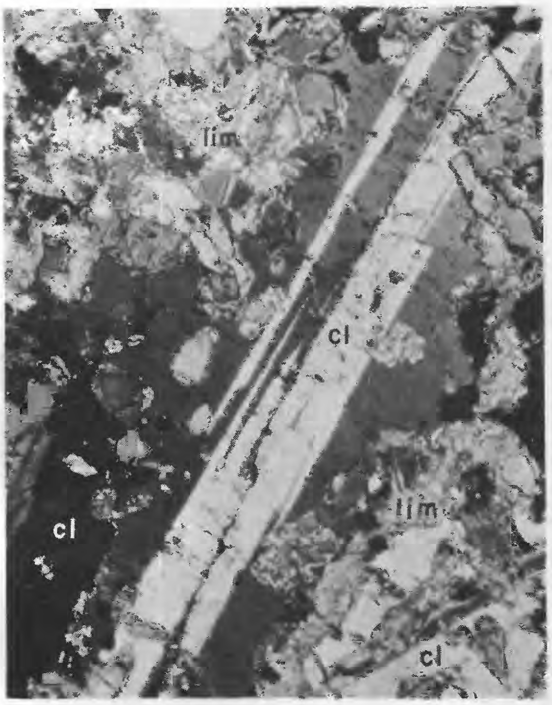

FIGURE 39.—Cleavelandite embayed by lithia mica. From the northeast part of zone 7. × 32.

FIGURES 36–43.—PHOTOMICROGRAPHS OF ZONES 6 AND 7. ALL ARE UNDER CROSSED NICOLS. Q, QUARTZ; mi, MICROCLINE; cl,

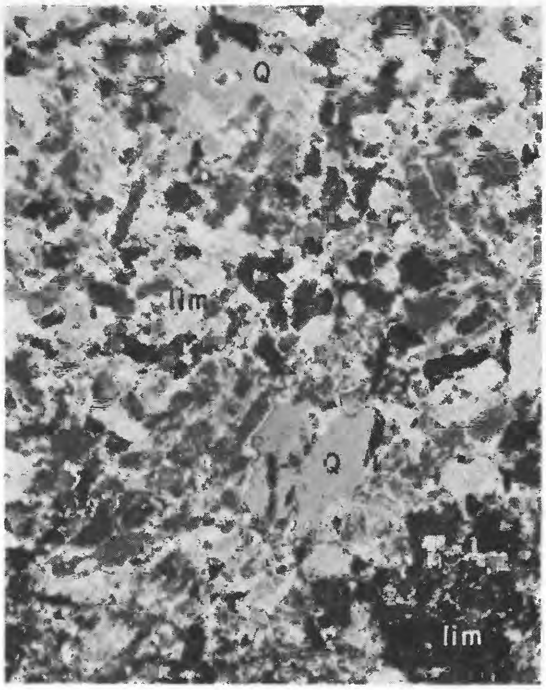

FIGURE 40.—Optically continuous patches of quartz surrounded by an aggregate of lithia mica. From near the northeast border of zone 7. × 32.

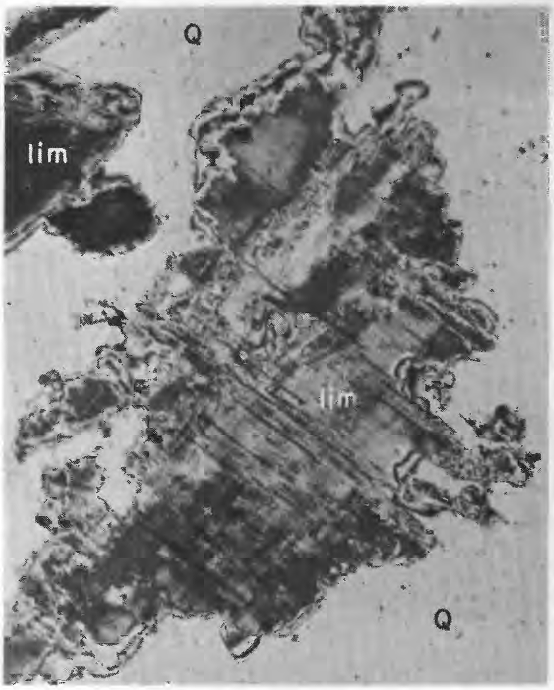

FIGURE 41.—Embayed inclusion of lithia mica in quartz. From the southwest part of zone 7. × 97.

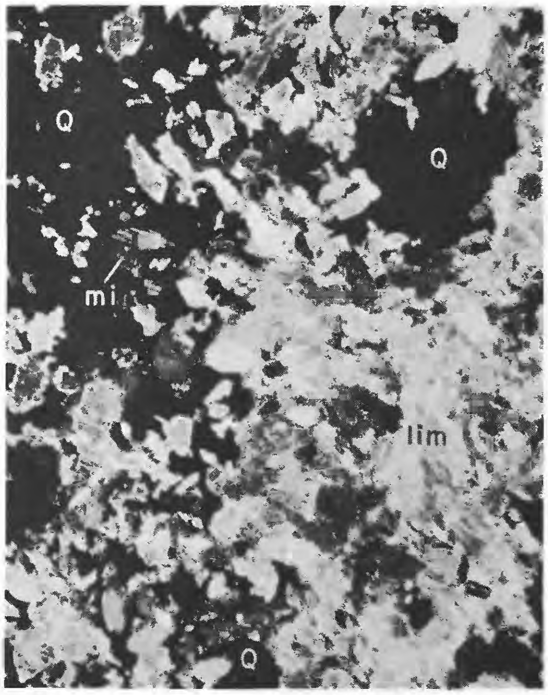

FIGURE 42.—Optically continuous quartz that has many inclusions of lithia mica and an irregular contact with an aggregate of lithia mica. The quartz has an embayed inclusion of microcline. From near the northeast border of zone 7. × 32.

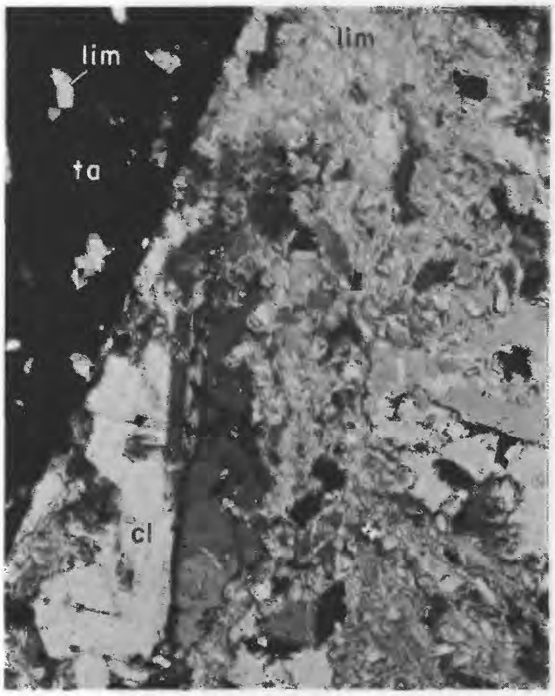

FIGURE 43.—Aggregate of lithia mica and cleavelandite in contact with a crystal face of tantalite. Lithia mica embays the cleavelandite. The tantalite has inclusions of lithia mica. From the northeast part of zone 7. × 32.

CLEAVELANDITE; mu, MUSCOVITE AND PINK MICA OF ZONE 6; lim, LITHIA MICA OF ZONE 7; ap, APATITE; ta, TANTALITE-COLUMBITE.

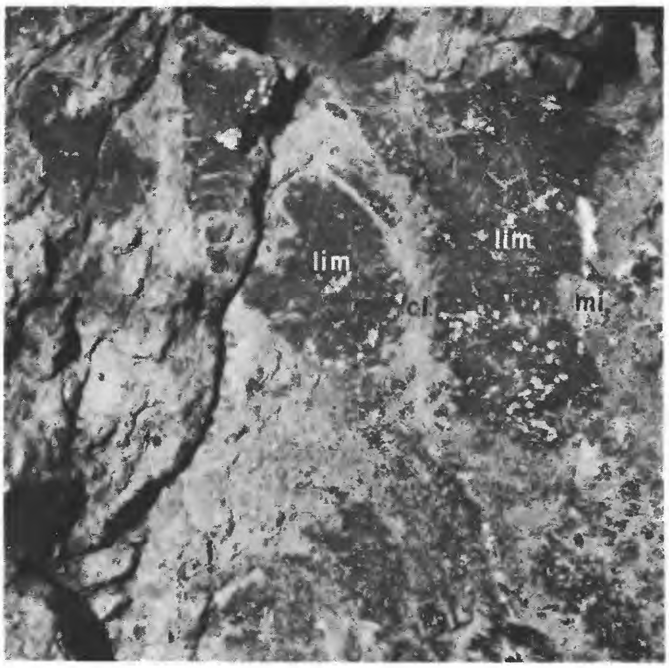

Figure 44.—Typical exposure of zone 7. Aggregates of dark-gray lithia mica (lim) are cut by veinlike aggregates of cleavelandite (cl). Microcline (mi) has crystal faces against the lithia mica aggregates. The gray color of the microcline is caused by poikilitic inclusions of lithia mica. Width of exposure shown in this photograph is about 5 feet. Fifty feet east-northeast of the intersection of cross sections *A–A'* and *B–B'* (pl. 9).

after the lithia mica aggregates had been established. On the other hand, there are megascopically visible veinlets of lithia mica that cut cleavelandite. These contradictory textural relations seem best interpreted as meaning that the cleavelandite and lithia mica formed at about the same time. Also, cleavelandite and lithia mica are more closely associated with each other than with microcline or quartz. Adamson (1942, p. 41–44) describes somewhat similar textural relations between cleavelandite and gray mica in the Varuträsk pegmatite.

The abundant lithia mica inclusions in microcline are not controlled by the microcline structure, and probably lithia mica began to crystallize while microcline was still forming. On the other hand, aggregates of lithia mica surround optically continuous grains of quartz (fig. 40), and formed after quartz began to crystallize.

Quartz has a generally interstitial relation to the other minerals that suggest most of it formed late. Despite the evidence already cited that part of the lithia mica followed quartz, there are also places where quartz embays coarse inclusions of lithia mica (fig.41). In many other places, as in figure 42, the interpretation of the texture is dubious, and the two minerals may have been contemporaneous. Quartz embays cleavelandite laths, much as it does in zone 5.

Cassiterite, apatite, and tantalite-columbite probably all formed early. A crystal face of tantalite shown in figure 43 is in contact with lithia mica and cleavelandite of the matrix. Some of the apatite and cassiterite have crystal faces against cleavelandite or sugary albite.

CLEAVELANDITE-MICROCLINE-LITHIA MICA REPLACEMENT UNIT

DESCRIPTION

The cleavelandite-microcline-lithia mica replacement unit is a small irregular body that extends outward from the core across zones 4, 5, and 6 (pl. 9). Very small outlying bodies of similar composition replace zone 3.

This replacement body, like zone 7, consists chiefly of cleavelandite, microcline, lithia mica, and quartz; furthermore, the mineralogic characteristics and the textures of these minerals are much the same in both the replacement body and zone 7 (table 10). The replacement body, however, also contains unreplaced relicts of the zones. Some of these are large enough to show separately on the geologic map; others that are too small to map form about 10 percent of the replacement unit. There are all gradations between these un-

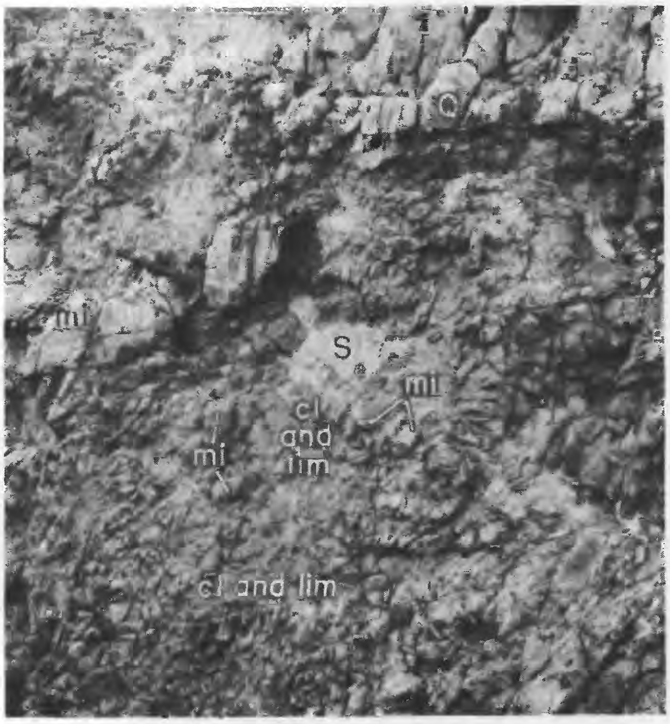

Figure 45.—Cleavelandite-microcline-lithia mica replacement unit where it replaces zone 5. Consists mainly of an aggregate of cleavelandite (cl), lithia mica (lim), and small irregular crystals of microcline (mi). Relicts of zone 5 are coarse spodumene (S), quartz (Q), and microcline (mi). Forty feet west-southwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9).

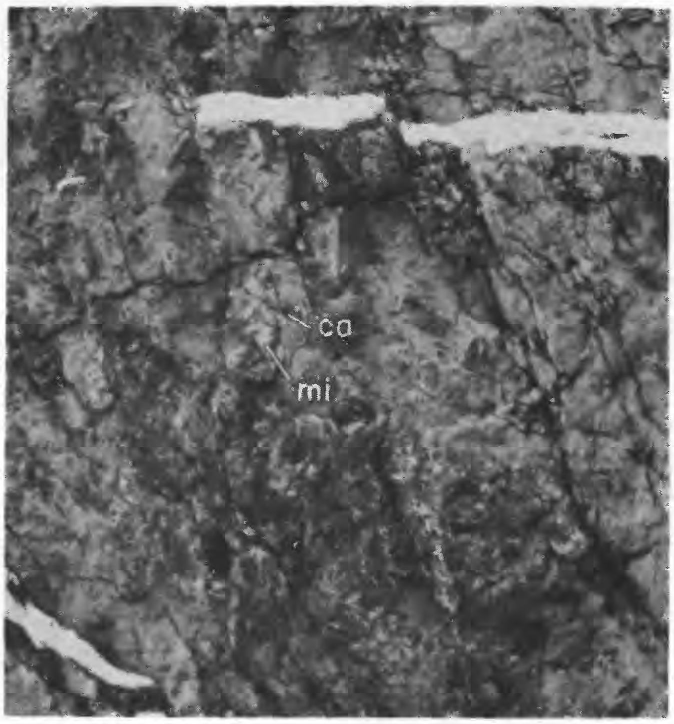

FIGURE 46.—Exposure of the cleavelandite-microcline-lithia mica replacement unit in a replaced part of zone 6, 20 feet northwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). Small remnants of the originally large crystals of microcline (mi) are all that remain of the primary rock. Otherwise the exposure consists chiefly of a fine-grained aggregate of cleavelandite, lithia mica, and quartz. Small black grains are cassiterite (ca). Width of exposure shown in the photograph is about 5 feet.

replaced materials and rock that consists almost entirely of the cleavelandite, lithia mica, and small irregularly shaped grains of microcline that are characteristic of this unit. Figure 45, for example, shows partly altered material of zone 5, and figure 46 shows an almost completely replaced part of zone 6. Probably about a third of the replacement body consists of partly replaced relict minerals of the zones, although in many exposures there is some uncertainty about which minerals are primary and which formed in the replacement stage.

The replacement unit contains massive quartz and large crystals of microcline and spodumene that have the same form as in zones 4, 5, and 6, and certainly are relict minerals. The same may be said for coarse cleavelandite, especially where it is at the edges of relict spodumene crystals. The only other common mineral of the zones is amblygonite, and it rarely occurs as a relict mineral.

Minerals that undoubtedly crystallized during the replacement stage include lithia mica, fine-grained cleavelandite, and small irregular crystals of microcline. These minerals appear together in aggregates that surround the relicts of primary minerals.

TABLE 10.—*Mineralogy and petrography of the cleavelandite-microcline-lithia mica replacement unit*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Cleavelandite

Size and shape: VF to M, mostly F; aggregates are mostly VC. Platy; rarely blocky; also sugary.

Refractive indices: $\alpha'=1.527$ to 1.531; mostly 1.527 to 1.529.

Megascopic textural relations: Relict cleavelandite occurs as aggregates of coarse plates, 1 to 2 inches long, surrounding spodumene crystals that are relicts of zone 5 and blades that are relicts of zone 4. Introduced cleavelandite is chiefly in irregular to veinlike aggregates consisting of randomly oriented platy crystals as much as 1 inch long. These aggregates embay and cut across microcline, spodumene, quartz, and aggregates of lithia mica. In a few places cleavelandite plates as much as one-fourth inch long form porous aggregates. Sugary albite occurs as aggregates containing cassiterite.

Microscopic textural relations: Laths of relict cleavelandite that project into quartz have crystal faces against quartz and are embayed by quartz, as in zones 4 and 5. Relict cleavelandite also is embayed by microcline and forms embayed inclusions in microcline. Introduced cleavelandite is associated with finely twinned, introduced microcline and with lithia mica. Cleavelandite inclusions disseminated through the microcline have irregular borders (fig. 49), ordinarily not diagnostic of the age relations of the two minerals. In places, however, cleavelandite has optically continuous inclusions of microcline, some of which have fine and some coarse twinning. Veinlets of albite and mica cut both varieties of microcline and follow contacts between grains of finely twinned microcline (fig. 50).

Additional data: Replaced parts of zones 5 and 6 contain so much more cleavelandite than do the zones themselves that most of the cleavelandite in these parts of the replacement unit must have been introduced. Some of the coarse cleavelandite is distorted.

Microcline

Size and shape: F to VC. Relict microcline is in rounded crystals that in replaced parts of zone 6 are as much as 8 feet long. Introduced microcline occurs as anhedral crystals, mostly F to M.

Megascopic textural relations: Relict crystals of microcline are embayed, veined, and occur as isolated remnants surrounded by aggregates that consist mainly of lithia mica and cleavelandite but also contain microcline (in variously oriented anhedral grains) and cassiterite. Introduced microcline is in small anhedral grains associated with cleavelandite and lithia mica in aggregates that embay, vein, and surround isolated remnants of relict spodumene (fig. 45), microcline, and quartz. Cleavelandite and lithia mica are in aggregates surrounding microcline and are also disseminated through microcline.

Microscopic textural relations: Much of the relict microcline (figs. 51–53) is coarsely twinned, like much of the microcline of zones 4 to 6, and it has many dusty inclusions. It forms crystal faces against quartz and is embayed by quartz (fig. 51), but also has graphic intergrowths and optically continuous inclusions of quartz. It

TABLE 10.—*Mineralogy and petrography of the cleavelandite-microcline-lithia mica replacement unit*—Continued

Microcline—Continued

- also contains embayed inclusions of cleavelandite. Introduced microcline tends to be more finely twinned and to contain fewer dusty inclusions than relict microcline. It is closely associated with lithia mica and cleavelandite, both of which are dispersed through the microcline as irregularly shaped grains (figs. 47–50). Finely twinned microcline forms rims on earlier microcline (fig. 54). It also embays cleavelandite, part of which is known from megascopic relations to be introduced. Both varieties of microcline are cut by veinlets containing quartz (fig. 52) albite, mica, or nearly untwinned microcline.

Lithia mica

- Size and shape: VF. Individual flakes are rarely more than one-sixteenth inch in diameter. Aggregates are M to C.
- Refractive indices: $\beta = 1.59$.
- Megascopic textural relations: Lithia mica forms irregular aggregates that embay and vein relict microcline, spodumene, and quartz. It also occurs as many separate grains disseminated through relict quartz and through both relict and introduced microcline and cleavelandite.
- Microscopic textural relations: Lithia mica occurs as irregular grains dispersed through all the other abundant minerals, both relict and introduced, and it also forms aggregates in contact with these minerals. It is associated mainly with finely twinned microcline and with cleavelandite (figs. 47–50), and tends to be concentrated near contacts of these two minerals. Inclusions of lithia mica are more abundant in microcline (especially introduced microcline) than in cleavelandite (fig. 48), and more abundant in cleavelandite than in quartz. Grains of lithia mica cut across contacts separating these minerals. Lithia mica grains show an imperfectly developed tendency to be oriented parallel to each other, partly along microcline twinning planes. Aggregates of lithia mica embay microcline. Very fine grained mica is along grain boundaries of other minerals, especially cleavelandite.
- Color: Greenish-gray.
- Additional data: $2V$ 30°.

Quartz

- Size and shape: Mostly F to M.
- Megascopic textural relations: Quartz occurs mainly as isolated relicts surrounded by introduced minerals. It also forms subgraphic intergrowths with relict microcline.
- Microscopic textural relations: Quartz is predominantly in relict grains and aggregates that embay relict cleavelandite and microcline, and have interstitial relations to these minerals. Veinlets of quartz cut both varieties of microcline. Lithia mica grains cut across some of these veinlets, and are cut by other veinlets. One veinlet abuts against cleavelandite (fig. 52), but does not cross the cleavelandite. Quartz along a contact between finely twinned microcline and lithia mica embays the microcline.

TABLE 10.—*Mineralogy and petrography of the cleavelandite-microcline-lithia mica replacement unit*—Continued

Cassiterite

- Size and shape: VF and F; subhedral to euhedral.
- Megascopic textural relations: Cassiterite is associated with sugary albite and commonly is euhedral against the albite.
- Microscopic textural relations: Euhedral grains of cassiterite are distributed along a contact between relict quartz and microcline. There are also subhedral inclusions of cassiterite in this same microcline (fig. 53).

Spodumene

- Size and shape: M to VC.
- Megascopic textural relations: Spodumene is mostly in small unmapped relicts of the zones; it also occurs as residual material surrounded by introduced minerals (fig. 45).

Apatite

- Size and shape: VF and F.
- Microscopic textural relations: Relict apatite is embayed and veined by quartz and cleavelandite, and forms euhedral inclusions in cleavelandite. Apatite is associated with Fe–Mn phosphates in a veinlet cutting lithia mica.

Tourmaline

- Size and shape: VF.

Beryl

- Size and shape: VF and F.
- Refractive indices: $\omega=1.589$.
- Color: White to faintly pink.

Fe–Mn phosphates

- Size and shape: VF and F.
- Microscopic textural relations: Fe–Mn phosphates are intergrown with quartz and cut by quartz veinlets. Veinlets with phosphates cut lithia mica.

Amblygonite (montebrasite)

- Size and shape: VF.
- Refractive indices: $\alpha=1.61$; $\gamma=1.64$. Indices indicate nearly pure montebrasite, according to Winchell and Winchell (1951, p. 224).
- Microscopic textural realtions: Very fine grained aggregates of amblygonite contain optically continuous relicts of quartz (fig. 55).
- Additional data: Large $2V$, optically positive. Mostly colorless in thin section, but some grains are pleochroic; X, yellow; Z, blue. Identified by X-ray (M. L. Lindberg, written communication, 1957).

Tantalite-columbite

- Size and shape: VF and F; subhedral to euhedral.

The habit of the newly formed cleavelandite is very different from that of the cleavelandite in the zones. It occurs as irregularly shaped aggregates, each consisting of many randomly oriented crystals. The aggregates cut across primary minerals, and are widely distributed through the unit. In contrast, the cleavelandite of the zones is mostly at the borders of spodumene crystals or spodumene pseudomorphs, where it appears as rosette-shaped aggregates in which the individual plates of cleavelandite are approximately normal to the spodumene crystal. Furthermore, the cleavelandite of the zones is mostly coarser grained, and has somewhat higher indices of refraction. Cleavelandite is so much more abundant in the replacement body than in unreplaced parts of zones 5 and 6 that this evidence alone would indicate that most of it was introduced.

The introduced microcline associated with this cleavelandite characteristically has abundant irregularly shaped inclusions of lithia mica (figs. 47–50). Inclusions of similarly irregular, but larger grains of cleavelandite are also disseminated through the microcline or distributed along contacts between microcline crystals (figs. 49, 50). The introduced microcline is finely twinned, in contrast to the more coarsely twinned relict crystals (figs. 51–53) that are similar to much of the microcline of zones 4–6. The finely twinned microcline in figure 48 is from a replaced spodumene crystal of figure 45, and thus must have formed during the replacement stage. The rim of late microcline surrounding earlier microcline in figure 54 is also finely twinned.

Lithia mica forms large aggregates and also occurs as inclusions disseminated through all of the other abundant minerals. The inclusions are chiefly in microcline, especially introduced microcline (fig. 48), but they are also found in cleavelandite and quartz.

Although most of the quartz is relict, there are a few late veinlets that cut microcline (fig. 52), and a small amount of anhedral quartz that is associated with lithia mica and microcline.

No phosphate mineral in the replacement body is known to be sufficiently abundant to account for the phosphorus that one would expect to be contributed by the preexisting amblygonite of the zones. Amblygonite does appear as a replacement mineral, however, as in figure 55, where it surrounds relicts of quartz. Amblygonite of this kind may be more abundant than the modes suggest. It is white, very fine grained, and megascopically has a nondescript appearance suggestive of an aggregate of very fine grained feldspar, quartz, and mica; it may easily have been overlooked in estimating the mode.

PARAGENESIS

Structures and textures previously described have been used as evidence to distinguish introduced minerals from relict minerals so that the paragenesis of the two ages of crystallization can be treated separately. Most of this evidence is megascopic. The main value of thin sections is to show the paragenesis among minerals after determining, from larger scale relations, which are relict and which were introduced.

The paragenesis of the relict minerals is the same as in unreplaced parts of the zones. The sequence of the major minerals is generally (1) spodumene, (2) cleavelandite, (3) microcline, and (4) quartz. Both the relict cleavelandite and the microcline have crystal faces against quartz and are embayed by quartz (fig. 51), just as they are in the zones.

Among the introduced minerals, the characteristically finely twinned microcline seems to have been generally the first to form, followed by cleavelandite and then by the widely disseminated lithia mica, but the proper interpretation of the textures is commonly not clear. Where veinlike aggregates of cleavelandite and lithia mica follow contacts between microcline crystals (fig. 50) or where a flood of cleavelandite and lithia mica cross a microcline crystal (fig. 49), the microcline probably formed early.

Aggregates of lithia mica embay microcline, and small grains of lithia mica cut across contacts of microcline and cleavelandite. The distribution of lithia mica inclusions is partly controlled by structures of the host minerals; this is most evident where it tends to concentrate near the contacts of microcline and cleavelandite. Nevertheless, part of the lithia mica inclusions in the feldspars may have formed early in the replacement stage, and the same may be said for cleavelandite included in microcline. The very close association of these minerals indicates extensive overlap in the paragenesis.

Late quartz appears as small veinlets (fig. 52) that cut both relict and introduced microcline, and as irregular grains embaying introduced microcline at a contact with lithia mica. Some of the veinlets cross lithia mica grains, and others are cut by lithia mica grains, thus demonstrating overlap.

Phosphate minerals also formed in the replacement stage. Figure 55, for example, shows remnants of quartz surrounded by finer grained introduced amblygonite. Iron-manganese phosphates appear not only as relict minerals, but also in veinlets that cut lithia mica and must have crystallized during or after the replacement stage.

CLEAVELANDITE-QUARTZ-LITHIA MICA REPLACEMENT UNIT

DESCRIPTION

The cleavelandite-quartz-lithia mica replacement unit is very rich in fine-grained cleavelandite (table 11). It cuts across the zonal structure in the southwesternmost part of the pegmatite. Zone 4 is the chief unit replaced; also a large block of zone 5, and small parts of zones 2, 3, and 6 are replaced.

Unreplaced parts of zones 4 and 5 that are large enough to show on the map (pl. 9) are completely surrounded by the replacement body. Other relicts of the zones are too small to map separately (fig. 56). The

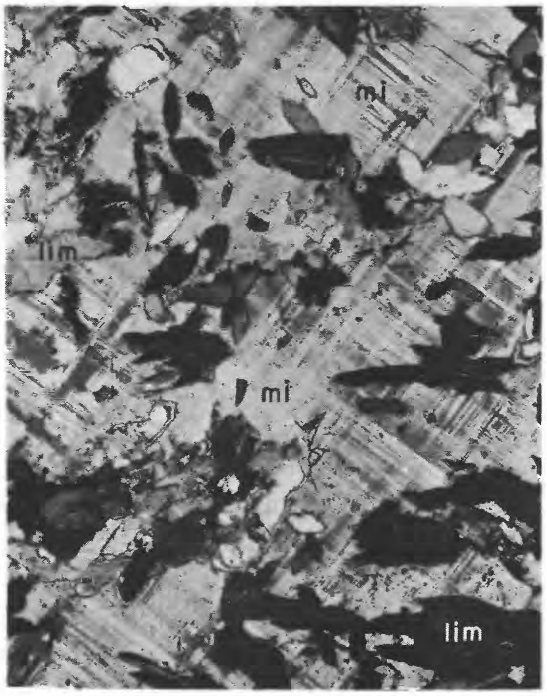

FIGURE 47.—Inclusions of lithia mica dispersed in microcline. Forty feet northwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 32.

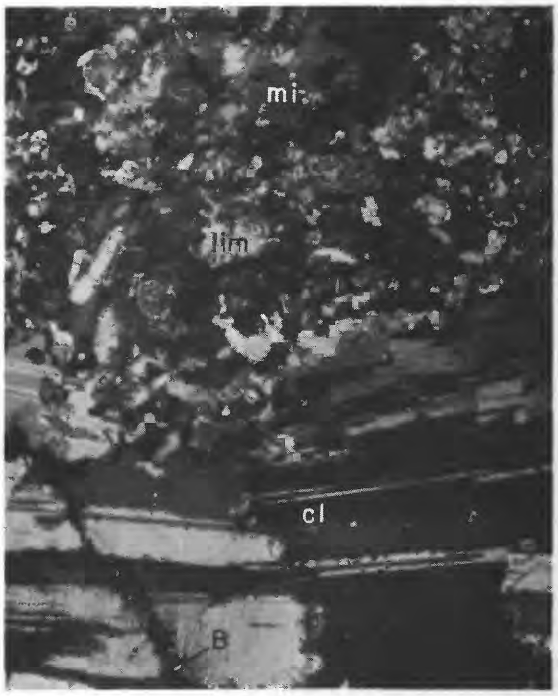

FIGURE 48.—Lithia mica disseminated through microcline in preference to cleavelandite. From within a replaced spodumene crystal shown in figure 45. Forty feet west-southwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 32.

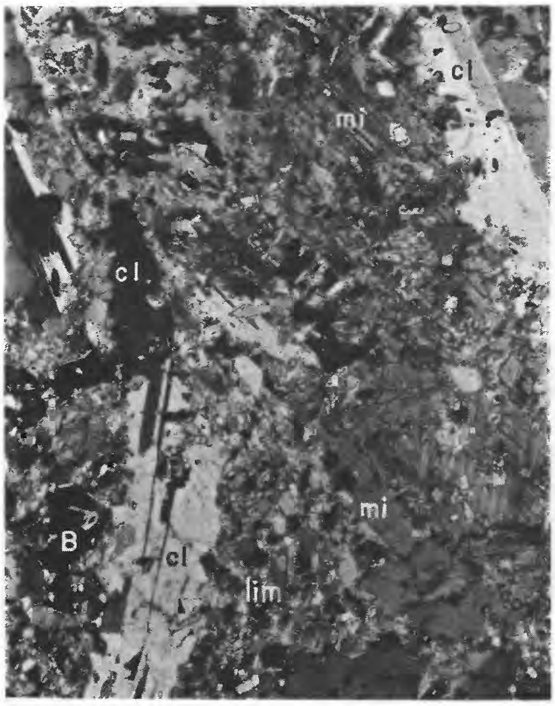

FIGURE 49.—Cleavelandite and lithia mica disseminated in a microcline crystal. Forty feet west-southwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9.) × 18.5.

FIGURE 50.—Cleavelandite distributed along the contact between two microcline crystals. Lithia mica appears both with the cleavelandite and as inclusions in the microcline. Forty feet west-southwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 32.

FIGURES 47–54.—PHOTOMICROGRAPHS OF THE CLEAVELANDITE-MICROCLINE-LITHIA MICA REPLACEMENT UNIT. ALL ARE

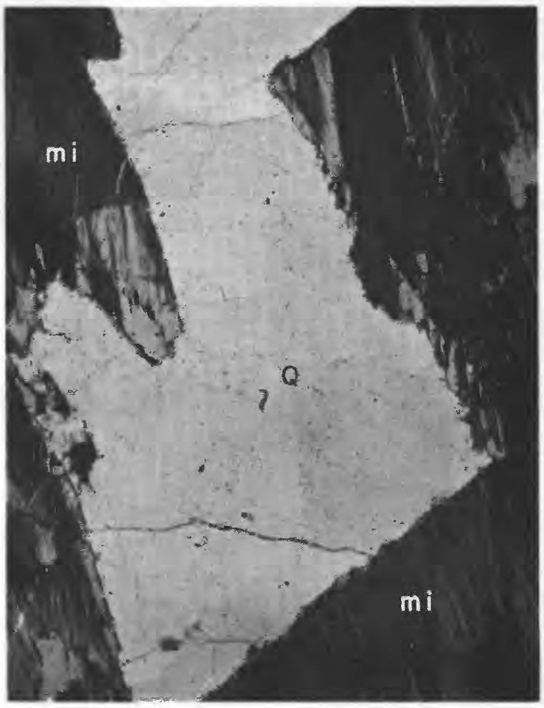

Figure 51.—Embayment of quartz in a coarsely twinned microcline. The quartz in the embayment is connected with a large body of quartz above the top of the photomicrograph. From a relict of zone 6, 40 feet northwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 18.5.

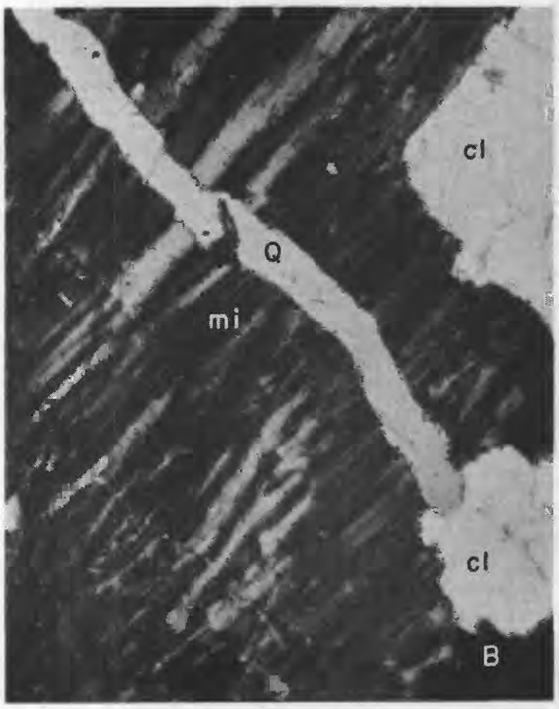

Figure 52.—Quartz veinlet cutting microcline and ending against cleavelandite. Forty feet northwest of the intersection of cross sections *A–A'* and *B–B'* (pl. 9.) × 49.

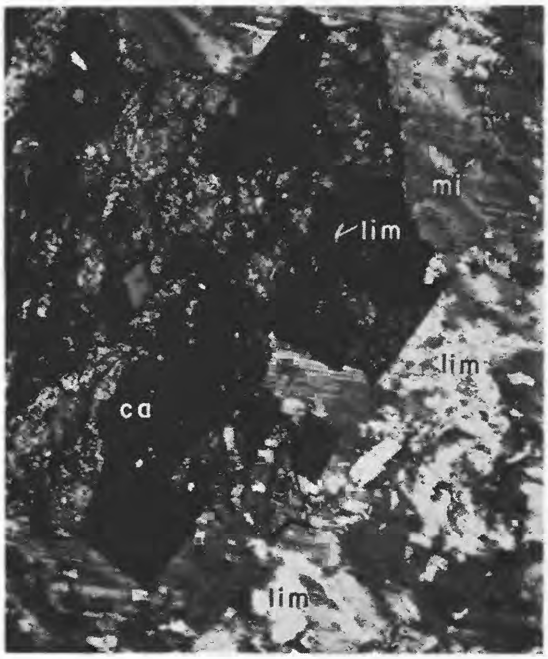

Figure 53.— Subhedral cassiterite, probably a primary mineral, surrounded by coarsely twinned microcline. Lithia mica is disseminated mainly in microcline, but a few small grains are in cassiterite. Ten feet south of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). × 32.

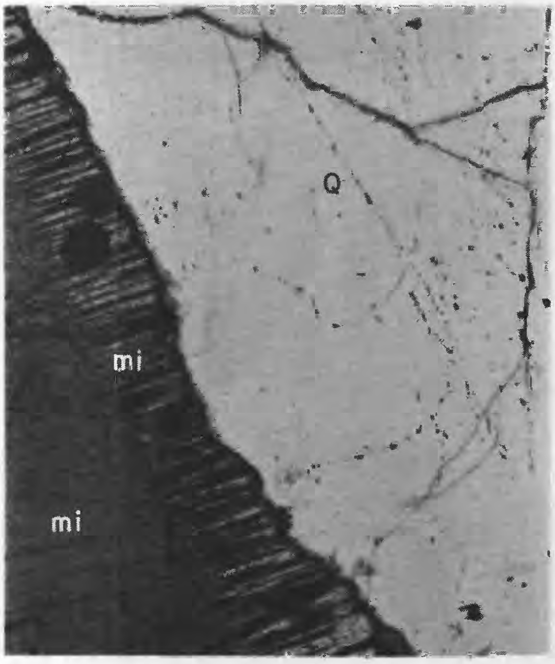

Figure 54.— Finely twinned microcline forming a rim on microcline that is otherwise nearly untwinned. From near the west edge of zone 7. × 97.

UNDER CROSSED NICOLS. cl, CLEAVELANDITE; mi, MICROCLINE; lim, LITHIA MICA; Q, QUARTZ; ca, CASSITERITE; B, BALSAM.

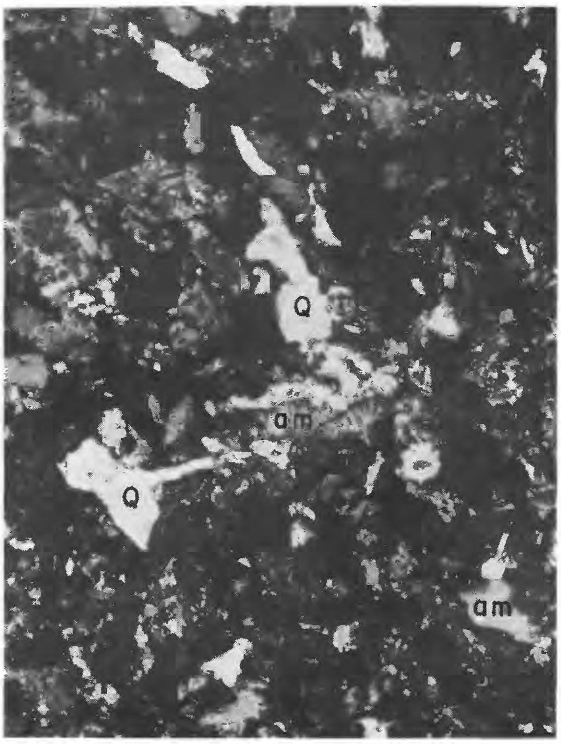

Figure 55.—Photomicrograph of the cleavelandite-microcline-lithia mica replacement unit. Crossed nicols. Optically continuous remnants of quartz (Q) in a matrix consisting chiefly of amblygonite (am). The matrix also contains very fine-grained material of low refractive index, probably clay, part of which has very low birefringence and part of which is probably isotropic. Forty feet northwest of the intersection of cross sections *A–A′* and *B–B′*. ×43.

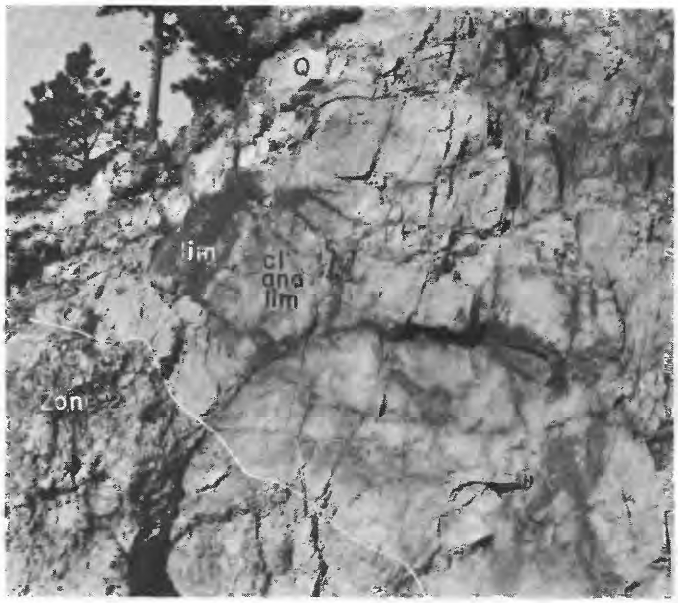

Figure 56.—Cleavelandite-quartz-lithia mica replacement unit in contact with zone 2 at the south border of the south segment. White areas, consisting mostly of quartz (Q), are relicts of zone 4. The darkest gray areas are aggregates of lithia mica (lim); lighter gray areas contain cleavelandite and lithia mica (cl and lim).

relatively coarse grained relict material is embayed and veined by finer grained aggregates consisting chiefly of cleavelandite and lithia mica. The introduced minerals generally pervade all primary minerals, and selectivity in the replacement is not pronounced. Microcline, however, is not common as a relict mineral, most of it having been destroyed, but a high proportion of the original quartz has been preserved.

Table 11.—*Mineralogy and petrography of the cleavelandite-quartz-lithia mica replacement unit*

[Minerals are listed in order of abundance. Modes are in table 19. Symbols denoting size of crystals are: VF, less than ¼ inch; F, ¼ to 1 inch; M, 1 to 4 inches; C, 4 to 12 inches; VC, more than 12 inches]

Cleavelandite

- Size and shape: VF to M; mostly F. Occurs in very large aggregates in which the crystals have an average length of one-half inch.
- Refractive indices: $\alpha'=1.528$ to 1.530.
- Megascopic textural relations: Sparse relict cleavelandite is in aggregates having the characteristics of cleavelandite in zones 4 and 5. Introduced cleavelandite is the predominant constituent of this unit. It occurs as aggregates of randomly oriented fine-grained laths. Quartz is cut by veinlets of cleavelandite. Lithia mica is disseminated through the cleavelandite.
- Microscopic textural relations: Relict cleavelandite laths that project into quartz have crystal faces against quartz and are embayed by quartz (fig. 57). Cleavelandite also appears as embayed inclusions in coarsely twinned microcline. Introduced cleavelandite is associated with lithia mica and finely twinned microcline in aggregates that cut across relict quartz. Aggregates of equidimensional untwinned albite form veinlets in coarsely twinned microcline.

Quartz

- Size and shape: VF to VC; mostly F and M. Anhedral.
- Megascopic textural relations: Quartz occurs mainly as irregular masses that are relicts of zones 4 and 5 (fig. 56). It also forms interstitial, possibly relict material in cleavelandite aggregates. Quartz is cut by veinlets containing cleavelandite and lithia mica.
- Microscopic textural relations: Relict, optically continuous grains of quartz are embayed, veined, and surrounded by aggregates of lithia mica (fig. 59), cleavelandite, and finely twinned microcline. Aggregates of very fine grained quartz cut across introduced cleavelandite and lithia mica.

Lithia mica (including a small quantity of relict muscovite)

- Size and shape: VF; rarely F. Aggregates are M to VC.
- Refractive indices: $\beta=1.58$, variable.
- Megascopic textural relations: Lithia mica is disseminated in cleavelandite. It also occurs as irregular aggregates in contact with cleavelandite and quartz. It veins and embays spodumene and beryl.
- Microscopic textural reltions: Lithia mica is associated with cleavelandite and finely twinned microcline, and it commonly forms disseminated inclusions in these minerals (fig. 62). It embays both the cleavelandite (fig. 63) and the microcline, but preferentially microcline, and it has optically continuous inclusions of the microcline

TABLE 11.—*Mineralogy and petrography of the cleavelandite-quartz-lithia mica replacement unit*—Continued

Lithia mica—Continued

(fig. 64). Lithia mica aggregates contain optically continuous relicts of quartz (fig. 59). Aggregates of lithia mica follow contacts between beryl and finely twinned microcline, and embay both of these minerals. Coarse mica (0.5 mm) is along the borders of spodumene crystals, as is muscovite in zone 5, and thus it is probably relict. This coarse muscovite is extensively veined and embayed by fine grained (0.02 mm) aggregates consisting mainly of lithia mica (fig. 58) but also containing albite. Very fine grained mica is along the borders of cleavelandite, as in the zones.

Additional data: $2V$ 30°. A few grains of mica have a faint brown absorption and lower refractive indices than normal lithia mica.

Microcline

Size and shape: VF to C; anhedral.

Megascopic textural relations: Relict microcline occurs as irregular masses surrounded and embayed by the aggregates of cleavelandite and lithia mica. Introduced microcline, associated with cleavelandite and lithia mica, is too fine grained for adequate megascopic examination.

Microscopic textural relations: Relict microcline has characteristics of the microcline in zones 4 and 5; it is coarsely twinned, contains embayed inclusions of cleavelandite, and is embayed by quartz, especially along twinning planes. It is also cut by veinlike material consisting of nearly untwinned microcline (fig. 65), and by veinlets consisting of untwinned, equidimensional albite. Finely twinned, introduced microcline embays relict quartz and beryl and has optically continuous inclusions of these minerals (fig. 61). Dusty inclusions are less abundant than in the relict microcline. Finely twinned microcline has euhedral inclusions of cassiterite.

Amblygonite

Size and shape: F to M; rounded.

Megascopic textural relations: Amblygonite occurs in relicts of blades from zone 4.

Cassiterite

Size and shape: VF; subhedral to euhedral.

Megascopic textural relations: Cassiterite is associated chiefly with introduced cleavelandite and lithia mica. Probably most of the cassiterite is introduced, but some may be relict.

Microscopic textural relations: Cassiterite occurs mostly as subhedral to euhedral crystals surrounded by lithia mica, cleavelandite, and finely twinned microcline (fig. 61). It is embayed by lithia mica.

Additional data: Twinned. Zoned crystals have an irregular pleochroic core and a nonpleochroic rim. X, light-brown; Z, red.

Beryl

Size and shape: F to M; subhedral to euhedral.

Refractive indices: ω=1.586 to 1.589.

Megascopic textural relations: All beryl, so far as known, is in relicts of the zones, but it is not sufficiently abundant to make adequate observations.

Microscopic textural relations: Beryl has euhedral inclusions of muscovite. It has crystal faces against lithia mica and finely twinned microcline, and also is embayed by these minerals and forms optically continuous inclusions within them (figs. 60, 61).

TABLE 11.—*Mineralogy and petrography of the cleavelandite-quartz-lithia mica replacement unit*—Continued

Spodumene

Size and shape: M to VC.

Megascopic textural relations: Spodumene has embayments and veinlike aggregates containing cleavelandite and lithia mica. Flakes of lithia mica are also dispersed through the spodumene, especially along cleavages.

Microscopic textural relations: Spodumene is embayed and veined by lithia mica, and has inclusions of lithia mica.

Apatite, tourmaline, and Fe–Mn phosphates

Size and shape: VF to F.

Megascopic textural relations: Not sufficiently abundant to make adequate observations. Most grains are probably relicts of zones.

Microscopic textural relations: Lithia mica contains euhedral inclusions of apatite.

Relict minerals form about one-fourth of this unit. Quartz is the most abundant relict mineral, just as it is the most abundant mineral of the replaced zones. Coarse cleavelandite and a few crystals of microcline having the same characteristics as in the zones are the only other abundant relict minerals. Relict microcline has the coarse twinning that was found also in microcline of zones 4 and 5. Other relict constituents of this unit include amblygonite, beryl, spodumene, tourmaline, muscovite, apatite, and iron-manganese phosphates.

The introduced material consists chiefly of fine-grained cleavelandite in aggregates of randomly oriented plates. Lithia mica is disseminated through the cleavelandite, and in many places it is so abundant that the aggregates take on the dark greenish-gray color of the mica. Finely twinned microcline is also associated with the cleavelandite and lithia mica, thus indicating that it was an introduced mineral. This microcline is similar to the introduced microcline of the cleavelandite-microcline-lithia mica replacement unit and also to the microcline of zone 7. Cassiterite appears mainly in association with the introduced minerals, and although some of it may be relict, the greater part probably crystallized during the formation of the replacement bodies.

PARAGENESIS

Where the textural relations between the relict minerals have been preserved, they indicate the same paragenesis as in zones 4 and 5. Quartz embays both microcline and cleavelandite (fig. 57), and the microcline contains embayed inclusions of cleavelandite. Relict muscovite appears as euhedral inclusions in beryl and as coarser crystals that embay spodumene (fig. 58) and occur along the borders of spodumene crystals, like much of the muscovite of zone 5.

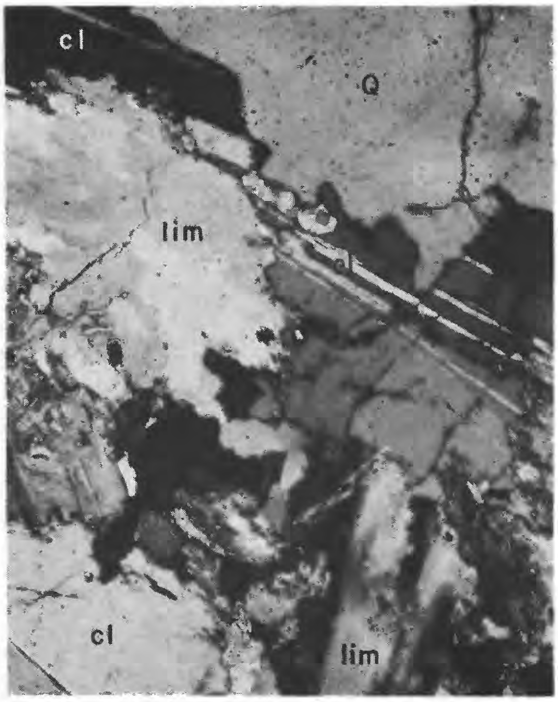

FIGURE 57.—Cleavelandite lath embayed by quartz. This texture is typical of the zones and is a relict of the zones. Lithia mica of the replacement stage is superimposed on these minerals. One hundred thirty feet southwest of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 41.

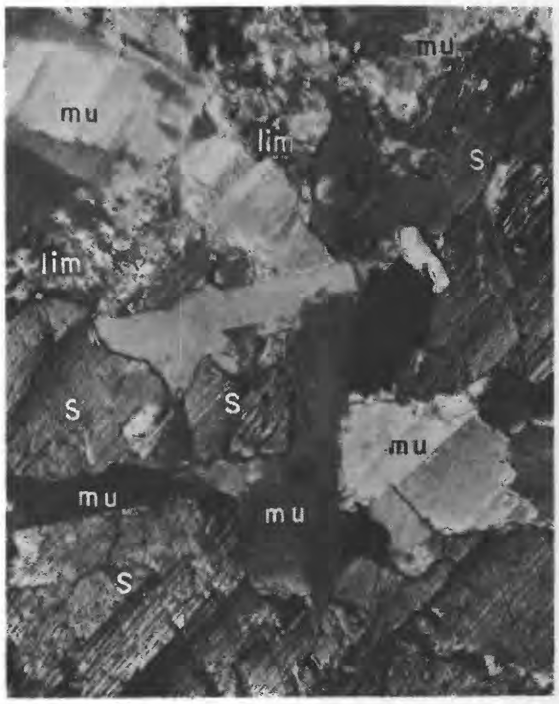

FIGURE 58.—Spodumene embayed by mica that probably is relict muscovite. Both spodumene and muscovite are cut by very fine grained lithia mica. Sixty feet west of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 35.

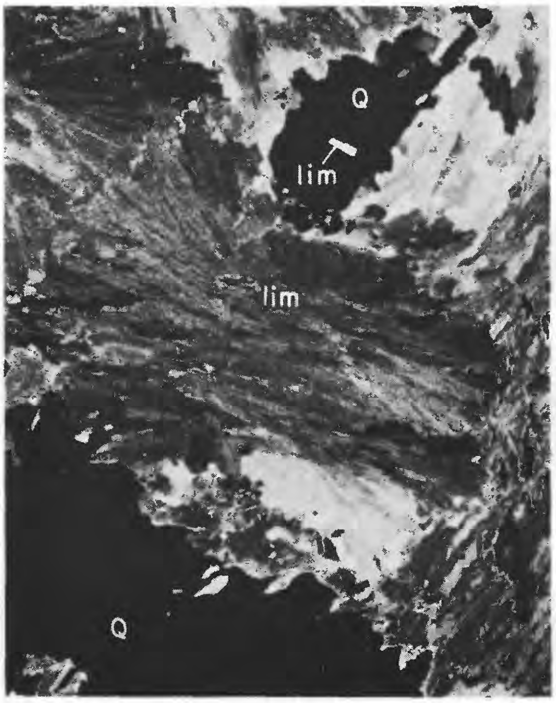

FIGURE 59.—Optically continuous grains of relict quartz in an aggregate of lithia mica. One hundred forty feet southwest of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 18.5.

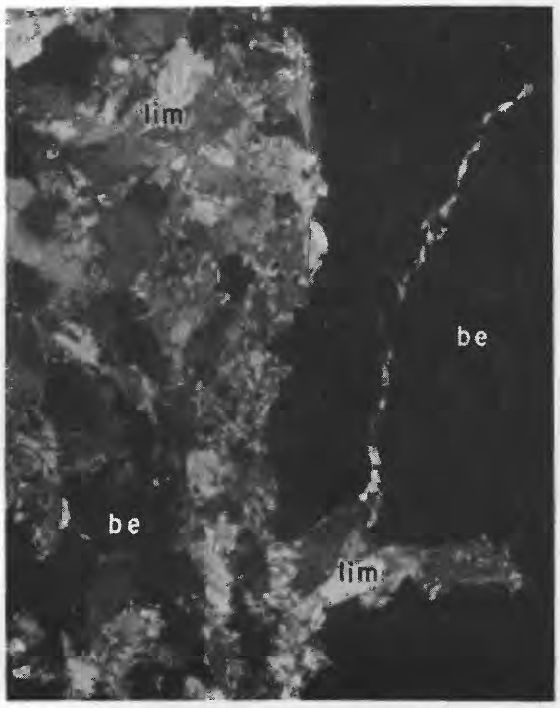

FIGURE 60.—Lithia mica that embays, veins, and has optically continuous inclusions of relict beryl. Sixty-five feet S. 75° W. of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 27.

FIGURES 57–64.—PHOTOMICROGRAPHS OF THE CLEAVELANDITE-QUARTZ-LITHIA MICA REPLACEMENT UNIT. ALL ARE UNDER
be, BERYL;

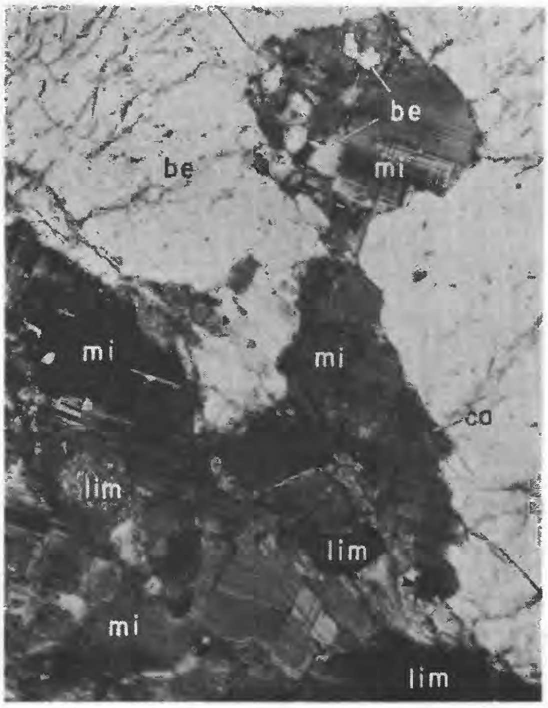

FIGURE 61.—Microcline that embays beryl and has optically continuous inclusions of beryl. The microcline also has inclusions of lithia mica and cassiterite. Sixty-five feet S. 75° W. of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 32.

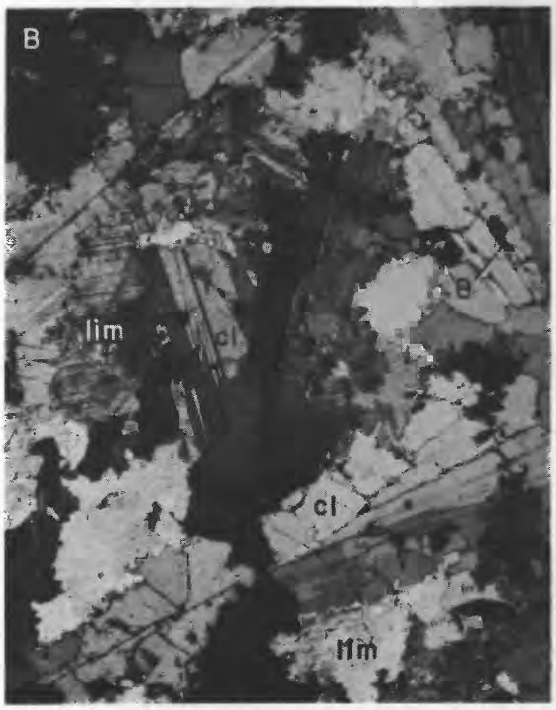

FIGURE 62.—Lithia mica disseminated through a radial aggregate of cleavelandite. One hundred thirty feet southwest of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 23.

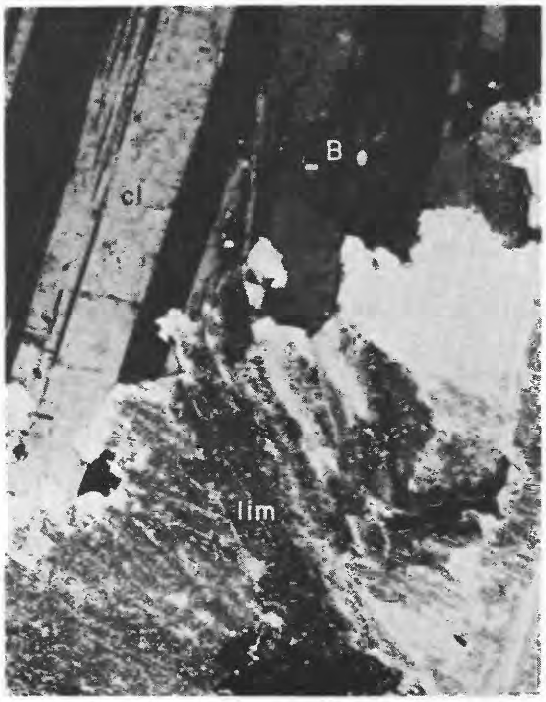

FIGURE 63.—Lithia mica cutting across a cleavelandite aggregate. One hundred forty feet southwest of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 45.

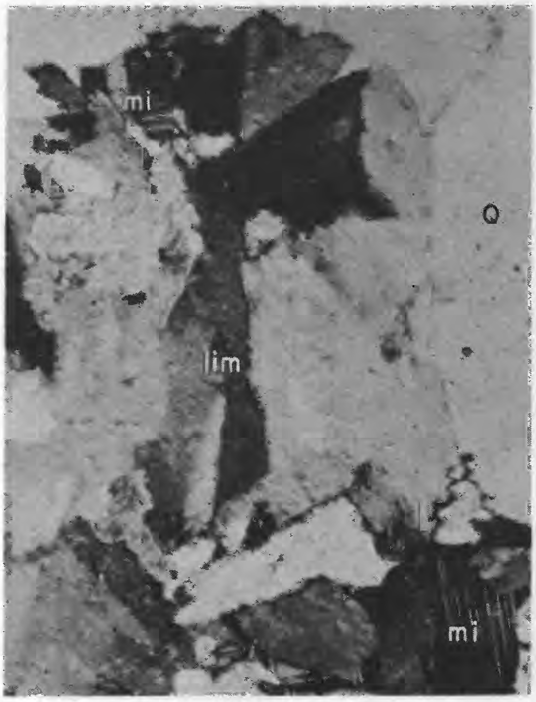

FIGURE 64.—An embayment in relict quartz consisting of lithia mica with optically continuous remnants of microcline. Eighty-five feet west of the intersection of cross sections *A–A′* and *B–B′* (pl. 9). × 97.

CROSSED NICHOLS; cl, CLEAVELANDITE; Q, QUARTZ; *lim*, LITHIA MICA; mu, MICROLINE; ca, CASSITERITE; S, SPODUMENE; B, BALSAM.

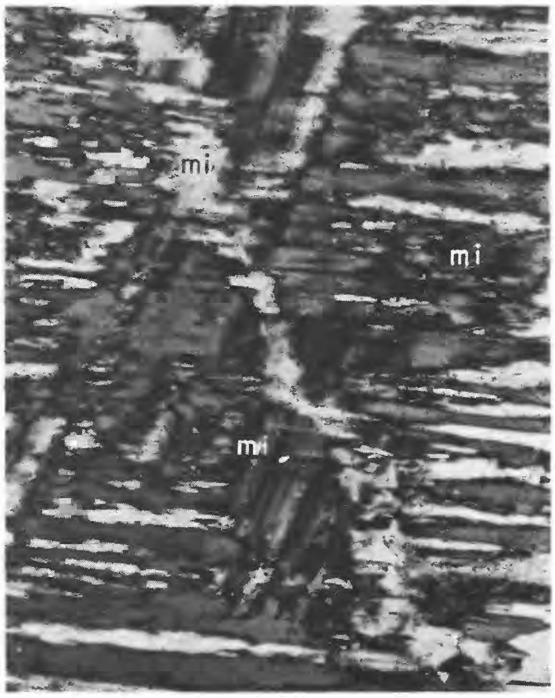

FIGURE 65.—Photomicrograph of the cleavelandite-quartz-lithia mica replacement unit. A veinlike streak of nearly untwinned microcline, crossing the photomicrograph from upper left to lower right, in coarsely twinned relict microcline (mi, microcline). Sixty feet west of the intersection of cross sections *A–A'* and *B–B'* (pl. 9). Crossed nicols. × 97.

Introduced minerals, consisting mostly of cleavelandite, lithia mica, and finely twinned microcline, occur as aggregates having textural relations that indicate replacement of the primary minerals. Figure 59, for example, shows optically continuous remnants of quartz surrounded by lithia mica. Beryl is extensively embayed by lithia mica and finely twinned microcline (figs. 60, 61). Spodumene and the primary muscovite along its contacts are greatly veined and embayed by very fine grained lithia mica. The relict microcline is cut by streaks of nearly untwinned microcline (fig. 65) and by veinlets of untwinned equidimensional albite that may have formed in the replacement stage.

Cleavelandite and lithia mica are so intimately associated that they probably formed in large part contemporaneously. Lithia mica commonly is disseminated through cleavelandite, as in figure 62. It also cuts cleavelandite in so many places (fig. 63) that much of it probably formed after most of the cleavelandite had crystallized. The introduced microcline crystallized early in the replacement stage; it is embayed by lithia mica and forms optically continuous remnants in an aggregate of lithia mica that embays relict quartz (fig. 64). Cassiterite is included in introduced microcline that embays relict beryl (fig. 61), and thus it also probably formed early. Most of the quartz is relict, but some of it is in very late aggregates that cut across introduced cleavelandite and lithia mica.

MINERAL DISTRIBUTION AND PARAGENESIS OF THE ENTIRE PEGMATITE

The paragenesis diagrams constructed from textural data indicate that, at any single spot in the pegmatite, albite was generally early to intermediate in age, and quartz formed late. Muscovite formed early in zones 1 and 2, later in zones 3 through 6, and the lithia mica of zone 7 and the replacement bodies generally followed the other minerals. Potassic feldspar was the first mineral in zone 3, an intermediate mineral in zones 4 and 5, and an early mineral again in zones 6 and 7 and the replacement units. Spodumene was the first mineral to form in zone 4, where it is preserved only as pseudomorphs, and was also the first mineral in zone 5. Similarly, amblygonite was an early mineral in these zones and in zone 2.

The minor minerals also have fairly consistent positions in the crystallization sequence. Tourmaline, apatite, and beryl formed early and largely contemporaneously with each other, though tourmaline was the first of these minerals to start crystallizing, and in zones 1 and 2 preceded all other minerals. Cassiterite formed somewhat later, and most of the iron-manganese phosphates formed very late.

There is no convincing evidence that the rock formed in more than one stage except in the replacement bodies. The textural relations indicate, on the contrary, a very great amount of overlap as the minerals crystallized in each unit. It may be supposed that the pegmatite crystallized from the wall inward, from zone 1 to zone 7, and that the replacement units formed last. This view of genesis has been widely adopted by students of pegmatites (Jahns, 1955, p. 1086); evidence for it is presented in later pages of this report and in many previous publications (Cameron and others, 1949, p. 101–105; 1954, p. 32; Jahns and others, 1952, p. 44–45; Jahns, 1955, p. 1086–1087; Page and others, 1953, p. 20–21; and Sheridan, 1955, p. 87–90). If this view be accepted, a complete discussion of the order in which minerals were precipitated from the fluid cannot be based solely on the textures, as in figure 13; the position of the minerals in the sequence of zones and replacement bodies must also be considered. Thus tourmaline, which appears in zone 1 and has textural relations indicating that it formed early in that zone, was among the first minerals to crystallize; and lithia mica, which appears only in zone 7 and the replacement units and has a late age in those units, was among the last min-

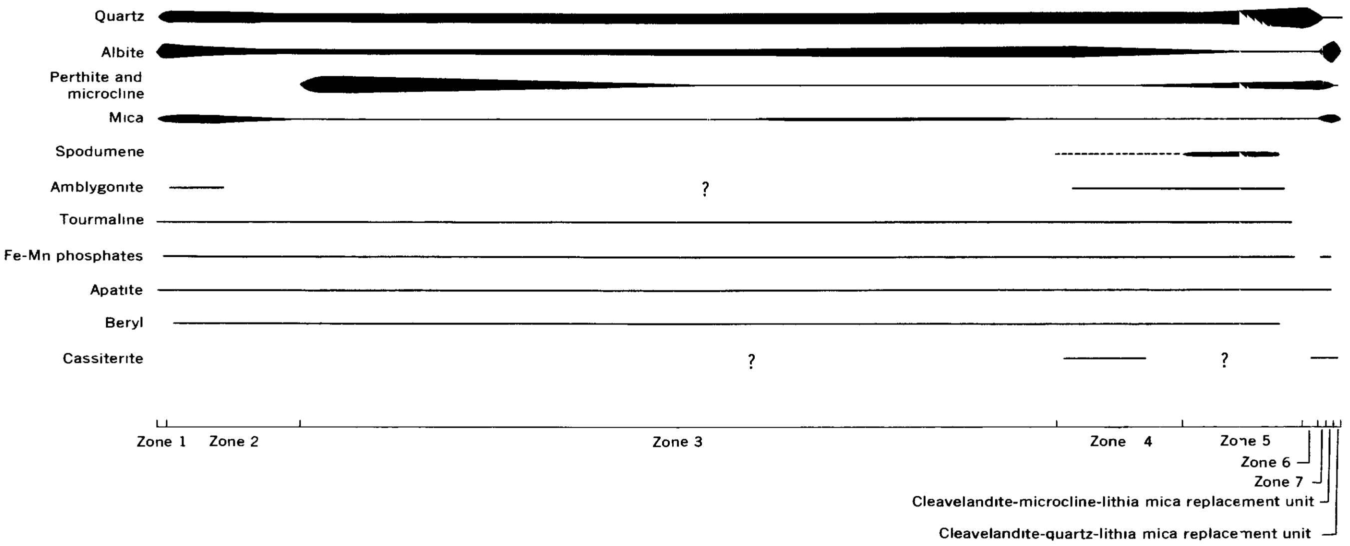

FIGURE 66.—Paragenesis of the Hugo pegmatite. The length marked for each unit along the horizontal axis is approximately proportional to the quantity of rock in the unit, and this is assumed to be proportional to the time required for crystallization. Relict minerals are excluded from the replacement bodies. Black areas are proportional to the abundance of the minerals. The spodumene of zone 4 was pseudomorphically replaced by other minerals of the zone.

erals to crystallize. The paragenesis diagram in figure 66 was constructed on this basis to show the complete paragenesis as here interpreted. The horizontal axis of this diagram is time; the length of time required for each unit to crystallize is assumed, in the absence of evidence to the contrary, to be proportional to the size of the unit.

Paragenesis as shown in figure 66 is thus largely based on the distribution of minerals within the pegmatite, which is shown graphically in figure 67. This graph was prepared from data in table 19, which was assembled to determine the chemical composition of the different parts of the pegmatite, as described in a later section of this report. In the paragenesis diagrams the relict materials of the replacement units are regarded as belonging to the zones, but in figure 67 and table 19 they are in the replacement units. Figure 67 applies to the entire pegmatite; a similar graph could be constructed for rock between an altitude of 4,442 feet and the surface, which contains the best-known part of the pegmatite, but it would show about the same relative proportions of the different units, except that zone 3a, which has been intensively mined, would be very small.

All but a very small part of this pegmatite is in the outer five zones, and the dominant minerals are quartz, feldspar, and mica. Quartz, albite, and mica (first muscovite and later lithia mica) crystallized throughout most of the time this pegmatite was forming. Potassic feldspar began to form in zone 3, and continued to crystallize through all later units. The large quantity of perthite in the outer part of zone 3, and the correspondingly great thickness of the black area representing perthite in figure 66, are reflected by a decrease in quartz, albite, and mica, and a thinning of the areas that represent these minerals on the paragenetic diagram. This does not necessarily mean that the rate of crystallization of quartz, albite, and muscovite was slower in the outer part of zone 3 than elsewhere; it may mean only that perthite crystallized rapidly. The constrictions and expansions that the paragenetic diagram shows for these four minerals in inner units may, however, reflect the influence of other mechanisms that will be discussed in later sections.

Spodumene and amblygonite crystallized in zones 4 and 5, and lithia mica in zone 7 and the replacement bodies. Amblygonite is also a minor accessory mineral in zone 2, and it either ceased to crystallize during the formation of zone 3 or has not been recognized there.

Among the minor minerals, apatite has the widest distribution, having crystallized in all zones. Tourmaline, beryl, and the iron-manganese phosphates are most abundant in outer units, but their crystallization continued at least as far inward as zone 5. Cassiterite, on the other hand, formed mainly in the inner zones and the replacement units.

COMPARISON OF THE ZONAL SEQUENCE WITH THAT IN OTHER PEGMATITES

The Hugo pegmatite contains 5 of the 11 mineral assemblages in the general sequence recognized by Cameron and others (1949, p. 59–70). Table 12 shows these mineral assemblages in order of their occurrence from outer to inner parts of zoned pegmatites. The table also

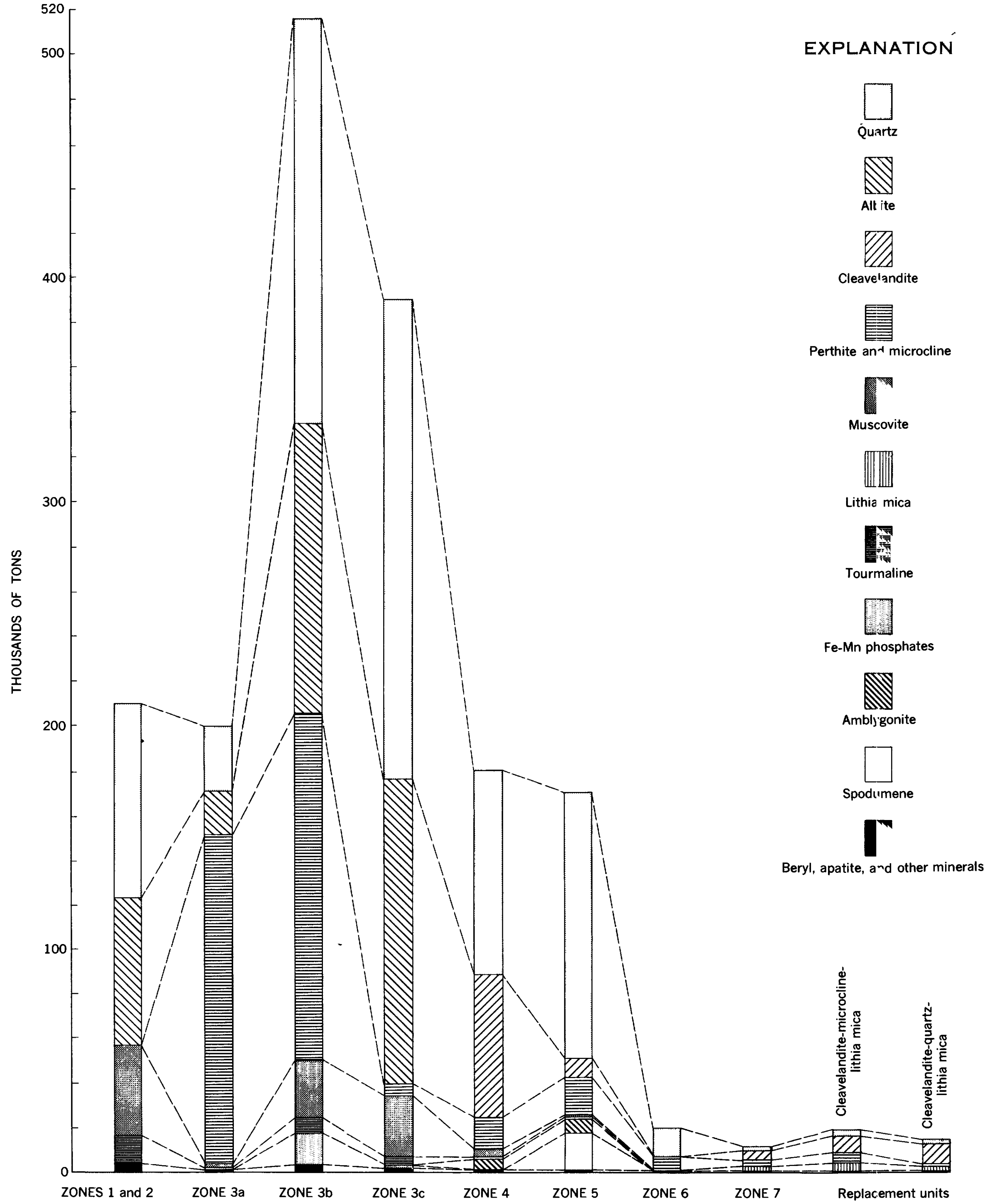

FIGURE 67.—Distribution of minerals in the Hugo pegmatite, based on data in table 19.

TABLE 12.—*Comparison of the sequence of mineral assemblages in the Hugo pegmatite with that of other pegmatites*

[×, mineral assemblage recognized in zones; ×?, assemblage observed, but exact position in sequence not known]

Mineral assemblage [1]	Hugo [2]	Southeastern States [1]	New England [1]	Petaca, N. Mex.[1]	Southern Black Hills, S. Dak.[1]	Bob Ingersoll No. 1	Bob Ingersoll No. 2	Dan Patch	Edison	White Cap	Peerless	Etta
1. Quartz, plagioclase, muscovite	× (1 and 2)	×	×	--------	×	×	×	×	×	×	×	×
2. Quartz, plagioclase	--------	×	×	--------	×	--------	×	×	×	--------	--------	
3. Quartz, plagioclase, perthite	× (3)	×	×	×	×	--------	--------	×	--------	--------	×	
4. Quartz, perthite	--------	×	×	×	×	×	×	×	--------	×	--------	
5. Quartz, plagioclase, perthite, amblygonite, spodumene	× (4 and 5)	--------	--------	--------	×	×	×	--------	--------	--------	×	×
6. Quartz, plagioclase, spodumene	--------	--------	×?	--------	×	--------	--------	--------	×	--------	--------	×
7. Quartz, spodumene	--------	--------	--------	--------	×	--------	×	--------	×	--------	--------	×
8. Plagioclase, lepidolite, quartz	--------	--------	×?	--------	×	×	--------	--------	--------	--------	--------	
9. Quartz, microcline	× (6)	--------	--------	--------	×	--------	--------	--------	--------	--------	×	
10. Plagioclase, lithia mica, microcline, quartz	× (7)	--------	--------	--------	×	--------	--------	--------	--------	--------	×	
11. Quartz	--------	×	×	×	×	--------	--------	×	--------	--------	--------	×

[1] From Cameron and others (1949, p. 61). Does not include pegmatites of the Carolina tin-spodumene belt, tin pegmatites of Alabama, and lithium-rich pegmatites of Maine and Massachusetts.

[2] Zone numbers in parentheses.

shows the assemblages that have been found in many of the pegmatite districts in the United States and in the largest zoned pegmatites of the Keystone district.

Zones 1 and 2 of the Hugo, like outer zones of many other pegmatites, consist of quartz, plagioclase, and muscovite of assemblage 1 (table 12). The muscovite content decreases inward, and much of the inner part of zone 2, where quartz and plagioclase are the only plentiful minerals, resembles assemblage 2. Perthite appears in abundance in zone 3, which thus corresponds to assemblage 3. In many pegmatites plagioclase decreases inward and quartz and perthite increase to form assemblage 4, but the Hugo has no unit of this composition. Lithium minerals first appear in assemblage 5, where they are associated with quartz, plagiclase, and perthite. From assemblages 5 to 7 of the general sequence, quartz and spodumene increase as other minerals decrease. In the Hugo pegmatite, the amblygonite- and spodumene-bearing units of zones 4 and 5 are generally typical of assemblage 5. Some parts of zone 5, however, consist only of quartz, plagioclase, and spodumene (assemblage 6) or quartz and spodumene (assemblage 7).

The gradual and progressive changes from assemblages 1 to 7 are marked by an increase in silica content. This increase continues in the inner parts of many pegmatites, and its ultimate expression is a quartz core (assemblage 11). A few pegmatities, including the Hugo, have zones of assemblage 9 consisting of quartz and nonperthitic microcline.

A strikingly different type of unit forms assemblage 8 or 10 in the inner parts of a few pegmatites. These assemblages consist largely of plagioclase and lithium-bearing mica, either lepidolite in assemblage 8 or lithia mica in assemblage 10. They are rich in alkalies and alumnia, and have a low silica content.

The sequence of assemblages 8 to 11, as presented in table 12, alternates between alkali-rich and silica-rich materials. Although this sequence is supported by data from several pegmatites, anomalies have been found in others. Quartz pegmatite (assemblage 11) is known in outer zones of pegmatites having lepidolite-rich inner units, as at the Brown Derby mine in Colorado (Hanley and others, 1950, p. 70; Staatz and Trites, 1955, p. 53) and in a pegmatite mapped by Vlassov (1955, fig. 2) in the Soviet Union. The Varuträsk pegmatite in Sweden has a unit containing cleavelandite and gray lepidolite, apparently assemblage 10, that is said to have formed by replacement after the quartz core had crystallized (Quensel, 1952, p. 55–56). Units of assemblages 8 and 10 in other pegmatites have commonly been regarded as replacement bodies, but some interpretations and the mapping on which they are based are hard to evaluate. At the Pidlite pegmatite in New Mexico, for example, Jahns (1953, p. 1086) mapped a lepidolite-rich replacement unit adjacent to a quartz core, and Page (1950, p. 21) mapped the same rocks as a lepidolite-rich core and a perthite-quartz intermediate zone.

Assemblage 9 precedes assemblage 10 in the Hugo and Peerless pegmatites, but no evidence is available to show the relation between these assemblages and assemblage 8. It is possible that assemblages 8 and 10 should be regarded as varieties of a single assemblage, and that the main difference between these two varieties is the lithium content of the mica.

The uncertainties about the sequence from assemblage 8 to 11, together with the apparent replacement origin of assemblages 8 and 10 in some pegmatites, leave open the possibility that the inner assemblages have a more complex origin than simple crystallization differentiation from a single homogeneous fluid. The contrast between the alkali-rich and silica-rich units may be a key to this problem, as further discussion in the section on the course of crystallization of the Hugo pegmatite will show.

REPLACEMENT FEATURES

REVIEW OF THE EVIDENCE FOR REPLACEMENT IN PEGMATITES

Several authors have attributed the origin of the Hugo pegmatite partly to replacement processes, but none have recognized replacement units having the structure or lithology described on previous pages. Ziegler (1914c, p. 275), for example, stated that amblygonite was deposited by solutions that followed fissures formed by faulting and brecciation in the central part of the Hugo pegmatite. Landes (1928) suggested that the Hugo and other pegmatites of the Keystone district crystallized first in a primary stage in which quartz and microcline were the dominant minerals, and then were extensively altered in two replacement stages. More recently Higazy (1949, p. 564–565) described replacement textures in perthite from the Hugo and other Keystone pegmatites, and stated that these textures support his theory that the pegmatites formed by replacement of schist, although the connection between the evidence and his conclusion is not apparent.

These diverse interpretations suggest a need to reexamine the evidence for the replacement processes that have been discussed so widely in the literature on pegmatites. Many writers have based their conclusions chiefly on textural relations between individual minerals, which despite their value in showing paragenesis do not necessarily indicate replacement of previously solidified rock. Another common argument is that such features as rosette-shaped aggregates and large crystals need support for their development, and thus must have formed in a previously solidified rock. Evidence of this sort has lost some of its force during recent years because extensive detailed mapping of pegmatites has made it possible to apply structural criteria that provide a firmer basis for distinguishing replacement bodies from the other internal units of pegmatites. The lack of opportunity to make detailed maps was a severe handicap to the early investigators. Landes (1928, p. 539, 543, and 549), for example, found that some minerals, such as tourmaline, are in more than one physical or chemical form, which he presumed to be of different ages, but the fact that these differences could be correlated with the zonal structure was not recognized.

Examples of the use of textural evidence are so abundant in the literature that only a few can be cited here. In the Keystone district Landes (1928, p. 547–548) found inclusions of quartz in spodumene and amblygonite (apparently in the Etta and Peerless pegmatites), and concluded that the quartz formed in a magmatic stage and the lithium minerals formed in a replacement stage. He found also that veins and apophyses of albite cut quartz, microcline, apatite, amblygonite, spodumene, and other minerals, and used this to show that the albite formed in a late replacement stage (Landes, 1928, p. 552). It can certainly be agreed that albite does cut these minerals, both in zones and replacement units, but this relation does not necessarily indicate that it formed in a metasomatic stage of crystallization. Furthermore, there is evidence of overlap between albite and these other minerals in the paragenesis, and microscopic relations indicate that quartz formed mostly later than albite, in spite of the veinlike form of much of the albite that is intergrown with quartz. Similar textural relations have been used in the same way not only by other writers on Black Hills pegmatites (as by Hess, 1925, p. 293) but also in other areas by such authors as Schaller (1925, p. 274–275) and Landes (1925, p. 362–363, 373–374; 1932, p. 389–390). Although replacement bodies may be present in these pegmatites, the adequacy of the textural evidence as proof of their existence is questionable.

Davidson and others (1946, especially p. 746–748) have discussed a similar problem regarding ilmenite in a gabbroic dike in Virginia. Petrographic evidence indicates that part of the ilmenite formed after associated minerals. Davidson and his coauthors point out, however, that this does not justify liberal use of the words "replacement" and "secondary." They consider that "replacement" should not include "late magmatic or deuteric changes" caused by "reactions with magma." They also believe that "secondary" should be restricted to minerals that are distinctly "later than magmatic minerals," and should not be based only "on the observation that a mineral is later than some other mineral" (Davidson and others, 1946, p. 747–748).

Many authors believe that minerals occurring in radiating masses, rosettes, or bursts must have formed by replacement of solid rock because they needed support to develop in this fashion. Hess (1925, p. 295) was the first to use this criterion when he applied it to the radiating disposition of spodumene crystals, and he cited pyrite balls in sediments as an analogous example. Landes (1928, p. 548–549) expressed the same view in his discussion of Keystone pegmatites.

Jahns (1953, p. 594) has stated that spodumene in rosettelike aggregates may have been supported by "the crystal-bearing liquid or by the crystal mesh." Earlier, Jahns (1946, p. 69, 238) considered that "bursts" and "rosettes" are "generally formed by replacement processes." His view seemed to be that radiating cleavelandite is in many replacement bodies, and that it occurs less commonly, and perhaps never, as a primary mineral.

At the Hugo, radiating structure is characteristic of cleavelandite in zones 4 and 5, spodumene in zone 5, and relicts of these minerals in the replacement units. Radiating structure is not characteristic of any introduced minerals of the replacement units. Similarly, elsewhere in the Keystone district, radiating cleavelandite and spodumene occur in inner zones, but not in replacement bodies. Possibly this is the natural form for cleavelandite to take if allowed to grow outward from solidified material into the liquid without interference. Spodumene in the Hugo and Etta pegmatites, as well as in others, forms an interlocking network of crystals; the radiating characteristic described by Hess is at junctures in this network. Minerals of the groundmass embay and vein the spodumene, and thus are at least in part younger than the spodumene. Probably the spodumene crystals in these radiating aggregates supported each other, and the network of spodumene crystals was attached to solidified pegmatite and extended into the liquid.

The large size of some crystals has also been cited as an example of unsupported structures that require a replacement origin (Hess, 1925, p. 290–291; Connolly and O'Harra, 1929, p. 238–239). Large crystals occur in nearly all zones of every zoned pegmatite, and if they formed by replacement, it is difficult to understand how the different mineral species forming large crystals were distributed among the zones in such a fashion as to form a consistent zonal sequence. Furthermore, the largest crystals are commonly potassic feldspar, considered by many writers to be the primary host that was later replaced by cleavelandite and lithium minerals. The large crystals, like the rosettes, may have obtained their support chiefly from other crystals during primary crystallization of the pegmatite.

Cameron and others (1949, p. 83–97) described replacement features in more exact terms than previous authors, and by distinguishing between replacement bodies, zones, and fracture fillings and describing all of them as mappable units, they put the entire matter on a more sound structural basis. They suggested using the term "replacement body" only where there is satisfactory evidence for the development of the unit at the expense of preexisting pegmatite that had completely crystallized before replacement began. According to Cameron and others (1949, p. 88), "The most easily recognized replacement bodies are those that are discordant to the structure of zones and fracture fillings, and have structures, textures, and minerals obviously inherited from adjacent rock of markedly different bulk composition." Although other replacement bodies are less apparent, Cameron and his coauthors showed that they can be recognized by use of different types of evidence. Criteria that they regarded of most value are: transection of structures, textures, and minerals; and pseudomorphism of structures, textures, and minerals. Replacement units that transect previous structures lack the matching walls of fracture fillings, but may be fracture controlled. Several of their examples are good illustrations of fracture-controlled replacement bodies, but these are mostly small and none of them have any direct bearing on the geology of the Hugo replacement units. They also described the quartz-spodumene replacement unit in the Giant-Volney pegmatite, Tinton, S. Dak., where the gneissoid structure of an intermediate zone is preserved in the replacement body. More recently, at the Pidlite pegmatite, Mora County, N. Mex., Jahns (1953, p. 1087–1089) has described a replacement unit rich in cleavelandite, lepidolite, and muscovite that according to him cuts across zones and contains relicts of those zones. Other replacement units, similar in structure and composition to the ones at the Hugo, have been described by Sheridan and others (1957, p. 15) in the Peerless pegmatite of the Keystone district.

Cameron and his coauthors cited other replacement units that do not seem to meet their strict requirements, and the origin of some of these units may be questioned. They stated that many replacement units follow zones, lie along zone contacts, or are parallel to keels or crests of pegmatites, as are many zones. Little or no evidence was presented to show that these are not zones. Furthermore, they did not demonstrate that these units are in any way out of harmony with adjacent units. In the Hugo pegmatite, replacement units of assemblage 10 are in some places nearer the outer border of the pegmatite than assemblages 3, 5, and 9, and they contain albite different from that in adjacent zones. Without at least this kind of evidence, a replacement origin seems doubtful.

It has been stated (Jahns, 1946, especially p. 50–51, 58, 74–75, and 88–90; Cameron and others, 1949, p. 85) that there are many large replacement units from which sheet mica is mined in the zoned pegmatites of the Petaca district, New Mexico. These units are virtually parallel to the zonal structure, and are said to have been formed by the introduction of albite, muscovite, and accessory minerals into border and wall zones consisting originally of quartz, potassic feldspar, and only small quantities of other minerals. The resulting units, where they are fully developed, consist of assemblage 1 (table 12), and they occur in wall zones in the normal structural position of this assemblage. Page and Norton found, from subsequent examination of the evidence in the field, that the so-called replacement units of the Petaca district have not only the same mineral assemblages but also the same textures as units that have been called zones in other localities. No relict textures or structures were observed. Sheet mica in wall zones of many Black Hills pegmatites is associated with quartz, plagioclase, and corroded crystals of perthite, without evidence that these units formed from previously consolidated pegmatite. These units are not significantly different from the mica-bearing units of the Petaca pegmatites.

Cameron and others (1949, p. 95) also described units in which individual minerals are selectively replaced, but they point out that these are not necessarily replacement units in the strict sense. Similarly, zone 4 at the Hugo contains blade-shaped aggregates that preserve the shape of spodumene crystals, but there is no evidence that this change took place after the entire zone had solidified. On the contrary, the evidence indicates that this texture developed during primary crystallization, but after the formation of the radial cleavelandite surrounding the blades.

The published discussions of replacement features in foreign pegmatites are similar to those for pegmatites in the United States, and many of the same criticisms apply. Some foreign pegmatites, however, may contain replacement units that are very much larger than any known in the United States. Two examples are the Manono pegmatite in the Republic of the Congo and the Bikita pegmatite of Southern Rhodesia, each of which is at least 1 mile long and several hundred feet thick. Though adequate detailed maps are not available, both of these pegmatites were examined briefly by Page in 1957 and notes concerning their geology can be presented. The Manono pegmatite has at least two main zones: a narrow wall zone of quartz, feldspar, and muscovite; and a core of quartz, feldspar, and spodumene. In places the core has been altered to a very large replacement unit in which allophane and cassiterite have been introduced; this unit is the source of the highest grade tin ore that has been found at this mine. The Bikita pegmatite contains several zones and also has large, irregularly shaped replacement units in which the textures of the zones are preserved. Petalite pseudomorphically replaced potassic and sodic feldspar in wall and intermediate zones containing perthite, plagioclase, quartz, mica, amblygonite, and spodumene. Spodumene probably replaced amblygonite, and eucryptite replaced spodumene.

Another example of a pegmatite having large replacement units may be the Varuträsk pegmatite in Sweden. Quensel (1952) stated that this pegmatite has several replacement units, and his map supports this by showing crosscutting contacts in several places. Much of the evidence presented in his text, however, is based on textural relations among the minerals, and clear structural evidence for the replacement origin of all these units was not discussed.

Replacement units are commonly said to be widespread in pegmatites (for example, Cameron and others, 1949, p. 84), but this can be true only if textures are accepted as evidence, in disregard of the fact that they may have formed by reaction between crystals and the rest liquid during primary crystallization. If only well-established criteria are applied, then it may be said that replacement bodies are not known to be widespread or large, at least in pegmatites of the United States. The Hugo replacement units are the most clearcut of any so far found in the southern Black Hills, yet they are very small in relation to the large size of this pegmatite.

REPLACEMENT IN THE HUGO PEGMATITE

The cleavelandite-microcline-lithia mica and cleavelandite-quartz-lithia mica replacement units of the Hugo pegmatite are irregularly shaped bodies that transect zones 2 through 6. They contain islands of unreplaced rock, some of which are large enough to show separately on the maps and sections. Diagnostic textures and minerals of the zones are well-enough preserved to be recognized in many places, despite the addition of fine-grained cleavelandite, lithia mica, and microcline. Blade-shaped aggregates preserved from zone 4, spodumene crystals of zone 5, and the coarse texture of zone 6 can all be recognized in parts of the replacement units. Zonal contacts can be traced with some confidence through the replacement units.

The replacement units are quite out of harmony with the zones in many of their characteristics. The introduced minerals of the replacement units belong to assemblage 10, but they extend nearly to the border of the pegmatite, and are in contact with zones containing assemblages 1, 3, and 5. The albite differs in several respects from the earlier albite of the associated zones. Contacts of the replacement units are gradational in an irregular and erratic fashion. In some places the introduced minerals are more abundant near contacts than in the inner parts of replacement units, unlike the consistent gradational changes from one zone to another. The replacement bodies contain a few porous aggregates of cleavelandite, and none of these were seen in the zones. The porous character suggests local reduction in volume where the replacement units developed.

The replacement units differ greatly in composition from adjacent rocks belonging to zones 2–6. The abundance of feldspar and mica causes them to have a very low content of SiO_2 and a high content of Al_2O_3 and alkalies. They are enriched in cassiterite, but most of the other accessory minerals are relicts from zones.

The two replacement bodies differ from each other in only a few respects. The content of SiO_2, Al_2O, and Li_2O is very nearly the same. The cleavelandite-quartz-lithia mica replacement unit contains more Na_2O and P_2O_5 and less K_2O than the cleavelandite-microcline-lithia mica unit (table 19). The chemical constituents of the replacement bodies must have been obtained not only from the replacing fluid but also from the breakdown of primary minerals. Differences between the two replacement bodies can be attributed largely to original differences in the replaced rock: the cleavelandite-quartz-lithia mica unit is chiefly in zone 4, which is relatively rich in Na_2O and lean in K_2O, and the cleavelandite-microcline-lithia mica unit is mostly in zones 5 and 6, which taken together are lean in Na_2O and rich in K_2O. The differences may also have been partly caused by changes in the character of the replacing fluid, both as it advanced through the rock, and as the composition changed progressively at the source. The principal change is that the Na:K ratio increases from the inner to the outer replacement unit.

The replacement was largely pervasive and nonselective. Although lithia mica preferentially replaced microcline in places, the dominant characteristic of the replacement bodies is the general dissemination of introduced cleavelandite, lithia mica, and microcline through the preexisting minerals.

Replacement textures are more common in the replacement units than in any of the zones except the cleavelandite-microcline-lithia mica core. These textures include embayments and veinlike aggregates of one mineral in another, ragged inclusions in optical continuity with nearby larger grains of the same mineral, pseudomorphic replacement of individual minerals by aggregates consisting of several minerals (figs. 45, 46), and the growth of a second generation of microcline on the borders of earlier crystals (fig. 54). At a larger scale, aggregates of cleavelandite, lithia mica, and microcline cut indiscriminately across the minerals of the zones.

Replacement features in the zones are restricted to textures. Zone 7 contains an impressive display of replacement textures, as shown in figure 44, but in other zones they are less common. The chief replacement textures of zones 1–6 include embayments, veinlike masses, optically continuous inclusions, rounded and corroded crystals, and pseudomorphs of individual minerals. Quartz, for example, commonly embays albite, and both of these minerals commonly embay other minerals. Perthite and amblygonite ordinarily have rounded and corroded borders.

All the minerals of zone 4 occur in the aggregates having the form of spodumene crystals. The sheath of cleavelandite that surrounds each of these aggregates has a form such that during resorption of spodumene by the liquid a cavity could have developed. The complete absence of relicts of spodumene and the heterogeneity of the minerals that are now in the aggregates suggest that the spodumene was removed in this way, rather than metasomatically replaced directly by the other minerals. The cavity thus formed was filled during crystallization of the other minerals of the zone.

The foregoing discussion and tables 2–4 and 6–11 indicate that replacement textures are generally more common in inner than in outer zones. Small embayments can be found in minerals of all zones; corrosion of potassic feldspar and amblygonite can be recognized in zones 3–5; pseudomorphs after spodumene are in zones 4 and 5; and the greatest abundance of replacement textures is in zone 7.

MINERAL VARIATIONS

The minerals and mineral groups represented in the Hugo pegmatite differ in composition, optical properties, or physical form from one unit to another. Changes that can be correlated with structural position in the pegmatite are most evident in feldspars, but can also be recognized in mica, quartz, lithium minerals, beryl, and tourmaline.

The principal change in potassic feldspar is the decrease in the abundance of perthitic albite from outer to inner units, and this doubtless reflects a corresponding decrease in the sodium content of the potassic feldspar prior to exsolution. Perthitic albite is especially abundant in zone 3. A sample from this zone contains 27.4 percent normative albite (Higazy, 1949, tables 1 and 4; norm recalculated), most of which must be in perthitic albite, although some is in corroded poikilitic inclusions and some in solid solution in microcline. In contrast, a sample of nonperthitic microcline from zone 6 contains 10.4 percent normative albite. Gridiron twinning is somewhat coarser in microcline of zones 4 to 6 than in other units, and in many places it is visible megascopically. Inclusions of lath-shaped albite are more abundant in zones 4 to 6 than in zone 3, and inclusions of lithia mica are so abundant in zone 7 and the replacement units that much of the microcline

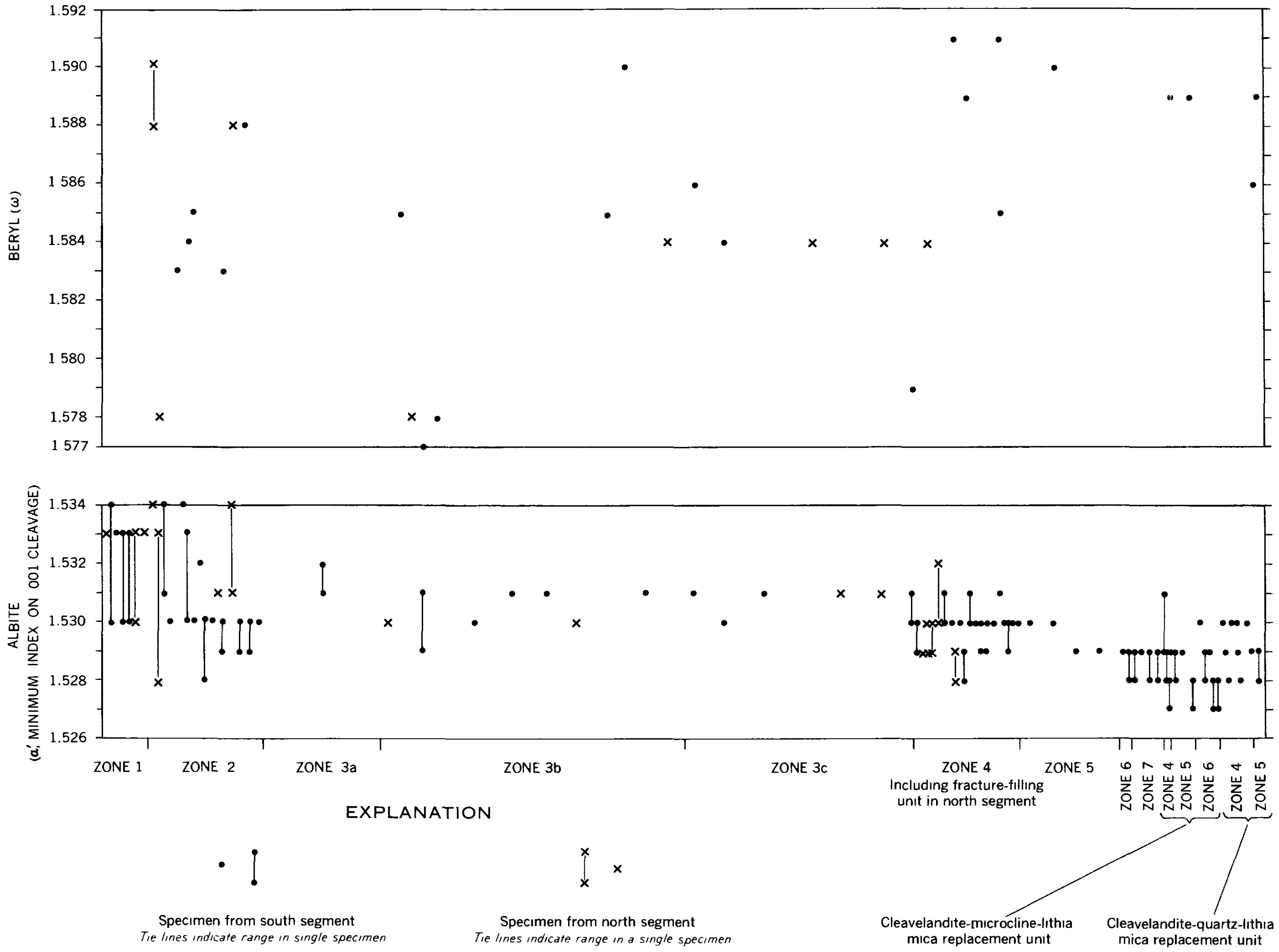

Figure 68.—Indices of refraction of albite and beryl in specimens from the Hugo pegmatite. The length marked for each unit along the horizontal axis is approximately proportional to the size of the unit except that zones 1 and 7 and the two replacement units are exaggerated five times.

has a gray color. The crystals of perithite and microcline in zones 3 to 6 are commonly very coarse grained and subhedral to euhedral. Microcline that crystallized in zone 7 and the replacement bodies, however, is dominantly anhedral and medium grained.

Albite changes conspicuously in its physical character from dominantly blocky or irregular grains and aggregates in the outer zones to platy cleavelandite in inner units. Cleavelandite first becomes common in the inner part of zone 2, and it forms almost all the albite in zones 4 and 5, where large radiating aggregates contain laths that are 1 to 2 inches long. Cleavelandite is the only variety of albite that formed in zone 7 and the replacement units; most of it lacks radial arrangement and individual plates are less than 1 inch long, although relict cleavelandite in the replacement units has the characteristics of cleavelandite in outer zones. Sugary albite is common in the cleavelandite-microcline-lithia mica replacement unit, and porous aggregates of fine-grained plates occur only in this unit.

The albite has a discernible tendency to decrease in refractive index from the outer to inner units of the pegmatite. As figure 68 shows, however, the total range is small, and there is extensive overlap from one unit to another. In zone 1 α' is 1.530 to 1.534; in zone 7 it is 1.528 to 1.529; and in the replacement units some of the introduced albite has α' as low as 1.527. These determinations were made by the immersion method in white light, correcting for temperature and using oils with an interval of 0.002 in index of refraction. Whether or not the refractive indices are correct in an absolute sense is less important than the relative changes from one part of the pegmatite to another. The position of each determination on the graph in figure 68 indicates the approximate position of the specimen with respect to the contacts of the unit from which it was collected.

TABLE 13.—*Partial chemical analyses, calculated anorthite content, and minimum refractive indices of cleavage fragments (α′) of albite from different units of the Hugo pegmatite*

[Mica is the most abundant contaminant]

Pegmatite unit	Field No.	Laboratory No.	Chemical analyses [1] (weight percent)			Spectrographic analyses [2] (weight percent)				Anorthite content [3] (mole percent)	α′ (yellow light)
			CaO	Na_2O	K_2O	K_2O	Li_2O	Rb_2O	Cs_2O		
Zone 1	JJN–59–58	269868D	0.42	11.2	0.28	0.29	0.002	0.003	<0.001	4.0	1.531
Do	JJN–78–46	269868C	.30	10.7	.09	------	------	------	------	3.0	1.530
Zone 2	JJN–152–46	269865	.02	11.6	.19	.26	.004	.004	<.001	.2	1.530
Zone 3b	JJN–162–46	269867	.02	11.4	.18	.19	.006	.001	<.001	.2	1.529
Zone 3c	JJN–155–46	269866	.03	11.6	.04	.13	.003	<.001	<.001	.3	1.529
Zone 4	JJN–108–46	269863	.02	11.4	.43	.63	.027	.013	<.001	.2	1.529
Zone 7	JJN–138–46	269864	.04	10.4	1.11	1.3	.083	.065	.011	.4	1.528
Cleavelandite-microcline-lithia mica replacement unit.	JJN–60–58	269868A	.04	11.7	.30	.26	.006	.008	<.001	.4	1.529
Cleavelandite-quartz-lithia mica replacement unit.	JJN–11–47	269868	.04	10.0	1.34	1.9	.38	.13	.014	.4	1.528
Do	JJN–61–58	269868B	<.01	11.8	.12	.16	<.001	<.001	<.001	<.1	1.528

[1] Analyst: Wayne Mountjoy, U.S. Geol. Survey. Na_2O and K_2O by flame photometer. CaO by automatic versene titration.

[2] Analyst: Harry Bastron, U.S. Geol. Survey.

[3] Calculated from the ratio of CaO to total of Na_2O and CaO. Other constituents disregarded.

Analyses of albite from different parts of the pegmatite, as shown in table 13, indicate that the change in the index of refraction can be attributed only in small part to a change in anorthite content. The α′ values for these samples were also obtained by the immersion method, but with yellow light and with a refractometer to determine the index of the oil. Each of the index values shown is an average of 10 to 20 grains from the analyzed sample. The two samples from zone 1, having α′ of 1.530 and 1.531, contain 3.0 and 4.0 percent anorthite. The samples from other units have α′ of 1.528 to 1.530, but the maximum anorthite content is 0.4 percent. Despite the small range in index of refraction, the analyses were expected to show a greater change in anorthite content than was actually found; published graphs generally indicate a change of 2 percent in anorthite content for each change of 0.001 in index of refraction.

Some of the samples in table 13 carry notable amounts of K_2O and the rare alkalies, but these are contributed largely by contaminating mica. Though some of this mica probably is a deuteric product and obtained part of its constituents from the plagioclase, there is no evident relation between the content of these alkalies and the character of the albite. Further study of the optical, chemical, and structural variations of the albite will require more precise techniques than were feasible in this study.

The literature on plagioclase suggests that peculiarities in the properties of highly sodic feldspar are not unusual. Emmons and others (1953, p. 39 and fig. 6) state that two index of refraction curves may be needed at the sodic end of the series—one for plagioclase in granite and the other for plagioclase in pegmatite. Their curves for plagioclase of An_0 to An_8 are at markedly lower index values than would be anticipated from the trend for plagioclase of higher An content, but they have no analyses between An_1 and An_{11}. Chayes (1954, especially p. 178–179) expresses doubt about some of Emmons' index determinations, but Chayes himself has a surprising distribution of α values for albite in the data he used in constructing refractive index curves (Chayes, 1952, table 2). For α of 1.528 he has an average of 1.8 percent anorthite in 4 determinations; at α of 1.529 the average anorthite content is only 1.1 percent in 10 determinations; and at α of 1.530 it is 1.6 percent in 2 determinations, which still is less than the anorthite content for α of 1.528; at α of 1.531 the anorthite content is 8.2 percent in 2 determinations, but at α of 1.532 it is 7.6 percent in only 1 determination. These figures indicate a spread of several percent in anorthite content for a single α value. Although such a spread may be attributed to experimental error, the cause is more likely to be in the properties of the mineral. Some uncertainty arises from the sparsity of data for plagioclase between An_4 and An_{13}. Chayes and Emmons together have only 4 determinations in this range, yet they have 20 for An_0 through An_4 and 18 for An_{13} through An_{25} (Chayes, 1952, p. 103–105; Emmons and others, 1953, table 3).

Observed variations in the properties of quartz from different units of the Hugo pegmatite are limited to the work done by Keith and Tuttle (1952, p. 234–237) on the high-low inversion temperatures, which they found to show consistent changes. The inversion temperature of quartz from the wall zone is relatively high; it decreases through succesive intermediate zones; and then rises as the core of the pegmatite is approached.

Mica ranges from the coarse-grained ruby muscovite of the outer part of the pegmatite, through fine-grained

TABLE 14.—*Spectrochemical analyses of mica from the south segment of the Hugo pegmatite*

[Analyst: C. E. Harvey, Univ. of Michigan, Engineering Research project M-978, supported by U.S. Signal Corps, under direction of E. W. Heinrich]

Pegmatite unit	Specimen	Composition (percent)												
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	Li_2O	MnO	SnO_2	Ga_2O_3	F	Total [1]
Zone 2	1299	45	37	2. 1	0. 29	0. 002	1. 6	10. 0	0. 43	0. 05	0. 019	0. 033	0. 88	97. 4
3a	1298	45	34	1. 4	. 05	. 002	1. 4	10. 8	. 27	. 08	. 05	. 033	. 65	93. 7
3b	1296	46	33	1. 9	. 06	. 004	1. 5	10. 4	. 87	. 08	. 042	. 037	1. 05	94. 9
4	1302	43	35	1. 5	. 03	. 002	1. 4	11. 5	1. 2	. 08	. 07	. 041	. 93	94. 7
4	1279	45	33	1. 6	. 04	. 004	1. 4	11. 3	1. 4	. 10	. 067	. 041	1. 05	95. 0
7	1282	48	32	. 85	. 14	. 008	. 37	11. 5	. 85	. 14	. 027	. 023	1. 7	95. 6

[1] Includes 0.006 percent TiO_2 in zone 2; 0.0004 percent Cr_2O_3 in zone 3a; 0.0007 percent Cr_2O_3 in zone 4 (both specimens); 0.001 percent BaO and 0.03 percent Ca_2O in zone 7.

TABLE 15.—*Chemical analyses of mica from the south segment of the Hugo pegmatite*

[Analyst: Charles Bentley, Engineering and Mining Experiment Station, South Dakota School of Mines and Technology]

Pegmatite unit	Specimen	Description of material	Composition (percent)			
			Li_2O	Na_2O	K_2O	FeO
Zone 1	JJN 69–46	A dark mica, not the normal muscovite of the border zone. β about 1.57; 2V, 30°; slightly pleochroic.	4. 02	------	------	------
6	JJN 77–46	Pink mica	. 41	------	------	------
7	JJN 160–46	Chiefly lithia mica. Contaminated by microcline, albite, and quartz.	. 98	0. 28	11. 00	0. 70
7	JJN 17–47	From stockpile of lithia mica. Ground and separated in liquid of 2.75 specific gravity. Sink fraction was sieved, and material passing 200 mesh was analyzed.	. 56	------	------	------
Cleavelandite-microcline-lithia mica replacement unit.	JJN 54–56	Typical aggregate of lithia mica and microcline with minor albite and quartz. Entire aggregate analyzed.	. 22	------	------	------
Cleavelandite-quartz-lithia mica replacement unit.	JJN 52–56	Lithia mica was concentrated by stage grinding to pass 28 mesh, then screened on 35 mesh. The virtually clean mica retained on the 35-mesh screen was analyzed.	1. 76	------	------	1. 61

white to yellow mica of intermediate zones, to the very fine grained greenish-gray lithia mica of the core and replacement units. The mica of zone 2 is as large, flat, and abundant as in many sheet-mica mines; it would be a major source of sheet mica except for its heavy air stain and its softness. Other units contain virtually no sheet mica.

The analyses in tables 14 and 15 show chemical differences among the micas of the different units. Two samples from zone 4 have very nearly the same composition, but samples collected from different units show significant differences in composition. From zone 2 to zone 7 the content of K_2O increases and the content of Na_2O decreases. Li_2O is low in zone 3a and also in zone 2, which contains the greatest concentration of mica in the pegmatite. The so-called lithia mica of zone 7 and the replacement units, which differs so greatly in physical form from the mica of other units, has as much as 1.76 percent Li_2O, but perhaps the main chemical difference between this mica and that of other units is the high content of fluorine and SiO_2 and the low content of combined Al_2O_3 and Fe_2O_3. These characteristics suggest that by detailed mineralogic study other significant differences could be found between this mica and the more nearly normal muscovite of the outer zones.

Differences in beryl from one unit to another are not pronounced, but figure 68 suggests a general increase in refractive index from the outer to the inner parts of the pegmatite. As the refractive index of beryl becomes greater, the BeO content decreases and the alkali content increases (Schaller, W. T., and Stevens, R. E., written communication, 1948).

Amblygonite analyses (table 16) indicate a decrease in Li_2O content from zone 2 through zone 5. Presumably this change is accompanied by an increase in the Na_2O content, as the two Na_2O determinations in table 16 suggest.

Tourmaline and apatite both change in color from one part of the pegmatite to another. Tourmaline in zone 1 and the outer part of zone 2 is black. In the inner part of zone 2, however, it is blue black. It is commonly blue in inner units, although partly black in zone 3. A bright-blue tourmaline is characteristic of the phosphate aggregates. Apatite is blue in zones 5 and 6, but commonly has a greenish cast in other units.

TABLE 16.—*Partial chemical analyses of amblygonite from the south segment of the Hugo pegmatite*

[Analyst of specimens from zones 4 and 5: Charles Bentley, Engineering and Mining Experiment Station, South Dakota School of Mines and Technology]

Zone	Specimen	Composition (in percent)					
		Al_2O_3	Li_2O	Na_2O	K_2O	H_2O	F
2[1]	49-841 CM	33.05	9.47	--------	--------	5.17	0.59
4	JJN 72-46	--------	8.98	1.92	Trace	--------	--------
4	JJN 5-46	--------	8.34	2.44	0.18	--------	--------
4	JJN 106-46	--------	8.36	--------	--------	--------	--------
4	JJN 108-46	--------	7.72	--------	--------	--------	--------
5	JJN 114-46	--------	7.78	--------	--------	--------	--------

[1] The Li_2O content of amblygonite from zone 2 was determined with flame photometer by W. W. Brannock; other constituents determined by M. K. Carron and Charlotte M. Warshaw, U.S. Geological Survey.

Some of the chemical constituents of the pegmatite enter different minerals in the different pegmatite units. Potassium, for example, is chiefly in muscovite in zones 1 and 2, but it is largely in microcline in other units. The iron-manganese phosphates are most common in zone 3; amblygonite is the dominant phosphate mineral in zones 4 and 5; and apatite appears in all zones. Lithium occurs in amblygonite in zone 2, in iron-manganese phosphates that are concentrated in zone 3, in amblygonite of zones 4 and 5, in spodumene of zone 5, and chiefly in mica in zone 7 and the replacement units.

EVIDENCE FOR MAGMATIC INTRUSION

The zoned pegmatites of the southern Black Hills are most abundant along the borders of areas containing intrusive bodies of pegmatitic granite. The area around Harney Peak contains the greatest quantity of pegmatitic granite, but similar rock is exposed in many other places. The many textural and mineralogic similarities between this rock and pegmatite have been described in geologic literature by such authors as Ziegler (1914c, p. 265), Paige (1925, p. 4), and Schwartz (1925, p. 648). The "granite" is a leucocratic rock consisting chiefly of large crystals of perthite and finer grained plagioclase and quartz. Much of it has a layered structure, layers rich in perthite alternating with layers consisting mainly of plagioclase and quartz. The mode of most of these granitic bodies is 35 to 55 percent plagioclase, 20 to 35 percent quartz, 15 to 30 percent perthite, and 5 to 10 percent other minerals, mainly muscovite and tourmaline. This rock has more plagioclase and less quartz than the Hugo pegmatite, but in a broad sense it resembles the Hugo, especially zones 1 to 3. Many geologists have supposed that the so-called granite and the zoned pegmatites are genetically related to each other, and recent areal mapping by Norton, J. A. Redden, and others has provided no reason to believe otherwise.

The following characteristics of the Hugo pegmatite suggest an intrusive origin and crystallization from the contact inward:

1. The contact is commonly sharp, whether it is between pegmatite and altered wallrock or between pegmatite and schist. Altered wallrock enriched in albite, muscovite, tourmaline, and apatite is at most 4 feet thick, and more commonly it is absent entirely. This alteration was probably caused by material contributed by the pegmatitic fluid to the schist.
2. Structural relations of fracture-filling and replacement units indicate that outer zones formed before inner zones, suggesting crystallization of a fluid inward from the contact. The quartz-cleavelandite fracture-filling unit cutting outer zones of the north segment is similar to zone 4 in composition and texture. It is best explained as an offshoot from zone 4 formed when solidified outer units were fractured and filled with rest liquid. Similarly, the replacement units extend outward from zone 7, as if formed by fluids that escaped from the rest liquid at a late stage of crystallization.
3. The character of many of the minerals shows a consistent and gradational change from the outer to the inner units of the pegmatite. The changes are in chemical composition, optical properties, or physical form.
4. Tapered crystals of beryl in zone 2 are normal to the pegmatite contact; the small end is nearest the contact, and the broad end is toward the center of the pegmatite. The shape of such crystals, in this and other Black Hills pegmatites, is best explained by growth inward from a favorably oriented seed near the pegmatite contact, so the tapered form could develop as new material was added to the sides and inner end of previously crystallized material. Jahns (1955, fig. 16) convincingly demonstrated this by illustrating a tapered perthite crystal that has phantoms showing the outline of the crystal at different stages of its development.
5. The pegmatite is discordant with the overall structure of the country rock in the surrounding area. Near the pegmatite, however, bedding is commonly nearly parallel to the contact, as if it has been forced into that position during intrusion.
6. The pegmatite does not contain relicts of minerals textures, and structures of the country rock. The only schist fragments in pegmatite are near the contact. They are surrounded by zones 1 and 2, and give every appearance of being in rolls of the contact that come from above or below.

Only Higazy (1949) has disputed the conclusion that the Hugo and other Black Hills pegmatites were at least partly magmatic. He proposed an origin by metasomatism of schist. Higazy's work consisted chiefly of making chemical analyses and petrographic studies of 16 specimens of perthite, 1 of microcline, 1 of cleavelandite, 1 of "albitite" (probably aplite), and 2 of schist. He assumed that the composition of perthite from a pegmatite is equivalent to the composition of the pegmatite itself and cited the Glendale pegmatite, 3 miles southeast of Keystone, as an example of a pegmatite that "consists of perthite only" (Higazy, 1949, p. 557). Actually, the Glendale pegmatite has more of both quartz and plagioclase than perthite; if it consisted solely of perthite, it would have been mined out years ago. There are pegmatites in the Black Hills in which perthite is the most abundant mineral, but they also contain almost as much quartz and plagioclase as perthite.

Higazy demonstrated in some detail that the composition of his perthite specimens falls near the orthoclase corner of the albite-anorthite-orthoclase system. By assuming that the perthite is equivalent to the rock as a whole, and that no other minerals were crystallizing at the same time, he showed that a magma of any likely composition could not produce a rock having the composition of perthite. He thus concluded that magmatic crystallization is impossible, and metasomatism is the only alternative. If all the minerals of the pegmatites had been taken into account, Higazy's entire line of argument would have lost its apparent relevancy.

Higazy (1949, p. 566), stated that "Whenever perthite forms pegmatitic pockets or forms a zone in a pegmatite body, its chemical composition should closely approximate the mother-liquor from which it crystallized." As Jahns (1955, p. 1093) has pointed out, Higazy discounted "the very real possibilities of fractional crystallization, resurgent boiling, and liquid immiscibility."

Higazy (1949, p. 562–565) also discussed the textural relations between albite and microcline in perthite. He showed that the albite is later than the microcline, but at most this proves only the age relation between these two minerals; it does not prove, as Higazy (1949, p. 579–580) thought, that both of these minerals necessarily formed by metasomatism of schist.

Some of the Black Hills schists contain porphyroblasts of perthite that Higazy (1949, p. 580) considered to be intermediate between unaltered schist and his perthite pegmatites. Higazy (1949, p. 557) found this type of rock in one outcrop only 36 yards long. Elsewhere similar rock occurs in only very small quantities in relation to the great quantity of pegmatite in the Black Hills, although under Higazy's theory it should be abundant. It seems more appropriate to ascribe the origin of this rock to potassium-bearing fluids escaping from the nearby pegmatites.

Later, Higazy (1953) determined the trace-element content of his perthite specimens, and used the results as evidence for the derivation of pegmatite from schist. He took the position (1953, p. 182–183), on geochemical grounds, that perthite in pegmatites derived from a magma should have more rubidium and less barium than the perthite of associated granite, and that it should have less chromium than nickel or cobalt. In comparing the Black Hills pegmatites with the granite, he used only one sample of perthite from granite, and for that sample he did not describe any lithologic differences from pegmatite, despite the known pegmatitic nature of the Harney Peak granite.

The analyses of perthite from pegmatite show a generally higher rubidium content than in perthite from the granite, and thus seem to be in accord with a magmatic derivation. Higazy concluded otherwise, however, because 2 of his 15 specimens contained less rubidium than the granite, and other samples "have unusually high Rb contents" and "cannot be considered as primary products of magmatic crystallization since such products generally have a much lower Rb content" (Higazy, 1953, p. 183).

Regarding the barium content, which should be highest in perthite from the granite, Higazy stated that "The Ba content of the phenocryst from granite and the value of its Ba/K (1000 Ba/K=1.6) are much lower than those of * * * most of the pegmatitic perthites (1000 Ba/K ranges from 1.9 to 14.7)" (Higazy, 1953, p. 183). Examination of Higazy's analytical data and recalculation of the Ba:K ratios[4] indicate that this statement does not show all the facts. Of the 15 samples of perthite from pegmatite, 8 have more barium and a higher Ba:K ratio than the granite, and 7 have less barium and a lower Ba:K ratio than the granite. The statement, "1000 Ba/K ranges from 1.9 to 14.7," applies only to the 8 specimens that have a higher ratio than the granite; the other 7 range from 0.2 to 1.0.

Similarly, the point that the chromium content should be less than nickel and cobalt if the origin is magmatic but is greater in these specimens seems to be stressed more than the analytical data warrant. None of the perthite specimens contained nickel or cobalt at a sensitivity limit of 2 ppm (parts per million). The only chromium values of 2 ppm or more were in 5 specimens: 4 of these have 3 ppm and 1 has 5 ppm chromium. Seven samples contained no detectable chromium, at a sensitivity limit of 1 ppm.

Neither the values for these metallic constituents nor the content of barium provide sufficient grounds for Higazy's conclusion. The rubidium data, if they can be interpreted at all, support a magmatic derivation. However, emphatic statements about the meaning of trace-element analyses seem not advisable until more information is available about the behavior of these elements under various physical and chemical conditions.

---

[4] Analytical data used in the recalculation are from Higazy (1949, table 1, and 1953, table 1). Specimen 7 was omitted because it is a porphyroblast in schist (Higazy, 1953, p. 177).

EVIDENCE FOR TEMPERATURE OF CRYSTALLIZATION

Several geothermometers can be applied to the Hugo pegmatite, and although debatable in some respects, they provide reasonably firm brackets indicating that crystallization was at temperatures between 300° and 650°C. They also suggest a progressive decrease in temperature from the outer to the inner parts of the pegmatite.

The solvus in the muscovite-paragonite system, as determined by Eugster and Yoder (1955), has been used by Grootemaat and Holland (1955) to determine crystallization temperatures at the Peerless pegmatite, and it can be applied just as well to the Hugo. Eugster (written communication, 1959) has since modified this solvus, and he says that the muscovite-albite solvus must lie nearer muscovite than the muscovite-paragonite solvus, although how much nearer is not known. Consequently any determinations of the paragonite content of Hugo micas, which are associated with albite, can provide minimum temperatures, and these temperatures may or may not be close to the actual temperatures.

The inferred temperatures based on the alkali analyses shown in table 17 range from a high of 450°C in zone 1 to a low of 290°C in zone 7. The mica collected from zones 1–3, yielding temperatures of 410° to 450°C, was typical of the relatively coarse muscovite associated with quartz and albite in these zones. The mica from zone 4, which indicates a temperature of 350°C, was from a pseudomorph after spodumene. The sample from zone 7, indicating 290°C, was a typical aggregate of lithia mica.

TABLE 17.—*Minimum temperatures of crystallization of mica from the Hugo pegmatite, determined from the muscovite-paragonite proportions*

[Analyses by flame photometer; analyst: C. G. Engel, U.S. Geological Survey]

Sample	Zone [1]	Weight percent		Paragonite (mole percent)	Minimum temperature of crystallization (° C) [2]
		Na_2O	K_2O		
1	JJN 51–58	0.84	9.9	11.8	450
1	JJN 52–58	.69	10.0	9.4	410
2	JJN 53–58	.83	10.5	10.5	430
2	JJN 54–58	.85	10.2	11.5	440
3b	JJN 55–58	.73	10.2	10.0	420
4	JJN 56–58	.52	10.5	6.7	350
7	JJN 57–58	.30	11.1	4.1	290

[1] All samples are from the south part of the south segment.

[2] From graph of the muscovite-paragonite solvus supplied by Hans Eugster (written communication, 1959).

These analyses were made with a flame photometer by Celeste G. Engel specifically for use in estimating temperature, and it is not surprising that they show lower values for Na_2O than the less precise spectrochemical analyses in table 14. Nevertheless, the reliability of the Engel analyses was tested by having one of the samples determined by several analysts using three different methods. The results shown in table 18 indicate that the Engel analyses can be accepted with confidence.

The chief value of these data is to establish that the temperatures were more than 400°C in zones 1–3, 350°C in zone 4, and 290°C in zone 7. If the solvus in the natural system is parallel to the determined muscovite-paragonite solvus, then the difference in the maximum (450°C) and minimun (290°C) temperature readings means that the temperature fell 160°C from zone 1 to zone 7.

TABLE 18.—*Comparative analyses of a sample of muscovite*[1] *from zone 2 of the Hugo pegmatite*

[Analyses by U.S. Geological Survey]

Analyst	Method	Composition (weight percent)				
		K_2O	Na_2O	Li_2O	Rb_2O	Cs_2O
C. G. Engel	Flame photometer	10.2	0.85			
Wayne Mountjoy.	do	10.3	.90			
W. W. Brannock	do	10.0	.84			
J. I. Dinnin	do	10.0	.80	0.27	0 30	<0.05
Fay Neuerburg	Wet chemical	10.31	.90	.25		
N. M. Conklin	Spectrographic	10.5	.98	.30	.39	.01

[1] Field No. of this sample is JJN 54–58; Geological Survey laboratory No. 271091.

Fluid inclusions provide another means for obtaining minimum temperatures because any determinations that are uncorrected for pressure probably are lower than the actual temperatures (Kennedy, 1950, p. 540–543). Weis (1953, p. 684) found fluid inclusions that he interpreted as primary in 1 specimen of beryl from zone 3 and 2 of quartz from unstated locations in the Hugo pegmatite. Temperatures from 19 inclusions in the beryl ranged from 309° to 353°C and had an arithmetic mean of 328°C. The range of 38 inclusions in the quartz was from 376° to 422°C; one of the quartz specimens had a mean of 398°C and the other 400°C. Weis found even greater ranges in specimens from other Black Hill pegmatites. One specimen from the Peerless pegmatite, for example, ranged from 257° to 405°C (Weis, 1953, p. 681, 683). These ranges are so great that the figures can be used only in a general way. Nevertheless, the Hugo specimens suggest a temperature, uncorrected for pressure, between 320° and 400°C and this is in the same general range as the temperatures obtained from muscovite.

Calculation of actual temperatures from the fluid-inclusion measurements requires assumptions that introduce a high degree of uncertainty. Even if the pressure could be determined, the temperature correction required for this pressure cannot be known unless the composition of the fluid inclusions is known. Published data for correcting the temperatures are based on the properties of pure water (Kennedy, 1950, p. 540–543), and no correction can be made above the critical temperature of water. Consequently, this correction cannot be applied to the fluid-inclusion temperatures in either of the quartz samples from the Hugo, but can be applied to those in the beryl crystal. Furthermore, although the fluid inclusions in beryl are probably aqueous (Weis, 1953, p. 677–678, 689–690), they must contain materials in solution that increase the critical temperature and decrease the pressure correction (Kennedy, 1950, p. 543). Finally, the geometry of Kennedy's graph is such that very small errors in the temperature determinations would cause very large errors in the correction for pressure. Disregarding these uncertainties, Kennedy's graph indicates that, at 4 miles depth (the greatest depth he uses), the correction for the temperature of 328°C indicated by inclusions in beryl is +185°C, and thus the original temperature would be 513°C.

Weis (1953, p. 693) used his temperature data from several Black Hills pegmatites to suggest that inner zones crystallized at lower temperatures than outer zones; but, as he points out, the great range in temperatures even from single crystals makes his evidence very weak. Furthermore, the apparent temperature increases inward at the Peerless pegmatite (Weis, 1953, fig. 7). The only other pegmatite in which Weis thought he had clear evidence for the temperature trend is the Highland Lode near Custer, where the temperatures are about the same in two intermediate zones and much lower in a unit he called a plagioclase-quartz core of the pegmatite (Weis, 1953, p. 679–680). In actual fact, however, this pegmatite does not have an exposed plagioclase-quartz core (Page and others, 1953, pl. 23), and the source of Weis' samples is in doubt. Weis' data leave open the possibility that the apparent, uncorrected temperatures increase inward. This could be so if the alkali content of the fluid trapped in inclusions during crystallization is greater in inner than in outer zones; certain trends in pegmatite differentiation suggest this possibility (compare with Jahns, 1955, p. 1094–1095). The pressure correction would be less in the alkali-rich material (Kennedy, 1950, p. 543), and this compositional difference could thus cause the uncorrected temperatures to be higher in inner than in the outer zones, even if the actual temperatures were the reverse.

The lowest maximum temperature that can be demonstrated for the Hugo pegmatite is based on the presence of spodumene. Roy and others (1950, p. 159) showed that alpha spodumene is stable only below 500°C at low pressures in a hydrous environment; their work suggests further that at only slightly lower temperatures petalite or eucryptite should form. D. B. Stewart (oral communication, 1961) has found that the maximum temperature at which alpha spodumene is stable increases to 600°C at 4,000 bars H_2O pressure, and this suggests an approximate upper limit for the temperature of zone 5 in the Hugo pegmatite.

A few Black Hills pegmatites intruded into high-grade metamorphic rocks south of Harney Peak contain sillimanite and lack muscovite, either in their outer parts or through their entire thickness. The pegmatites are unmetamorphosed, and the sillimanite is evidently primary. Data presented by Yoder and Eugster (1955, p. 263, 264) show that the temperature boundary between muscovite + quartz and potassic feldspar + sillimanite + vapor is at about 650° to 675°C at H_2O pressures of 15,000 to 30,000 psi. More recently, H. P. Eugster (oral communication, 1957) has found that the temperature may be much lower—perhaps between 500° and 600°C. The absence of sillimanite within the Hugo pegmatite suggests a crystallization temperature below this level; on the other hand, the presence of a small quantity of sillimanite in schist within 2 feet of the pegmatite suggests that temperatures were higher prior to crystallization.

Stability relations in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O offer ways of estimating temperature of crystallization. Only about 6 percent of the material in the Hugo pegmatite is outside of this system, and thus the composition of the natural system is as close to the composition of the experimental system as one will ordinarily find.

The firmest temperature obtainable from this system is at the crest of the feldspar solvus. Two feldspars, potassic and sodic, crystallize simultaneously from the liquid only where the solidus is depressed (as by high H_2O pressure) to a temperature below the solvus. Otherwise a single feldspar crystallizes, and the only way it can be converted to two feldspars is by unmixing at the solvus.

The Hugo pegmatite contains abundant evidence that both albite and potassic feldspar formed simultaneously as original minerals. The concentration of albite in zone 3c and potassic feldspar in zone 3a can scarcely be explained as unmixing of a single feldspar. The cleavelandite sheaths around crystals and pseudomorphs of spodumene in zones 4 and 5 are entirely separate from the large microcline crystals of these same units. The replacement units contain relict and introduced crystals of both feldspars, and it would be difficult or impossible to explain all of these by unmixing.

Crystallization temperatures of zone 3 and all succeeding units therefore must have been below the crest of the solvus. By increasing the H_2O pressure so as to depress the crystallization temperatures in the experimental albite-orthoclase-quartz system, Tuttle and Bowen (1958, p. 82–83) found that a H_2O pressure of 3,600 kg per sq cm is required in order that two feldspars may crystallize from the liquid. The lowest temperature of crystallization at this pressure is about 655°C. The Hugo temperature could have been lower than this, in response to the depressing effects of greater gas pressure or additional constituents, or they could have been higher if the gas pressure was less than the total pressure (Tuttle and Bowen, 1952, p. 38). The temperature could not, however, have been greater than the temperature of the crest of the solvus. The top of the solvus is at 660°C at 1,000 bars H_2O pressure and 715°C at 5,000 bars total pressure (Bowen and Tuttle, 1950, p. 496; Yoder and others, 1957, p. 208). It rises greatly with slight increase in anorthite content (Yoder and others, 1957, figs. 45 and 46). The anorthite content of the Hugo plagioclase is negligible, however, and even if the small amount of deuteric apatite found in the thin sections was derived from the alteration of calcium-bearing plagioclase, the anorthite content at the time of primary crystallization must still have been small. Consequently the solvus probably does not extend much above 700°C at any reasonable pressure, and the crystallization temperatures would have to be less than this.

In theory, the composition of coexisting plagioclase and potassic feldspar can be fitted to the feldspar solvus to determine temperature of crystallization, but this procedure is accompanied by several uncertainties. The main one arises from the fact that the solvus is different for the different high- and low-temperature forms of feldspar (Tuttle and Bowen, 1958, p. 17–28), and the form of the Hugo feldspars at the time of crystallization is not known. Furthermore, exsolution and deuteric reactions have changed the composition of the Hugo feldspars to an unknown but probably small degree since crystallization. These deficiencies in data make precise estimates of temperature from the composition of the coexisting feldspars impossible, but some guesses can be offered.

The composition of the Hugo albite is very near An_0. Yoder and others (1957, p. 211–213) show that a decrease in anorthite content of plagioclase formed with potassic feldspar can be correlated with an increase in pressure and a decrease in temperature. Their diagrams for 5,000 bars H_2O pressure suggest a temperature for the Hugo of very much less than 700°C. Tuttle and Bowen (1958, fig. 10) indicated a temperature of 500°C for An_0 on the solvus for orthoclase cryptoperthite, but the solvuses for other forms of feldspar are much lower.

The potassic feldspar of the Hugo must have been on the solvus at the time it originally crystallized, and although it has undergone subsequent changes (especially exsolution to form perthite), the bulk composition of the aggregate should be virtually the same as the composition of the original homogeneous feldspar. The perthite of zone 3 has 27.4 percent normative albite, and the microcline zone 6 has 10.4 percent normative albite (Higazy, 1949, tables 1 and 4; norms recalculated). The different published solvuses suggest temperatures of 500° to 600°C for the perthite and 400° to 500°C for the microcline (Bowen and Tuttle, 1950, fig. 3; Yoder and others, 1957, fig. 38; Tuttle and Bowen, 1958, figs. 7, 10, 11, and 17).

Barth (1956, p. 15) has published a graph showing estimated temperature of crystallization plotted against the ratio of Ab in potassic feldspar to Ab in coexisting albite. The Hugo temperatures from this graph would be 550°C for zone 3 and 365°C for zone 6.

The temperature data, taken together, indicate that the pegmatite formed at less than 700°C, and probably at least in part at less than 600°C. There is evidence that the temperatures may have been as low as 410° to 450°C in zones 1–3 and as low as 290° to 350°C in zones 4–7. The temperature of zone 4 is bracketed at between 350°C (from muscovite) and 600°C (from spodumene). The muscovite temperatures suggest that zones 1–3 formed at temperatures of 50° to 100°C greater than zone 4, and that zone 4 formed at a temperature of about 60°C greater than zone 7. The data regarded as a whole are consistent with an estimate of 500° to 650°C for zones 1–3, 400° to 600°C for zones 4–6, and 350° to 500°C for zone 7.

CHEMICAL COMPOSITION

The chemical composition of each of the pegmatite units has been calculated from the modes (table 19), using the data in table 20 for the chemical composition of each mineral. The modes are visual estimates in which large errors are unlikely, inasmuch as the minerals can be easily recognized. More accurate data could be obtained only by mining very large samples from this pegmatite.

Even large errors in the modes would have small effect on the calculated chemical composition of table 19. For example, in the mode for the pegmatite as a whole, if the albite were increased from 26 to 34 percent, and this were offset by a decrease of potassic feldspar from 21 to 15 percent and of mica from 6 to 4 percent, the chemical composition would be changed as follows: SiO_2 from 77.9 to 78.6 percent; Al_2O_3 from

TABLE 19.—*Estimated composition of the Hugo pegmatite*

Pegmatite unit	Tons of rock		Mode (percent) [1]											Calculated chemical composition (percent) [2]										
	Between altitude of 4,442 ft and surface	In entire pegmatite	Quartz	Albite	Perthite and microcline	Mica	Amblygonite	Spodumene	Tourmaline	Heterosite [3]	Apatite	Beryl	Cassiterite	SiO_2	Al_2O_3	$Fe_2O_3+FeO+MgO$	CaO	Na_2O	K_2O	Li_2O	P_2O_5	H_2O	F	Other constituents [4]
North segment																								
Zones 1 and 2: Quartz-albite muscovite pegmatite.	25,000	45,000	45	35	------	15	------	------	2.5	------	0.5	0.3	------	78.3	13.1	0.8	0.3	4.3	1.6	Tr	0.2	0.9	0.2	0.3
Zone 3b: Quartz-perthite-albite pegmatite	130,000	175,000	35	25	30	5	------	------	2	0.5	.3	.2	------	76.3	13.5	.7	.2	4.0	4.2	Tr	.3	.4	.1	.3
Zone 3c: Quartz-albite pegmatite	70,000	230,000	55	35	1	7	------	------	1	.2	.2	.2	------	83.7	9.9	.4	.1	4.1	.9	Tr	.2	.4	.1	.2
Zone 4: Quartz-cleavelandite pegmatite	10,000	15,000	55	35	5	3	------	------	------	------	Tr	.1	------	85.3	9.0	.1	Tr	4.2	1.2	Tr	------	.2	Tr	Tr
South segment																								
Zones 1 and 2: Quartz-albite-muscovite pegmatite.	120,000	165,000	40	30	------	20	0.1	------	7	0.5	0.5	0.7	------	73.5	15.3	1.9	0.3	3.9	2.1	0.1	0.5	1.3	0.2	0.9
Zone 3a: Perthite-quartz-albite pegmatite	10,000	200,000	15	10	75	1	------	------	.3	------	.3	.2	Tr	69.8	16.9	.2	.2	3.5	8.9	Tr	.1	.3	Tr	.1
Zone 3b: Quartz-perthite-albite pegmatite	210,000	340,000	35	25	30	5	------	------	1	4	.5	.2	Tr	73.8	12.8	1.9	.3	3.9	4.1	Tr	1.9	.6	.1	.6
Zone 3c: Quartz-albite pegmatite	125,000	160,000	55	35	2	7	------	------	1	.5	.2	.2	------	83.3	10.0	.5	.1	4.1	1.0	Tr	.3	.4	.1	.2
Zone 4: Quartz-cleavelandite-microcline-amblygonite pegmatite.	130,000	165,000	50	35	8	2	3	Tr?	.2	Tr	.3	.3	Tr	81.3	10.3	.1	.2	4.2	1.5	.3	1.6	.3	.1	.1
Zone 5: Quartz-microcline-spodumene pegmatite.	110,000	170,000	70	5	10	.5	4	10	.1	Tr	.3	.1	------	86.6	7.3	.1	.2	.9	1.6	.9	1.0	.3	.1	Tr
Zone 6: Quartz-microcline pegmatite	15,000	20,000	65	Tr	35	Tr	------	------	------	------	.5	------	------	87.0	6.8	Tr	.3	.4	5.2	------	.2	.1	Tr	------
Zone 7: Cleavelandite-microcline-lithia mica pegmatite.	10,000	11,000	15	35	25	25	------	------	------	------	.4	------	0.7	66.4	19.5	.2	.2	4.4	6.5	.2	.2	1.3	.4	.7
Cleavelandite-microcline-lithia mica pegmatite (replacement unit).	15,000	19,000	15	40	25	20	Tr	.5	.1	Tr	.4	.1	.7	67.4	18.9	.2	.2	4.9	5.9	.2	.2	1.1	.3	.7
Cleavelandite-quartz-lithia mica pegmatite (replacement unit).	10,000	15,000	15	70	4	10	1	Tr	.2	.1	.4	.1	.2	69.9	17.9	.2	.2	8.1	1.8	.2	.7	.6	.2	.2
Composition of the north segment:																								
Between altitude of 4,442 feet and surface	235,000	------	44	30	17	7	------	------	1.7	0.3	0.3	0.2	------	79.1	12.2	0.6	0.2	4.1	2.8	Tr	0.2	0.4	0.1	0.3
In entire pegmatite	------	465,000	47	32	12	7	------	------	1.5	.3	.3	.2	------	80.5	11.5	.6	.2	4.1	2.2	Tr	.2	.4	.1	.2
Composition of the south segment:																								
Between altitude of 4,442 feet and surface	755,000	------	46	27	14	7	1.1	1.5	1.6	1.3	.4	.3	Tr	78.4	11.7	1.0	.2	3.6	2.6	.2	1.2	.6	.1	.4
In entire pegmatite	------	1,265,000	41	24	24	6	1.0	1.3	1.4	1.2	.4	.3	Tr	77.0	12.5	.9	.2	3.5	3.6	.2	1.1	.5	.1	.4
Composition of both segments:																								
Between altitude of 4,442 feet and surface	990,000	------	46	28	15	6	.8	1.1	1.6	1.1	.4	.3	Tr	78.6	11.8	.9	.2	3.7	2.6	.2	.9	.6	.1	.4
In entire pegmatite	------	1,730,000	43	26	21	6	.7	1.0	1.4	1.0	.4	.3	Tr	77.9	12.2	.8	.2	3.7	3.2	.2	.9	.5	.1	.3

---

[1] Estimated to the nearest 5 percent for all minerals forming 10 percent or more of any unit. Totals for each unit are between 98 and 102 percent. Tr means the mineral has been recognized but forms less than 0.1 percent of the rock.

[2] See table 20 for mineral compositions used in calculating chemical composition. Tr means less than 0.05 percent.

[3] Includes all phosphates except amblygonite and apatite.

[4] Includes B_2O_3, BeO, Cs_2O, MnO, Mn_2O_3, SnO_2, Ta_2O_5, and Nb_2O_5.

TABLE 20.—*Data used to calculate composition and density of the Hugo pegmatite*

[Mineral constituents given in percent]

Mineral	Density	SiO_2	Al_2O_3	Fe_2O_3+ FeO+MgO	CaO	Na_2O	K_2O	Li_2O	P_2O_5	H_2O	F	Other constituents	Remarks
Quartz	2.65	100.0											
Albite	2.62	68.8	19.5		0.03	11.5	0.2						CaO, Na_2O, and K_2O based on table 13. Remainder assigned to Al_2O_3 and SiO_2 in the molecular ratio 1:6.
Perthite (zone 3)	2.57	64.69	19.79	0.18	.02	3.19	11.95			0.27			From Higazy (1949, table 1), analyst B. Braun.
Microline (other units)	2.56	64.20	19.38	.07	.02	1.21	14.95			.27			
Mica (zones 1-3)	2.85	45.4	35.4	1.9		.8	10.2	0.3		5.0	0.9	0.1 MnO	Na_2O and K_2O from table 17. Li_2O from tables 14, 15 and 18. Otherwise based on tables 14 and 15. H_2O obtained by subtraction from 100.
Mica (zones 4-5)	2.85	44.0	34.0	1.6		.5	10.5	1.3		7.0	1.0	.1 MnO	
Mica (zone 7 and replacement units).	2.9	48.0	32.0	.9		.3	11.1	.9		5.0	1.7	.1 MnO	
Amblygonite	3.0		34.8			2.2	.1	8.2	47.6	5.2	1.9		Na_2O, Li_2O, and K_2O from analyses of specimens from zones 4 and 5 shown in table 16. Remainder calculated as 85 percent montebrasite and 15 percent amblygonite.
Spodumene	3.15	64.5	27.4	.8	.4	1.3		5.62					Li_2O from one analysis by Charles Bentley. Al_2O_3 and SiO_2 are in the molecular ratio 1:4; remainder assumed.
Tourmaline	3.15	34.9	29.4	19.2		3.0				3.5		10.0 B_2O_3	Calculated from the formula: $Na_2O \cdot 5FeO \cdot MgO \cdot 6Al_2O_3 \cdot 12SiO_2 \cdot 4H_2O \cdot 3B_2O_3$.
Heterosite	3.40			38.36	1.37				43.45	4.82		12.08 Mn_2O_3	From analysis of material collected near Hill City, S. Dak. (Schaller, 1911, p. 77-78).
Apatite	3.2				54.7				41.5		3.8		Calculated as $Ca_5P_3O_{12}F$. Average ω of 1.63 indicates nearly pure fluorapatite (Winchell and Winchell, 1951, fig. 113, p. 200).
Beryl	2.73	64.9	18.3			1.0		.6		2.2		12.6 BeO .4 Cs_2O	BeO obtained from refractive index and graph by W. T. Schaller and R. E. Stevens (Norton and others, 1958, fig. 1). Alkalies and H_2O assumed. Remainder assigned to Al_2O_3 and SiO_2 in the molecular ratio 1:6.
Cassiterite	7.0											100.0 SnO_2	

12.2 to 11.9 percent; Na_2O from 3.7 to 4.4 percent; and K_2O from 3.2 to 2.3 percent. If quartz were decreased from 43 to 35 percent, and each feldspar were increased by 4 percent, the change would be: SiO_2 from 77.9 to 75.2 percent; Al_2O_3 from 12.2 to 13.8 percent; Na_2O from 3.7 to 4.3 percent; and K_2O from 3.2 to 3.7 percent. Not only are errors of this magnitude unlikely, but even if they exist, they would have little or no effect on the conclusions reached in this report.

The iron-manganese phosphates, which form only a small part of any pegmatite unit, were calculated as heterosite because it is the most abundant of these minerals in present exposures, including recent mine openings. The heterosite is at least partly an alteration product of triphylite, but it is not certain that all of the heterosite formed in this way or that the alteration took place in relatively recent time. In the absence of evidence to this effect, the calculations are based on present exposures, in which heterosite is dominant, rather than on any supposed parent material.

In calculating the overall composition of each segment and of both segments together, it is necessary to estimate the quantity of rock in each unit. Such estimates have been made for rock between the surface and an altitude of 4,442 feet (the floor of the lowest mine level), which includes the best known part of the pegmatite, and also for the entire pegmatite, including rock eroded and mined from above the present surface and rock below the lowest mine level.

The volume of rock in each unit was determined by dividing the pegmatite into small blocks by means of vertical and horizontal sections, chiefly those shown in plates 9 and 10 but also others where needed. Volume was converted to tonnage by using an average specific gravity of 2.66, calculated from the densities of the minerals shown in table 20 and weighted according to the quantities of these minerals. Inaccuracies in the tonnage estimates can be introduced by misinterpretations of the structure, but these are probably not large, as the pegmatite is so well known in three dimensions from the extensive exposures on the surface and in underground workings. Some units (for example, zones 2 and 3b) are better exposed than others (for example, zone 5), and the tonnage estimates are probably correspondingly better. The volume of replacement units was difficult to estimate because they have no evident structural control, and thus could be somewhat larger than shown in table 19. Despite any such error, the replacement units surely form only a very small part of the pegmatite.

Data for determining the size and shape of the pegmatite below the lowest mine level and above the present surface have inadequacies that cause the tonnage estimates for the entire pegmatite to be less reliable than the estimates for rock between the lowest mine level and the surface. The structure suggests that the bottom of the north segment is at an altitude of about 4,280 feet and the south segment at 4,360 feet. More reliable data for the size and shape of the pegmatite units at depth can be obtained only by drilling or mining.

Fortunately the estimates of the quantity of rock above the present surface can be verified by use of the production figures. Table 1 shows that about 193,000 tons of potash-feldspar concentrates had been produced when the mine was mapped in the summer and fall of 1946. The actual quantity of potash feldspar obtained from the Hugo would be somewhat less than this because the concentrates contained some quartz, albite, and other impurities, and a part of the reported production may have been from the Roy pegmatite. On the other hand, a significant quantity of potash feldspar went into the dump, and probably the pegmatite mined from above the present surface contained somewhat more than 193,000 tons of perthite and microcline.

The estimates of the quantity of rock and potassic feldspar above the present surface used in compiling table 19 are given below:

Estimates of quantity of rock and potassic feldspar above the present surface

Zone	Tons of pegmatite	Percent perthite and microcline	Tons of perthite and microcline
North segment			
1 and 2	25,000	0	0
3b	25,000	30	7,500
4	3,000	5	150
South segment			
1 and 2	20,000	0	0
3a	190,000	75	142,500
3b	130,000	30	39,000
4	25,000	8	2,000
5	55,000	10	5,500
6	5,000	35	1,750
7 and replacement units	10,000	15	1,500
Total	488,000		199,900

The very close agreement between the estimated quantity of potash feldspar (199,900 tons) and the actual production (193,000 tons) suggests that virtually the only rock eroded from this pegmatite before mining was in the border and wall zones, and that all the rest must now be in the dumps. A reasonable estimate for the quantity of rock in the dumps (after subtracting the quantity of material mined from the Roy pegmatite) is 220,000 tons. Pegmatite above the present surface may then be accounted for as follows:

	Tons
Potash feldspar mined	193, 000
Other minerals produced (mostly scrap mica and amblygonite)	5, 000
Eroded from zones 1 and 2	45, 000
Dumps	220, 000
Total	463, 000

This total of 463,000 tons agrees much more closely with the 488,000 tons estimated from maps and sections than could reasonably be expected, and the estimates of pegmatite above the present surface seem to be correct.

Table 19 shows that the only great difference between the composition of the block of pegmatite between the lowest mine level and the surface and that of the entire pegmatite is in K_2O, which is 2.6 percent in the former and 3.2 percent in the latter. The potassic feldspar content of the rock removed by mining accounts for this difference. Otherwise the data are consistent in indicating an overall content of about 78 percent SiO_2, 12 percent Al_2O_3, 3.7 percent Na_2O, 1 percent each of P_2O_5 and total iron and magnesium oxides, and 0.2 percent Li_2O. The water content of 0.5 percent, although based solely on water shown in a few minerals in table 20, probably is very nearly correct. A similar estimate made of drill core at the Diamond Mica pegmatite, 0.2 miles southeast of the Hugo mine, was 0.8 percent H_2O; chemical analyses of this same drill core by M. Balazs and L. C. Peck showed 0.62 percent H_2O.

It is noteworthy that Na_2O exceeds K_2O even though this mine has been a very large source of potash feldspar. The Li_2O content is lower than one might expect from the fact that this pegmatite contains minable deposits of lithium minerals. Such elements as boron, beryllium, tin, tantalum, and niobium are also concentrated in some units, but together they form less than 0.3 percent of the whole pegmatite. Other constituents are probably even more insignificant.

The variation diagram in figure 69 shows that in most respects the Hugo pegmatite is in accord with the compositional trends in the series of rocks ranging from tonalite through granodiorite and adamellite to calc-alkali and alkali granite. The highly silicic nature of the Hugo pegmatite is perhaps the most noteworthy feature of this diagram. The Diamond Mica pegmatite, also represented in the variation diagram, is a homogeneous pegmatite between alkali granite and the

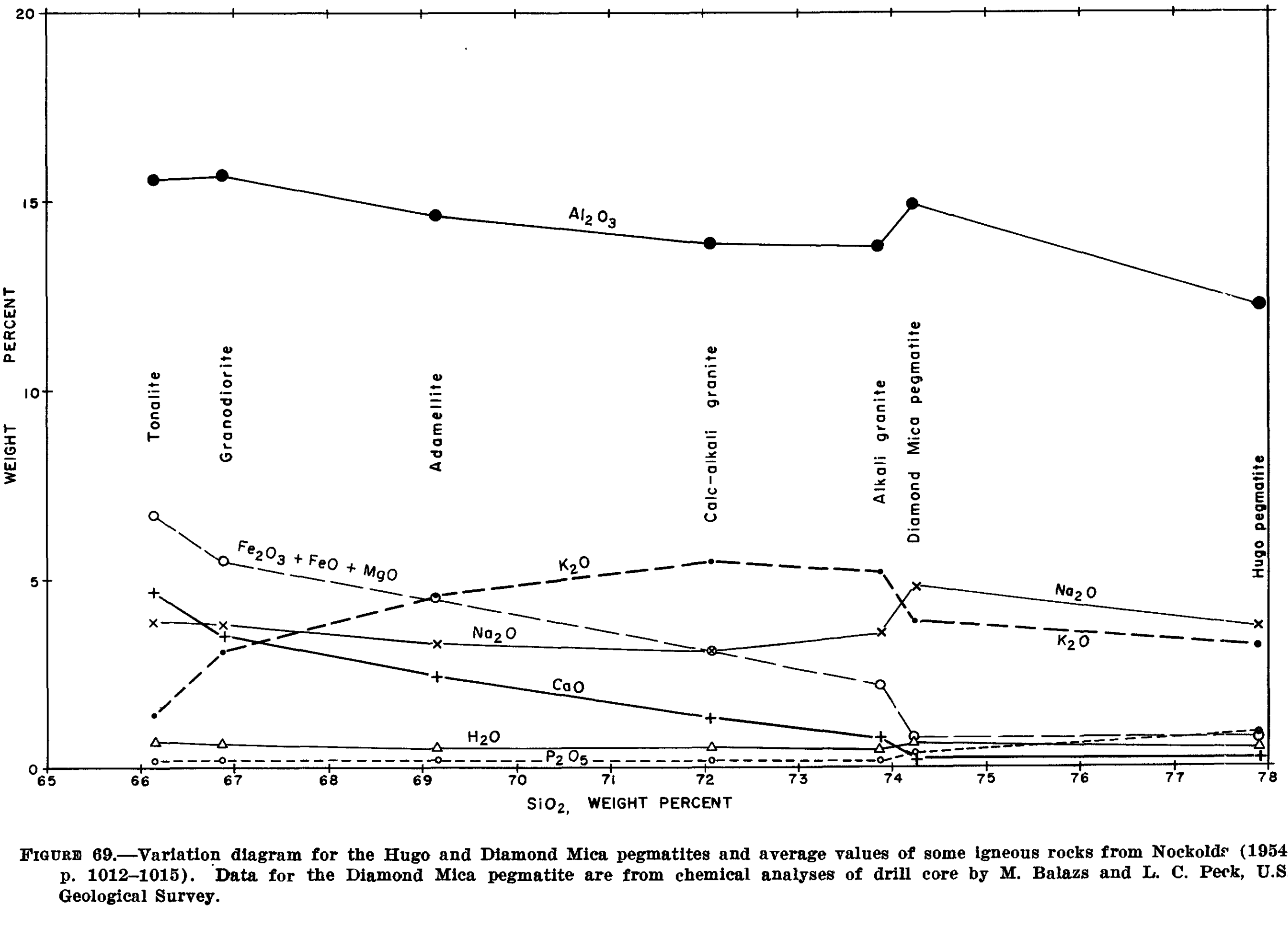

FIGURE 69.—Variation diagram for the Hugo and Diamond Mica pegmatites and average values of some igneous rocks from Nockolds (1954, p. 1012–1015). Data for the Diamond Mica pegmatite are from chemical analyses of drill core by M. Balazs and L. C. Peck, U.S. Geological Survey.

TABLE 21.—*Mineralogic and chemical changes associated with the formation of the core and replacement units*

Pegmatite unit	Estimated tonnage of rock	Estimated mineral composition [1]												Estimated chemical composition [1]	
		Quartz		Albite		Microcline		Mica		Amblygonite		Spodumene		SiO_2	
		Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons
Pegmatite between altitude of 4,442 ft and surface															
Present composition of zone 7 and replacement units:															
Zone 7: Cleavelandite-microcline-lithia mica pegmatite	10,000	15	1,500	35	3,500	25	2,500	25	2,500	------	------	------	------	66.4	6,640
Cleavelandite-microcline-lithia mica replacement unit	15,000	15	2,250	40	6,000	25	3,750	20	3,000	Tr	------	0.5	75	67.4	10,110
Cleavelandite-quartz-lithia mica replacement unit	10,000	15	1,500	70	7,000	4	400	10	1,000	1	100	Tr	------	69.9	6,990
Total (tons)	35,000		5,250		16,500		6,650		6,500		100		75		23,740
Original composition of zonal material that was subsequently replaced:															
Zone 4: Quartz-cleavelandite-microcline-amblygonite pegmatite	10,000	50	5,000	35	3,500	8	800	2	200	3	300	Tr?	------	81.3	8,130
Zone 5: Quartz-microcline-spodumene pegmatite	10,000	70	7,000	5	500	10	1,000	.5	50	4	400	10	1,000	86.6	8,660
Zone 6: Quartz-microcline pegmatite	5,000	65	3,250	Tr	------	35	1,750	Tr	------	------	------	------	------	87.0	4,350
Total (tons)	25,000		15,250		4,000		3,550		250		700		1,000		21,140
Inferred composition of the material that had to be added to form the core and replacement units	10,000	------	------	------	------	------	------	------	------	------	------	------	------	26	2,600
Mineralogic changes during formation of core and replacement units:															
Minerals added	------	------	------	------	12,500	------	3,100	------	6,250	------	------	------	------	------	------
Minerals subtracted	------	------	10,000	------	------	------	------	------	------	------	600	------	925	------	------
Entire pegmatite															
Present composition of zone 7 and replacement units:															
Zone 7: Cleavelandite-microcline-lithia mica pegmatite	11,000	15	1,650	35	3,850	25	2,750	25	2,750	------	------	------	------	66.4	7,304
Cleavelandite-microcline-lithia mica replacement unit	19,000	15	2,850	40	7,600	25	4,750	20	3,800	Tr	------	0.5	95	67.4	12,806
Cleavelandite-quartz-lithia mica replacement unit	15,000	15	2,250	70	10,500	4	600	10	1,500	1	150	Tr	------	69.9	10,485
Total (tons)	45,000		6,750		21,950		8,100		8,050		150		95		30,595
Original composition of zonal material that was subsequently replaced:															
Zone 4: Quartz-cleavelandite-microcline-amblygonite pegmatite	14,000	50	7,000	35	4,900	8	1,120	2	280	3	420	Tr?	------	81.3	11,382
Zone 5: Quartz-microcline-spodumene pegmatite	12,000	70	8,400	5	600	10	1,200	.5	60	4	480	10	1,200	86.6	10,392
Zone 6: Quartz-microcline pegmatite	8,000	65	5,200	Tr	------	35	2,800	Tr	------	------	------	------	------	87.0	6,960
Total (tons)	34,000		20,600		5,500		5,120		340		900		1,200		28,734
Inferred composition of the material that had to be added to form the core and replacement units	11,000	------	------	------	------	------	------	------	------	------	------	------	------	17	1,861
Mineralogic changes during formation of core and replacement units:															
Minerals added	------	------	------	------	16,450	------	2,980	------	7,710	------	------	------	------	------	------
Minerals subtracted	------	------	13,850	------	------	------	------	------	------	------	750	------	1,105	------	------

Hugo pegmatite in its content of SiO_2 and most other constituents. The diagram shows that with increase in SiO_2, there is a general decrease in Al_2O_3, iron and magnesium oxides, and CaO. The H_2O content is nearly constant, and so also is the P_2O_5 content except that it increases in pegmatite. K_2O increases from tonalite to calc-alkali granite, and then decreases from calc-alkali granite to pegmatite. The curve for Na_2O generally goes in an opposite direction from that for K_2O, but both of these constituents are less abundant in the Hugo than in the Diamond Mica pegmatite. The Hugo and Diamond Mica pegmatites each have more Na_2O than K_2O, although the opposite is true in average granitic rocks.

The north and south segments differ from each other chiefly in the content of K_2O and Na_2O. The south segment has more K_2O, caused mainly by the great quantity of perthite-rich pegmatite in zone 3a; the north segment has more Na_2O, caused by the large tonnage of albite-rich pegmatite in zone 3c. The south segment, however, also has more K_2O and less Na_2O than the north segment in zones 1 and 2, and similarly has more Al_2O_3 and less SiO_2 in these units. The only other significant difference is the greater amount of P_2O_5 and Li_2O in the south segment. Otherwise the two segments have a similar composition.

The chemical compositions of the different units indicate progressive changes from the outer to inner

TABLE 21.—*Mineralogic and chemical changes associated with the formation of the core and replacement units*—Continued

Pegmatite unit	Estimated tonnage of rock	Estimated chemical composition [1]—Continued													
		Al_2O_3		Na_2O		K_2O		Li_2O		P_2O_5		H_2O		F	
		Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons
Pegmatite between altitude of 4,442 ft and surface—Continued															
Present composition of zone 7 and replacement units:															
Zone 7: Cleavelandite-microcline-lithia mica pegmatite	10,000	19.5	1,950	4.4	440	6.5	650	0.2	20	0.2	20	1.3	130	0.4	40
Cleavelandite-microcline-lithia mica replacement unit	15,000	18.9	2,835	4.9	735	5.9	885	.2	30	.2	30	1.1	165	.3	45
Cleavelandite-quartz-lithia mica replacement unit	10,000	17.9	1,790	8.1	810	1.8	180	.2	20	.7	70	.6	60	.2	20
Total (tons)	35,000		6,575		1,985		1,715		70		120		355		105
Original composition of zonal material that was subsequently replaced:															
Zone 4: Quartz-cleavelandite-microcline-amblygonite pegmatite	10,000	10.3	1,030	4.2	420	1.5	150	.3	30	1.6	160	.3	30	.1	10
Zone 5: Quartz-microcline-spodumene pegmatite	10,000	7.3	730	.9	90	1.6	160	.9	90	2.0	200	.3	30	.1	10
Zone 6: Quartz-microcline pegmatite	5,000	6.8	340	.4	20	5.2	260	--------	--------	.2	10	.1	5	Tr	--------
Total (tons)	25,000		2,100		530		570		120		370		65		20
Inferred composition of the material that had to be added to form the core and replacement units	10,000	45	4,475	15	1,455	11	1,145	0	[2]—50	0	[2]—250	3	290	1	85
Mineralogic changes during formation of core and replacement units:															
Minerals added	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Minerals subtracted	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Entire pegmatite—Continued															
Present composition of zone 7 and replacement units:															
Zone 7: Cleavelandite-microcline-lithia mica pegmatite	11,000	19.5	2,145	4.4	484	6.5	715	0.2	22	0.2	22	1.3	143	0.4	44
Cleavelandite-microcline-lithia mica replacement unit	19,000	18.9	3,591	4.9	931	5.9	1,121	.2	38	.2	38	1.1	209	.3	57
Cleavelandite-quartz-lithia mica replacement unit	15,000	17.9	2,685	8.1	1,215	1.8	270	.2	30	.7	105	.6	90	.2	30
Total (tons)	45,000		8,421		2,630		2,106		90		165		442		131
Original composition of zonal material that was subsequently replaced:															
Zone 4: Quartz-cleavelandite-microcline-amblygonite pegmatite	14,000	10.3	1,442	4.2	588	1.5	210	.3	42	1.6	224	.3	42	.1	14
Zone 5: Quartz-microcline-spodumene pegmatite	12,000	7.3	876	.9	108	1.6	192	.9	108	2.0	240	.3	36	.1	12
Zone 6: Quartz-microcline pegmatite	8,000	6.8	544	.4	32	5.2	416	--------	--------	.2	16	.1	8	Tr	--------
Total (tons)	34,000		2,862		728		818		150		480		86		26
Inferred composition of the material that had to be added to form the core and replacement units	11,000	51	5,559	17	1,902	12	1,288	0	[2]—60	0	[2]—315	3	356	1	105
Mineralogic changes during formation of core and replacement units:															
Minerals added	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
Minerals subtracted	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

[1] From table 19.

[2] The minus quantities may be caused by errors in the modes.

parts of the pegmatite. SiO_2 shows a general increase from zone 1 to 6; zones 3a and b are low in SiO_2 and 3c is high, but the overall SiO_2 content of zone 3 is in accord with the general trend. Al_2O_3 tends to decrease from zone 1 to 6. Na_2O is nearly constant from zone 1 to 4 and very low in zones 5 and 6. K_2O is high in zones 3, 6, and 7, and low in other zones. Similarly, P_2O_5 is high in zones 3b, 4, and 5, and Li_2O is high in zones 4 and 5.

The composition changes greatly in zone 7 and the replacement units. These are very low in SiO_2 and high in Al_2O_3, Na_2O, and K_2O. They are also relatively rich in water and fluorine.

These trends are brought out more effectively by the variation diagrams in plates 11 and 12. The points on the solid lines show the composition of all zones nearer the pegmatite contact, and the points on the dashed lines show the composition of all inner units. If the pegmatite crystallized from the contact inward, the solid lines show the approximate composition of crystallized rock and the dashed lines show the approximate composition of the fluid at different stages during the formation of the pegmatite. The figures for the core and replacement bodies, taken from table 21, are at best approximate because the quantities of rock in the replacement units are not well known. Various factors can be suggested that would cause the solid and dashed lines to be slightly in error as indicators of the composition of the crystalline and fluid phases, but there is no evidence that these errors are large.

The greatest changes shown by the variation diagrams are in the inner part of the pegmatite. In the outer units the dashed lines indicate residual enrichment of the fluid in SiO_2, P_2O_5, and Li_2O; in the inner units there is a very great decrease in these constituents as they are used up by abundant quartz, amblygonite, and spodumene. In contrast, the content of Al_2O_3, Na_2O, and K_2O indicated by the dashed lines decreases slightly in outer units rich in mica and feldspar, then begins to rise in zone 5, and finally these constituents are used up in the mica and feldspar of the core and replacement bodies.

Although the present composition of the Hugo pegmatite indicates that the fluid from which it was derived consisted chiefly of SiO_2, Al_2O_3, Na_2O, and K_2O, the mineralogy suggests that the fluid also contained more than ordinary quantities of phosphorus (iron-manganese phosphates, amblygonite, and apatite), water (mica), lithium (spodumene, amblygonite, triphylite-lithiophilite, and lithium-rich mica), fluorine (lithia mica), boron (tourmaline), beryllium (beryl), tin (cassiterite), and tantalum and niobium (tantalite-columbite).

Any differences between the composition of the rock and that of the original fluid should be explained by the addition of materials to the wallrocks. The altered schist is so thin, however, that it indicates loss of no large quantity of material. The principal constituents introduced into this rock were alkalies (plagioclase and muscovite), boron (tourmaline), and phosphorus (apatite). The abundance of tourmaline in zones 1 and 2 suggests that iron and magnesium from the wallrock were added to the pegmatite fluid.

The original content of water, fluorine, and perhaps other volatile constituents is not so easily established. Many authors have supposed that the pegmatite fluid was enriched in hyperfusible constituents. Bowen (1928, p. 302) states that the principal effects of these constituents would be "to lower the temperatures of crystallization, to increase the fluidity, to facilitate the separation and interaction of phases, and to modify the course of crystallization only in moderate degree except in very late stages." The low temperatures, large crystals, and the existence of replacement units extending outward from the core of the pegmatite all suggest a high content of hyperfusibles. The mineralogy of the pegmatite and of altered material in the country rock indicates that the predominant hyperfusibles were water, boron, and fluorine, but only water and fluorine are known to be common in inner units that apparently formed at very low temperatures.

Water may have escaped in some quantity during crystallization. Prior to the intrusion of the pegmatites, regional metamorphism had proceeded to the stage in which staurolite and, in areas south of the Hugo mine, sillimanite developed in the metamorphic rocks, and was well beyond the stage in which hydrous minerals are normally formed. In areas containing many pegmatites, however, staurolite and sillimanite have been altered to hydrous minerals, indicating that the pegmatites contributed water to the country rock. The abundance of mica produced by this alteration suggests that potassium was also added to the country rock, although it may have been derived from nearby minerals.

Nevertheless, Tuttle and Bowen (1952, p. 38–39) show that even with abundant water at very high pressures the crystallization of a quartz-feldspar liquid would be well above 600°C. Further, they discuss the likelihood that in many igneous rocks the feldspars first crystallize as a single phase above 660°C and later unmix to form two feldspars. On the other hand, Ramberg (1956, p. 209) takes the view that the temperatures were too low for crystallization from a magma-like fluid, and that a metasomatic origin is the only possible explanation.

A discussion that starts from the field evidence provided by the Hugo and other Black Hills pegmatites would proceed differently. These pegmatites are intrusive rocks having characteristics that suggest crystallization from a fluid. Further, they crystallized at low temperatures, and two feldspars formed as original constituents of the rocks. From this basis, and within the limitations set by present chemical knowledge of silicate systems, the only feasible conclusion is that the fluid contained more water, fluorine, and other volatiles than is now apparent from the composition of the Hugo pegmatite. The effect of fluorine in depressing the crystallization temperature of quartz-feldspar systems is especially notable (Tuttle and Wyllie, 1957, p. 1807). The many ways in which laboratory data fit the conditions suggested by the Hugo pegmatite encourage the belief that further work on systems containing the volatiles and other constituents here indicated for the pegmatite fluid will be in even closer accord.

COURSE OF CRYSTALLIZATION

Primary crystallization of zoned pegmatites from the contact inward is appealing as an explanation for such features as the segregation into zones, the systematic variations in the character of different minerals, and the chemical trends indicated by these phenomena.

More direct evidence, however, has been obtained from the structural relations between zones and crosscutting fracture-filling and replacement units. The replacement units of the Hugo pegmatite extend outward from the lithologically similar core, and cut across outer zones. The quartz-cleavelandite fracture filling that cuts outer zones of the north segment is similar to zone 4, and can best be interpreted as an offshoot from zone 4.

Similar relations have been observed elsewhere in the Black Hills. At the Hardestey Homestead mine, Page and Hanley (in Page and others, 1953, p. 127–128, and fig. 15) mapped a quartz fracture-filling unit that cuts outer zones and extends for 20 feet into the country rock; it also can be distinguished as a fracture filling in the outer 10 feet of the quartz core before it merges with the core and ceases to be distinguishable as a fracture filling. These relations make it apparent that the quartz fracture filling formed while the central part of the quartz core was still crystallizing; it intruded the outer part of the quartz core, the outer zones, and country rock. In the New York pegmatite, southwest of Custer, a fracture-filling unit contains two zones that are mineralogically identical with the two innermost zones of the pegmatite (Page and others, 1953, p. 167). This fracture filling must have been injected just before the innermost zones of the pegmatite crystallized. At the Big Chief pegmatite in the Keystone district, quartz fracture-filling units can be traced directly out of the quartz core into the outer zones.

If crystallization was from the contact inward, it follows logically that after the border and wall zones crystallized and sealed the pegmatite chamber, crystallization thereafter must have taken place in a virtually closed system. In recent literature (for example, Jahns, 1955, p. 1087) the term "restricted system" has been used; this term is appropriate because of the probability that hydrothermal or pneumatolytic fluids escaped from the pegmatite into the country rock. Under this concept of crystallization in a restricted system, the minerals of the zones formed chiefly by fractional crystallization from the pegmatite fluid. The border zone was the first and the core was ordinarily the last unit to form. A few pegmatites, like the Hugo, contain replacement units that were the last, or at least nearly the last, parts of the pegmatite to form.

The course of crystallization of the Hugo pegmatite is illustrated by the variation diagrams of plates 11 and 12 and also by the quartz-albite-microcline triangular diagram of figure 70. The points on the triangular diagram are based on modes in table 19 and plate 12, and on "norms" calculated from the chemical composition in table 19 and plate 11. These points show the aggregate composition of all units of the pegmatite that lie within successive zonal boundaries. The compositions should be about equal to the composition of the pegmatite fluid; thus the diagram shows the course of crystallization with respect to the three major constituents. In the "norms" all K_2O is assigned to microcline, all Na_2O to albite, and all excess SiO_2 to quartz. Remaining constituents, including excess Al_2O_3, are omitted. These remaining constituents form only a small part of the pegmatite fluid at any of the points on the diagram: their total ranges from 1.0 to 7.0 percent, including 0.7 to 3.9 percent excess Al_2O_3.

The two segments are shown separately because to combine them on these diagrams would conceal significant differences that may have been brought about shortly before crystallization. The two segments are connected, and they are so similar to each other that they presumably were derived from a single original fluid. As plate 10 shows, however, the inner zones of one segment are entirely separated from the inner zones of the other. Residual fluids from the north segment possibly escaped into the south segment during the crystallization of zone 4, and they may have caused the upset in equilibrium that led to the resorption of spodumene. Otherwise, except in zones 1, 2, and the outer part of zone 3, the two segments must have crystallized virtually independently.

The greatest difference between the two segments is that the south contains more K_2O and less Na_2O than the north segment. This reflects mainly the large quantity of perthite in zone 3a of the south segment, and of albite in zone 3c of the north segment, but even in inner units the south segment has more K_2O and less Na_2O than the north.

The south segment is at a higher altitude than the north segment; thus K_2O is concentrated in the higher, and Na_2O in the lower segment. Similarly, within the individual segments, K_2O is concentrated in the upper levels in zones 3a, 3b, and 6, and Na_2O at lower altitudes in zone 3c.

The perthite-rich hoods are not exactly at the top of the pegmatite. In this and other Black Hills pegmatites they have an asymmetric form such that they extend much farther down the hanging-wall side than the footwall side of the pegmatite, as in cross section *A–A′*. This structural form cannot be explained by means of floating of crystals or an immiscible liquid, even if there were other evidence for such mechanisms. Furthermore, the concentration of K_2O in the upper segment, and in the upper parts of that segment, and the corresponding concentration of Na_2O at lower levels probably cannot have been caused by the migration of

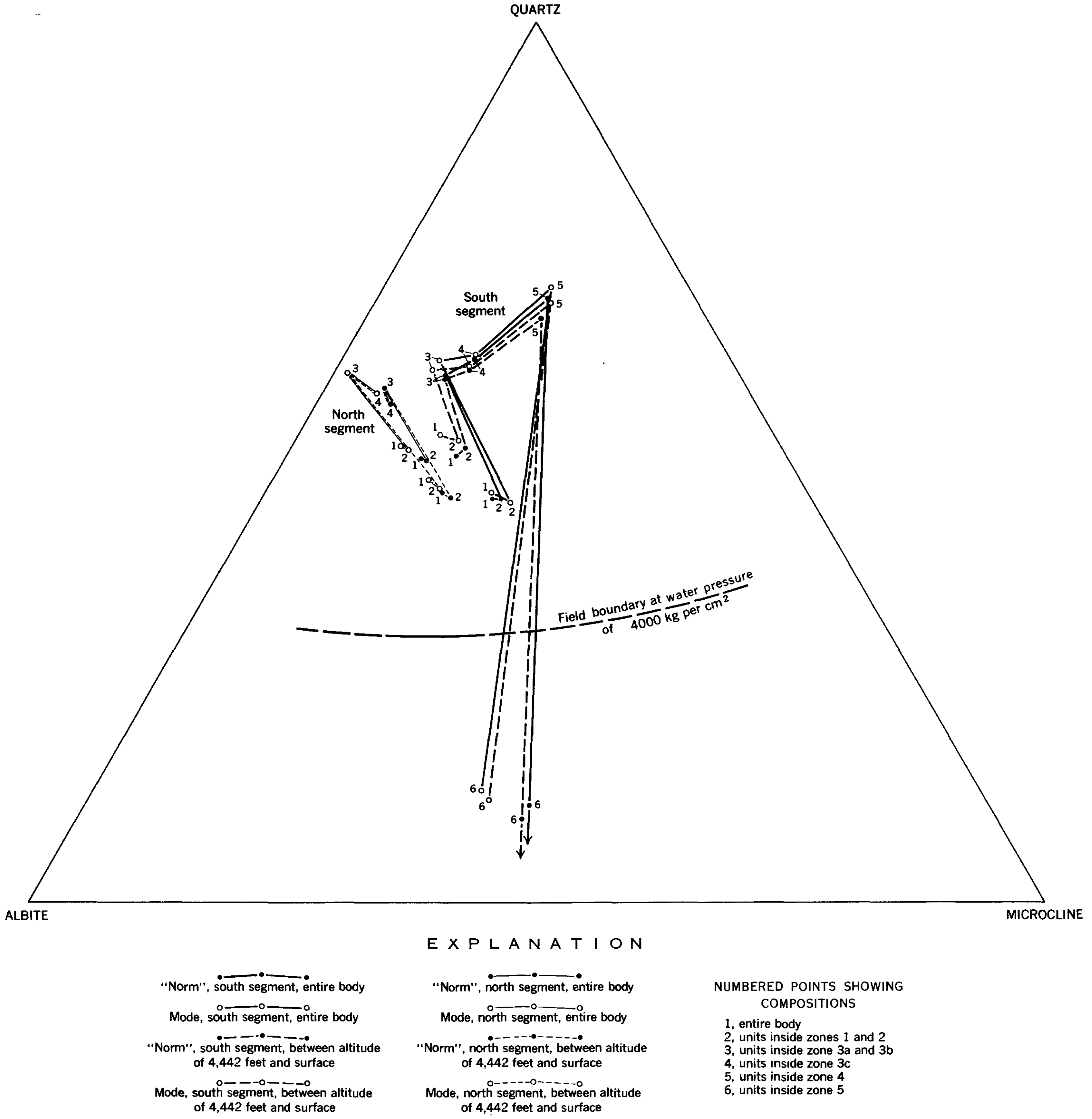

Figure 70.—Quartz-albite-microcline diagram showing the course of crystallization of the two segments of the Hugo pegmatite. The modes were obtained from data in plate 12. In zone 3, 80 percent of the perthite was assigned to microcline, and 20 percent was assigned to albite. The "norms" were obtained from plate 11 by calculating all Na_2O as albite, all K_2O as microcline, and all unused SiO_2 as quartz. The field boundary is from Tuttle and Bowen (1958, fig. 38).

large quantities of these materials from one segment to the other during crystallization, especially after the solidification of outer zones and the formation of a barrier of solid rock between the two segments.

The conclusion seems inescapable that this separation took place in the fluid before crystallization began. Wahl (1946) has argued that thermal diffusion accompanied by convection may be a cause of differentiation in a magma. Kennedy (1955, especially p. 497) has shown that volatiles coordinated with other materials should concentrate in the upper part of a magma chamber, and Bowen (1933, p. 123) pointed out that potassium forms more volatile compounds than sodium does. Thus it may be supposed that potassium was carried upward in association with volatiles, and sodium was left behind. A review of the literature suggests no other likely mechanism for separating one alkali from another, though one may well exist.

In spite of the differences in alkalies, figure 70 shows that the courses of crystallization in the north segment and the outer zones of the south segment are nearly parallel. From points 1 to 2, albite was the only feldspar to crystallize, and although some K_2O went into muscovite, the liquid was enriched with respect to $KAlSi_3O_8$. From points 2 to 3 the liquid is enriched in SiO_2, depleted in $KAlSi_3O_8$, and remains virtually the same in its content of $NaAlSi_3O_8$. From points 3 to 5 in the south segment the enrichment in SiO_2 continues, and the liquid is also enriched in $KAlSi_3O_8$ and depleted in $NaAlSi_3O_8$. The north segment, from points 3 to 4, is enriched in $KAlSi_3O_8$ as quartz and albite go into zone 3c.

At point 5 in figure 70 only the small quantity of material in zones 5 to 7 and the introduced constituents of the replacement bodies have yet to crystallize. After point 5, however, SiO_2 is greatly depleted as it is used in abundance to form quartz-rich pegmatite of zones 5 and 6. The remaining material, which appears in zone 7 and the replacement units, is too deficient in silica to be plotted on a quartz-feldspar diagram.

The variation diagrams in plates 11 and 12 show the same general trends. They indicate that during crystallization of outer zones the fluid was continuously impoverished in Na_2O, K_2O, and Al_2O_3, and enriched in SiO_2, P_2O_5, and Li_2O; then in inner units these trends are reversed.

The Hugo pegmatite consists mainly of quartz, albite, and microcline, and if the modal mica is converted to normative feldspar only about 6 percent of the material in the pegmatite remains to be accounted for in other minerals. Although these other constituents doubtless introduce unknown complications, the chemical behavior of the natural system can be discussed in the light of laboratory data for the system quartz-albite-orthoclase-water. The field boundary between quartz and feldspar in this system is shown on figure 70, as determined by Tuttle and Bowen (1958, fig. 38), at a water pressure of 4,000 kg per sq cm. This pressure is the highest at which Tuttle and Bowen determined the field boundary, and it is the lowest pressure at which two feldspars and low quartz formed together in equilibrium. In natural systems the position of the field boundary would vary with changes in pressure and composition.

Both quartz and feldspar crystallized in zone 1 of the Hugo pegmatite; thus the fluid must have been on the field boundary at the very start. This is to be expected if the pegmatite is a residual product of a granitic magma. At the beginning of crystallization, from point 1 to point 2 in figure 70, albite was the only feldspar to form, and the composition must have been to the left of the feldspar solvus. At point 2, however, coexisting microcline began to be precipitated, implying that this point is on the feldspar solvus.

This is at best a simplified way of describing circumstances that undoubtedly were much more complicated. The evidence that the fluid in the upper part of the chamber was enriched in K_2O and gave rise to two feldspars in zones 3a and b, and that the fluid lower down was enriched in Na_2O and yielded albite as the only feldspar in zone 3c, indicates that the course of crystallization must have been slightly different at the upper and lower levels. At the top of the pegmatite the fluid reached the solvus at a very early stage, and two feldspars were able to crystallize simultaneously; at the bottom, however, the fluid did not reach the solvus until zone 4 began to crystallize.

The high SiO_2 content at the outset of crystallization and the progressive enrichment in SiO_2 from points 2 to 5 raise difficult problems. Inasmuch as quartz and the two feldspars crystallized simultaneously, the composition of the liquid must at virtually all times have been on the field boundary and within the two-feldspar region at the temperatures and pressures prevailing during crystallization. This circumstance leads readily to the inference that during crystallization the field boundary shifted from point 2 to point 5, presumably in response to increasing volatile pressure. On the other hand, the composition indicated for the Hugo pegmatite in figure 70 is much nearer the quartz apex of the diagram than is the field boundary in the laboratory system, and furthermore, the trend toward the quartz apex shown by points 2 to 5 is the opposite of the trend found at high pressure in the laboratory. Tuttle and Bowen (1958, fig. 20) found that the field boundary shifts toward SiO_2 at H_2O pressures ranging from 0 to about 350 kg per sq cm, and shifts away from SiO_2 at the higher pressures that may be expected in deep-seated intrusives.

Probably any attempt made here to explain the silica-rich nature of the Hugo pegmatite would be premature. Future laboratory studies of systems containing quartz, low albite, and microcline, together with muscovite, lithium minerals, and the other constituents of the pegmatite, may show that the crystallizing liquid is rich in SiO_2, and that it shifts toward higher SiO_2 as the gas pressure increases and the crystallization temperature decreases. An uncertainty that may be pertinent to this discussion is how excess Al_2O_3 affects the course of crystallization. It surely was important in this pegmatite, because it gave rise to a significant quantity of muscovite, but its effect on the quartz-feldspar field boundary has yet to be determined in the laboratory. Another uncertainty, in discussing the discrepancy between the quartz-feldspar field boundary and the actual composition of the pegmatite, is whether a gas rich in SiO_2 is likely to have been involved. Any suggestion to this effect would, however, be difficult to reconcile with evidence from the composition of the replacement units, which indicates that the gas is likely to be rich in alkalies and Al_2O_3, but not in SiO_2.

In this account of the course of crystallization it has been assumed for the sake of simplicity that all the minerals in any single zone formed simultaneously, and that crystallized pegmatite and liquid were not separated by a significant thickness of material consisting of a meshwork of crystals and interstitial liquid. Evidence from the paragenetic studies indicates that this is not so. Spodumene in zone 5, for example, crystallized before the minerals in contact with it, and when any single spodumene crystal formed, the quartz and feldspar that were precipitated at the same time may have been some distance away, perhaps in zone 4 or even zone 3.

The crystal meshwork probably contained many isolated bodies of liquid, and these bodies probably did not have exactly the same composition at all times, nor is it likely that they were under exactly the same physical conditions as the main body of liquid. Inhomogenities developed in this way, perhaps accompanied by local trapping of coexisting gas, may explain the irregularities in the distribution of certain minerals. Muscovite-rich and phosphate-rich aggregates in parts of zone 3 may be in places where water and phosphorus were concentrated locally by this means. Small deviations from the field boundary in the quartz-feldspar system may have caused quartz or feldspar to stop crystallizing for a short time.

Such local differences in composition or physical conditions would also cause crystallized material to be out of equilibrium with the fluid, and thus be partly responsible for the textures indicating corrosion of some minerals. Yet the main cause probably was normal reaction between crystals and liquid as the liquid changed composition during crystallization. Such a mineral as the potassic feldspar that was the parent of perthite in zone 3 was not immune to alteration shortly after it crystallized. Progressive changes in the composition of the fluid as crystallization proceeded should be accompanied by reaction with previously formed crystals to maintain equilibrium (compare with the discussion by Tuttle and Bowen, 1958, p. 66–67). It is expectable, rather than "troublesome" (Jahns, 1955, p. 1097), that this mineral could be precipitated during most of the time that the pegmatite was crystallizing, and yet simultaneously the crystals previously formed could be corroded by the residual fluid.

Crystallization of the inner units, accompanied as it was by the crystallization of the replacement bodies from an apparently hydrous fluid, requires a more complex process than the earlier stages. Laboratory data are as yet inadequate for more than a cursory discussion of the chemistry of these late stages. Tuttle and Bowen (1958, p. 84–89) have shown that, in granites containing an excess of alkalies over the alumina required for feldspar, there can be a continuous gradation from magma to hydrothermal solution. In the simple laboratory systems this does not apply where alumina is in excess, as in mica-bearing rocks such as the Hugo pegmatite, but Tuttle and Bowen (1958, p. 89) state that a continuous gradation may still be possible in natural systems containing Li_2O, fluorine, and other volatile constituents.

A continuous gradation of this sort in the Hugo pegmatite seems very unlikely. The very great contrast between zones 5 and 6, which are rich in SiO_2, and zone 7 and the replacement bodies, which are rich in alkalies and Al_2O_3, is evidence that these are derived from two separate fluids of markedly different composition. The ability of the replacing material to penetrate solid rock suggests that it had many of the properties of a gas. The alkali-rich units contain appreciable quantities of H_2O and fluorine, which presumably were the main volatile constituents. Any conclusion regarding the nature of the fluid from which the other units formed must account for the fact that the crystalline products are abnormally rich in SiO_2—86.6 percent in zone 5 and 87.0 percent in zone 6.

To explain the high SiO_2 content, Jahns (1955, p. 1094; 1956) has proposed resurgent boiling in which the alkalies (and presumably Al_2O_3) entered the vapor phase and SiO_2 was the chief constituent remaining. If H_2O was the chief constituent of the escaping material, the critical pressure would be far too low to permit boiling or even the existence of a vapor phase. Thus it must be assumed that Jahns believes the H_2O-rich phase had such a high content of dissolved material that its critical pressure was raised to a high value. A complete description of this proposal, however, has yet to be published.

Another mechanism is available that might have the same effect, but would not require a high critical pressure for the watery fluid. While the relatively dry outer zones were crystallizing, the rest liquid must have been progressively enriched in H_2O. When the H_2O content reached the maximum possible, which according to Goranson (1931) is not more than 10 percent, a phase rich in H_2O would separate, and the dissolved materials would then be divided between this phase and the silicate rest liquid.

Whether this H_2O rich phase moves outward or deposits its crystalline products in the center of the pegmatite depends on the relation of the vapor pressure to the total pressure. Throughout the period of crystallization of the pegmatite the vapor pressure must have been nearly as great as the total pressure, because a high vapor pressure, not just pressure alone, is required to depress the liquidus to the low temperatures indicated for this pegmatite (compare with Tuttle and Bowen, 1952, p. 38). The escape of this fluid to form replacement units extending into the outer part of the pegmatite suggests that the vapor pressure increased until it exceeded the external pressure. Similar fluids, entering the wallrocks of other Black Hills pegmatites, may also have produced such effects as the microline porphyroblasts in schist and the alteration of sillimanite and staurolite to mica and other minerals.

The field evidence is in accord with this means of removing alkalies and Al_2O_3 from the residual fluid and leaving a silica-rich material that crystallized mainly as quartz. Unfortunately, the laboratory evidence regarding behavior in the end stages of pegmatite processes can be summed up by quoting Tuttle and Bowen (1958, p. 35), who say in reference to work on the SiO_2–H_2O system that as yet "it is futile to attempt to * * * apply the results" to "the quartz cores of pegmatites." Tuttle and Bowen (1958, p. 89–91) presented results indicating that the vapor is richer than the liquid in SiO_2, whereas the contrary seems to have been true in the Hugo pegmatite. Yoder and others (1957, p. 208) found in their study of the system albite-orthoclase-water at 5,000 bars pressure that the gas phase probably contains "about 1 to 2 percent of the feldspar components."

The small size of zone 7 and the replacement units indicates that the separation of the alkali-rich and silica-rich fluids was a relatively minor event in the history of this pegmatite. The geology of this pegmatite does not support the statement by Jahns (1955, p. 1097), in regard to pegmatites in general, that "many impressive aggregates of replacement material * * * seem much better attributed to the activities of condensed vapors formed by resurgent boiling of rest-liquid." The structures and textures of the Hugo zones require no great quantity of replacement, and pegmatites observed by the authors elsewhere are similar in this respect. Furthermore, it is hard to identify just which minerals of the zones would be the replacement materials of Jahn's proposal. Nearly all the minerals of the zones corrode or embay other minerals, and there is no clear way to distinguish two suites of minerals formed separately, as there is in the replacement units.

Replacement bodies are not prominent elsewhere in the Black Hills, but pegmatites that have quartz-rich inner zones also have irregularly distributed aggregates containing muscovite or albite that may be a product of an alkali-rich fluid. Page and others (1953, p. 15) described muscovite-rich aggregates as of possible replacement origin. Although such units may account for the subtraction of material from the rest liquid so that quartz cores can form, they do not interfere significantly with the major elements of the zonal structure.

ORIGIN

During early geologic work in the Keystone district the pegmatites were generally considered to be of intrusive magmatic origin. Many early writers seemed to think the subject scarcely warranted discussion (Paige, 1925, p. 4–5).

Ziegler (1914c, p. 275) may have digressed from prevailing opinion when he attributed the formation of amblygonite to solutions that entered the pegmatite after solidification. Otherwise, Ziegler's writings regarding genesis (1913, p. 1056; 1914c) were designed primarily to support his opinion that the pegmatites are gradational between the so-called Harney Peak granite and quartz veins; in a list of minerals (1914b, p. 604–605) he indicated that all the prominent minerals of pegmatites are primary. Ziegler's statement regarding amblygonite, although since quoted to support other arguments (Landes, 1928, p. 538), was meant to show that his pegmatitic phase can be subdivided into an older mica-spodumene type and a younger amblygonite type, and that these are steps in a gradational sequence from granite to quartz veins.

Since 1925, those who have studied Keystone pegmatites have arrived at conclusions regarding genesis that can be divided into three categories:

1. Crystallization of a magmalike fluid in a restricted system. This fluid may give rise to hydrothermal or pneumatolytic solutions that cause a relatively minor amount of replacement of previously crystallized pegmatite (Page and others, 1953, p. 17–24; Sheridan and others, 1957, p. 18–21).
2. Crystallization in two or more stages, of which the first was magmatic and the others hydrothermal. Replacement is of major quantitative importance. The hydrothermal fluids were from one or more sources outside the pegmatite (Hess, 1925) or within the pegmatite (Landes, 1928).
3. Metasomatic replacement of metamorphic rocks (Higazy, 1949).

The evidence described in previous pages indicates that the Hugo pegmatite was formed by the injection and crystallization of an essentially magmatic fluid consisting chiefly of SiO_2, Al_2O_3, Na_2O, and K_2O. It contained much less CaO, iron oxides, and MgO than the common magmatic rocks. On the other hand, it was enriched in P_2O_5, Li_2O, H_2O, fluorine, B_2O_3, BeO, and SnO_2.

Crystallization proceeded systematically from the contact inward such that a series of zones was formed that corresponds with the sequence observed in many other pegmatites. Temperatures were probably less than 650°C even in the early stages of crystallization, and may have been as low as 300°C in zone 7. Chemical and physical characteristics of the minerals changed progressively from the outer to the inner units.

Throughout most of the time that the pegmatite was crystallizing, the fluid was enriched in SiO_2 and depleted in Al_2O_3, Na_2O, and K_2O. The final expression of this trend was the crystallization of the quartz-rich pegmatite of zones 5 and 6.

At a late stage a fluid rich in volatiles, Al_2O_3, Na_2O, and K_2O separated from the silica-rich liquid. This fluid escaped outward to form replacement bodies that cut across outer zones.

INDUSTRIAL MINERALS

Potash feldspar has been the principal product of the Hugo mine, and a large part of the original reserves have been extracted. Concentrations of scrap mica and beryl in zone 2 have been recently mined, and may be more important in the future. Spodumene and amblygonite have been obtained from zone 5. The other industrial minerals of the pegmatite shown in table 19 are important only as possible byproducts.

All these minerals are in the dumps as well as in unmined rock. Probably at least 150,000 tons of rock could be mined from the dumps as of 1946. In the future this material may be reworked for its content of potash and soda feldspar, scrap mica, beryl, amblygonite, and other minerals.

POTASH FELDSPAR

All but a small proportion of the potash feldspar has been mined from the hood-shaped units of zones 3 a and 3b at the top of the pegmatite. A significant quantity has also been extracted from zones 5 and 6, and some from zone 4 and the replacement units. An estimated 420,000 tons of rock were mined to produce 193,000 tons (46 percent) of potash feldspar.

The potash feldspar ranges from the highly perthitic material of zone 3 to the nonperthitic microcline of zone 6. At the time the mine was mapped, crystals between 5 and 20 feet long contained most of the exposed potash feldspar. Although much of the potash feldspar, especially in zone 3, is intergrown with quartz, albite, and muscovite, very little of it is contaminated by tourmaline.

SCRAP MICA AND BERYL

Scrap mica and beryl are abundant in zone 2 along the footwall of the south segment. They also occur in other units (table 19), and small quantities can be recovered as byproducts in mining of potash feldspar.

The mica of zone 2 is dominantly medium to very coarse grained, and thus can be recovered readily by hand-cobbing. It is a light-ruby color, heavily air stained, very soft, and contains many inclusions of tourmaline and other minerals. Herringbone structure is so abundant that only a very small proportion of sheet mica can be recovered, and because the quality is also low, the chief value of this muscovite has been as scrap mica.

Most of the beryl of zone 2 is sufficiently coarse grained for hand-cobbing. It is largely subhedral to euhedral in form and breaks freely from the surrounding rock. The index of refraction of the ordinary ray of beryl from zone 2 in the south segment ranges from 1.583 to 1.588, indicating a content of 12.2 to 12.8 percent BeO according to a graph by W. T. Schaller and R. E. Stevens (in Norton and others, 1958, fig. 1).

LITHIUM MINERALS

Spodumene and amblygonite have both been mined from zone 5, where they occur as very coarse crystals that are readily concentrated by hand-cobbing. Amblygonite in zone 4 has a relatively small grain size, and not much of it has been recovered. The tonnage produced and the reserves of lithium minerals are small in comparison with major lithium mines, and the Hugo is not of great importance as a source of lithium.

The spodumene is partly altered by micaceous and clay minerals, and much of it is so friable that it breaks easily in the hand. Three samples have been analyzed by Charles Bentley, Engineering and Mining Experiment Station, South Dakota School of Mines and Technology:[5]

	Percent Li_2O
Hard spodumene	5.84
Highly friable spodumene	5.26
Spodumene of intermediate friability	5.62

Amblygonite in zone 5 occurs as large nodular aggregates and rounded crystals, some weighing tens or

---

[5] The first two samples were collected by W. C. Stoll, U.S. Geological Survey.

even hundreds of tons. Most of the mining was prior to World War II, but some amblygonite has been extracted recently.

The lithia mica of zone 7 and the replacement units resembles lepidolite in many respects, but the content of lithium is too low to be accepted in available markets.

OTHER MINERALS

Cassiterite is an abundant accessory constituent of zone 7 and the replacement units, but the total tonnage is too small to be considered as a significant source of tin. Tantalite-columbite occurs with the tin in these units and also occurs in other units, but no rich concentrations were observed.

REFERENCES CITED

Adamson, O. J., 1942, Minerals of the Varuträsk pegmatite. [Part 21], The feldspar group: Geol. Fören. Stockholm, Förh., v. 64, p. 19–54.

Barth, T. F. W., 1956, Studies in gneiss and granite. [Part 1], Relations between temperature and the composition of the feldspars: Skr. Norske Vidensk.-Akad. Mat.-Naturv. Klasse 1956, p. 1–16.

Bastin, E. S., Graton, L. C., Lindgren, Waldemar, Newhouse, W. H., Schwartz, G. M., and Short, M. N., 1931, Criteria of age relations of minerals, with especial reference to polished sections of ores: Econ. Geology, v. 26, p. 561–610.

Bowen, N. L., 1928, The evolution of the igneous rocks: Princeton, N.J., Princeton Univ. Press, 322 p.

——— 1933, The broader story of magmatic differentiation, briefly told, *in* Ore deposits of the Western States (Lindgren volume): New York, Am. Inst. Mining Metall. Engineers, p. 106–128.

Bowen, N. L., and Tuttle, O. F., 1950, The system $NaAlSi_3O_8$–$KAlSi_3O_8$–H_2O: Jour. Geology, v. 58, p. 489–511.

Brush, G. J., and Dana, E. S., 1880, On the mineral locality at Branchville, Connecticut, [Fourth paper], Spodumene and the results of its alteration: Am. Jour. Sci., 3d ser., v. 20, p. 257–285.

Cameron, E. N., Jahns, R. H., McNair, A. H., and Page, L. R., 1949, Internal structure of granitic pegmatites: Econ. Geology Mon. 2, 115 p.

Cameron, E. N., and others. 1954, Pegmatite investigations 1942–45, in New England: U.S. Geol. Survey Prof. Paper 255, 352 p.

Chayes, Felix, 1952, Relations between composition and indices of refraction in natural plagioclase: Am. Jour. Sci., [Bowen volume] p. 85–105.

——— 1954, A test of the revised determinative chart for plagioclase: Am. Jour. Sci., v. 252, p. 172–180.

Connolly, J. P., and O'Harra, C. C., 1929, The mineral wealth of the Black Hills: South Dakota School Mines Bull. 16, 418 p.

Davidson, D. M., Grout, F. F., and Schwartz, G. M., 1946, Notes on the ilmenite deposit at Piney River, Virginia: Econ. Geology, v. 41, p. 738–748.

Davies, J. F., 1957, Geology of the Winnipeg River area (Shatford Lake–Ryerson Lake), Lac du Bonnet Mining Division, Manitoba: Manitoba Dept. Mines and Natural Resources, Mines Branch, Pub. 56–1.

Emmons, R. C., ed., and others, 1953, Selected petrogenic relationships of plagioclase: Geol. Soc. America Mem. 52, 142 p.

Eugster, H. P., and Yoder, H. S., Jr., 1955, The joint muscovite-paragonite, *in* Abelson, P. H., Annual report of the Director of the Geophysical Laboratory: Carnegie Institution of Washington Yearbook 54, 1954–55, p. 124–126.

Goranson, R. W., 1931, The solubility of water in granite magmas: Am. Jour. Sci., 5th ser., v. 22, p. 481–502.

Grootemaat, T. B., and Holland, H. D., 1955, Sodium and potassium content of muscovites from the Peerless pegmatite, Black Hills, South Dakota [abs.]: Geol. Soc. America Bull., v. 66, p. 1569.

Guiteras, J. R., 1940, Mining of feldspar and associated minerals in the southern Black Hills of South Dakota: U.S. Bur. Mines Inf. Circ. 711.

Hanley, J. B., Heinrich, E. W., and Page, L. R., 1950, Pegmatite investigations in Colorado, Wyoming, and Utah, 1942–44: U.S. Geol. Survey Prof. Paper 227, 125 p.

Heinrich, E. W., 1948, Pegmatites of Eight Mile Park, Fremont County, Colorado: Am. Mineralogist, v. 33, p. 420–448, 550–587.

Hess, F. L., 1911, Lithium, *in* Mineral resources of the United States, 1909: Washington, U.S. Geol. Survey, pt. 2, p. 649–653.

——— 1925, The natural history of the pegmatites: Eng. & Mining Jour.-Press, v. 120, p. 289–298.

Higazy, R. A., 1949, Petrogenesis of perthite pegmatites in the Black Hills, South Dakota: Jour. Geology, v. 57, p. 555–581.

——— 1953, Observations on the distribution of trace elements in the perthite pegmatites of the Black Hills, South Dakota: Am. Mineralogist, v. 38, p. 172–190.

Jahns, R. H., 1946, Mica deposits of the Petaca district, Rio Arriba County, New Mexico: New Mexico Bur. Mines and Mineral Res. Bull. 25, 289 p.

——— 1953, The genesis of pegmatites: Am. Mineralogist, v. 38, p. 563–598, 1078–1112.

——— 1955, The study of pegmatites, *in* Bateman, A. M., ed., Fiftieth anniversary volume, Part 2: Econ. Geology, p. 1025–1130.

——— 1956, Resurgent boiling and the formation of magmatic pegmatites [abs.]: Geol. Soc. America Bull., v. 67, p. 1772.

Jahns, R. H., and others, 1952, Mica deposits of the southeastern Piedmont, Part 1, General features: U.S. Geol. Survey Prof. Paper 248–A, p. 1–101.

Johnston, W. D., Jr., 1945, Beryl-tantalite pegmatites of northeastern Brazil: Geol. Soc. America Bull., v. 56, p. 1015–1069.

Keith, M. L., and Tuttle, O. F., 1952, Significance of variation in the high-low inversion of quartz: Am. Jour. Sci., [Bowen volume], p. 203–280.

Kennedy, G. C., 1950, "Pneumatolysis" and the liquid inclusion method of geologic thermometry: Econ. Geology, v. 45, p. 533–547.

——— 1955, Some aspects of the role of water in rock melts, *in* Poldervaart, Arie, ed., Crust of the earth—a symposium: Geol. Soc. America Special Paper 62, p. 489–503.

Landes, K. K., 1925, The paragenesis of the granite pegmatites of central Maine: Am. Mineralogist, v. 10, p. 353–411.

——— 1928, Sequence of mineralization in the Keystone, South Dakota, pegmatites: Am. Mineralogist, v. 13, p. 519–530, 537–558.

——— 1932, The Baringer Hill, Texas, pegmatite: Am. Mineralogist, v. 17, p. 381–390.

Mason, Brian, 1942, Some iron-manganese phosphate minerals from the pegmatite at Hühnerkobel in Bavaria: Geol. Fören. Stockholm, Förh, v. 64, p. 335–340.

Middleton, Jefferson, 1927, Feldspar, *in* Mineral resources of the United States, 1924: Washington, U.S. Geol. Survey, pt. 2, p. 19–25.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. America Bull., v. 65, p. 1007–1032.

Norton, J. J., Griffitts, W. R., and Wilmarth, V. R., 1958, Geology and resources of beryllium in the United States, *in* United Nations, Survey of raw material resources: Internat. Conf. Peaceful Uses Atomic Energy, 2d, Geneva, 1958, Proc., v. 2, p. 21–34.

Page, L. R., 1950, Uranium in pegmatites: Econ. Geology, v. 45, p. 12–34.

Page, L. R., and others, 1953, Pegmatite investigations 1942–45, Black Hills, South Dakota: U.S. Geol. Survey Prof. Paper 247, 229 p.

Paige, Sidney, 1925, Pre-Cambrian rocks, *in* Darton, N. H., and Paige, Sidney, Central Black Hills, South Dakota: U.S. Geol. Survey Geol. Atlas, Folio 219, p. 3–5.

Quensel, Percy, 1952, The paragenesis of the Varuträsk pegmatite: Geol. Mag., v. 89, p. 49–60.

Ramberg, Hans, 1956, Pegmatites in west Greenland: Geol. Soc. America Bull., v. 67, p. 185–213.

Roy, Rustum, Roy, D. M., and Osborn, E. F., 1950, Compositional and stability relationships among the lithium aluminosilicates: eucryptite, spodumene, and petalite: Am. Ceramic Soc. Jour., v. 33, p. 152–159.

Runner, J. J., and Hamilton, R. G., 1934, Metamorphosed calcareous concretions and their genetic and structural significance: Am. Jour. Sci., 5th ser., v. 28, p. 51–64.

Schaefer, V. J., 1946, The production of ice crystals in a cloud of supercooled water droplets: Science, v. 104, p. 457–459.

Schaller, W. T., 1911, Mineralogical notes, series 1: U.S. Geological Survey Bull. 490, 109 p.

——— 1925, The genesis of lithium pegmatites: Am. Jour. Sci., 5th ser., v. 10, p. 269–279.

Schwartz, G. M., 1925, Geology of the Etta spodumene mine, Black Hills, South Dakota: Econ. Geology, v. 20, p. 646–659.

——— 1928, The Black Hills mineral region: Am. Mineralogist, v. 13, p. 56–63.

Schwartz, G. M., and Leonard, R. J., 1926, Alteration of spodumene in the Etta mine, Black Hills, S. Dak.: Am. Jour. Sci., 5th ser., v. 11, p. 257–264.

Shaub, B. M., 1937, Contemporaneous crystallization of beryl and albite vs. replacement: Am. Mineralogist, v. 22, p. 1045–1051.

Sheridan, D. M., 1955, Geology of the High Climb pegmatite, Custer County, South Dakota: U.S. Geol. Survey Bull. 1015–C, p. 59–98.

Sheridan, D. M., Stephens, H. G., Staatz, M. H., and Norton, J. J., 1957, Geology and beryl deposits of the Peerless pegmatite, Pennington County, South Dakota: U.S. Geol. Survey Prof. Paper 297–A, p. 1–47.

Staatz, M. H., and Trites, A. F., Jr., 1955, Geology of the Quartz Creek pegmatite district, Gunnison County, Colorado: U.S. Geol. Survey Prof. Paper 265, 111 p.

Tuttle, O. F., and Bowen, N. L., 1952, The system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2, *in* Adams, L. H., Annual report of the Director of the Geophysical Laboratory: Carnegie Institution of Washington Yearbook 51, 1951–52, p. 37–41.

——— 1958, Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O: Geol. Soc. America Mem. 74, 153 p.

Tuttle, O. F., and Wyllie, P. J., 1957, Hydrothermal studies in the systems $NaAlSi_3O_8$ (albite)–H_2O–HF and granite–H_2O–HF [abs.]: Geol. Soc. America Bull., v. 68, p. 1807.

Vlassov, K. A., 1955, Les différenciations par émanation et par cristallisation comme facteurs de concentration des éléments rare: Colloque Int. Pétrog.

Wahl, Walter, 1946, Thermal diffusion—convection as a cause of magmatic differentiation, [Part 1]: Am. Jour. Sci., v. 244, p. 417–441.

Weis, P. L., 1953, Fluid inclusions in minerals from zoned pegmatites of the Black Hills, South Dakota: Am. Mineralogist, v. 38, p. 671–697.

Winchell, A. N., and Winchell, Horace, 1951, Elements of Optical mineralogy—an introduction to microscopic petrography, Part 2, Descriptions of minerals: 4th ed., New York, John Wiley & Sons., 551 p.

Yoder, H. S., Jr., and Eugster, H. P., 1955, Synthetic and natural muscovites: Geochim. et Cosmochim. Acta, v. 8, p. 225–280.

Yoder, H. S., Jr., Stewart, D. B., and Smith, J. R., 1957, Ternary feldspars, *in* Abelson, P. H., Annual report of the Director of the Geophysical Laboratory: Carnegie Institution of Washington Yearbook 56, 1956–57, p. 206–214.

Ziegler, Victor, 1913, Lithia deposits of the Black Hills: Eng. and Mining Jour., v. 96, p. 1053–1056.

———1914a, The minerals of the Black Hills: South Dakota School Mines Bull. 10, 250 p.

———1914b, The mineral resources of the Harney Peak pegmatites: Min. and Sci. Press, v. 108, p. 604–608, 654–656.

——— 1914c, The differentiation of a granitic magma as shown by the paragenesis of the minerals of the Harney Peak region, S. Dak.: Econ. Geology, v. 9, p. 264–277.

INDEX