Beryl Deposits of the Beecher No. 3-Black Diamond Pegmatite Custer County South Dakota

GEOLOGICAL SURVEY BULLETIN 1072-I

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By JACK A. REDDEN

CONTRIBUTIONS TO ECONOMIC GEOLOGY

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A study of a beryl deposit in pegmatite of the Black Hills, South Dakota

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By Jack A. Redden

ABSTRACT

The Beecher No. 3-Black Diamond pegmatite, near Custer, S. Dak., is one of the most important sources of beryl in the United States. The presence of abundant beryl was discovered in 1952, and 342 tons of beryl concentrates was produced from this deposit between 1952 and 1956.

The pegmatite is exposed in an elongate northward-trending area that is 1,750 feet long and a maximum of 160 feet wide. It forms a roughly pipelike mass that plunges gently southward and has on its crest many longitudinal ridges, or rolls, that plunge both northward and southward. The south end of the pegmatite is formed of two coalescing segments believed to have been injected at slightly different times.

The pegmatite can be subdivided into at least 5 zones and is cut by 2 kinds of fracture-filling units. The zones, numbered in order of position inward from the periphery, are constituted as follows: (1) quartz-muscovite-albite pegmatite (border zone), (2) albite-quartz-muscovite pegmatite (wall zone), (3) quartz-albite-muscovite-perthite-beryl pegmatite, (4) perthite-quartz-albite pegmatite, (5) perthite-quartz pegmatite. The fracture-filling materials are quartz-spodumene pegmatite and quartz pegmatite. An additional spodumene-rich zone was exposed by deeper mining after completion of the detailed investigation.

The pegmatite is believed to have been intruded as a mass of pegmatitic magma, which crystallized inward by progressive fractionation.

The pegmatite contains deposits of spodumene as well as beryl and could also yield a large amount of scrap mica as a byproduct. The main beryl deposit, containing 5 to 10 percent hand-cobbable beryl, is in zone 3; it occurs only in 1 roll on the crest of the pegmatite and along the contact between the 2 coalescing segments. Large reserves of finer grained beryl occur in the wall zone. The spodumene exposed by deeper mining is believed to occur in a zone that is still largely concealed and thus of unknown dimensions. Additional exploration for both beryl and spodumene is warranted.

INTRODUCTION

In June 1952 exposures of beryl-rich pegmatite were discovered on the Beecher No. 3 claim, about 4½ miles south of Custer, Custer County, S. Dak. (fig. 21). This is in an area known for its deposits

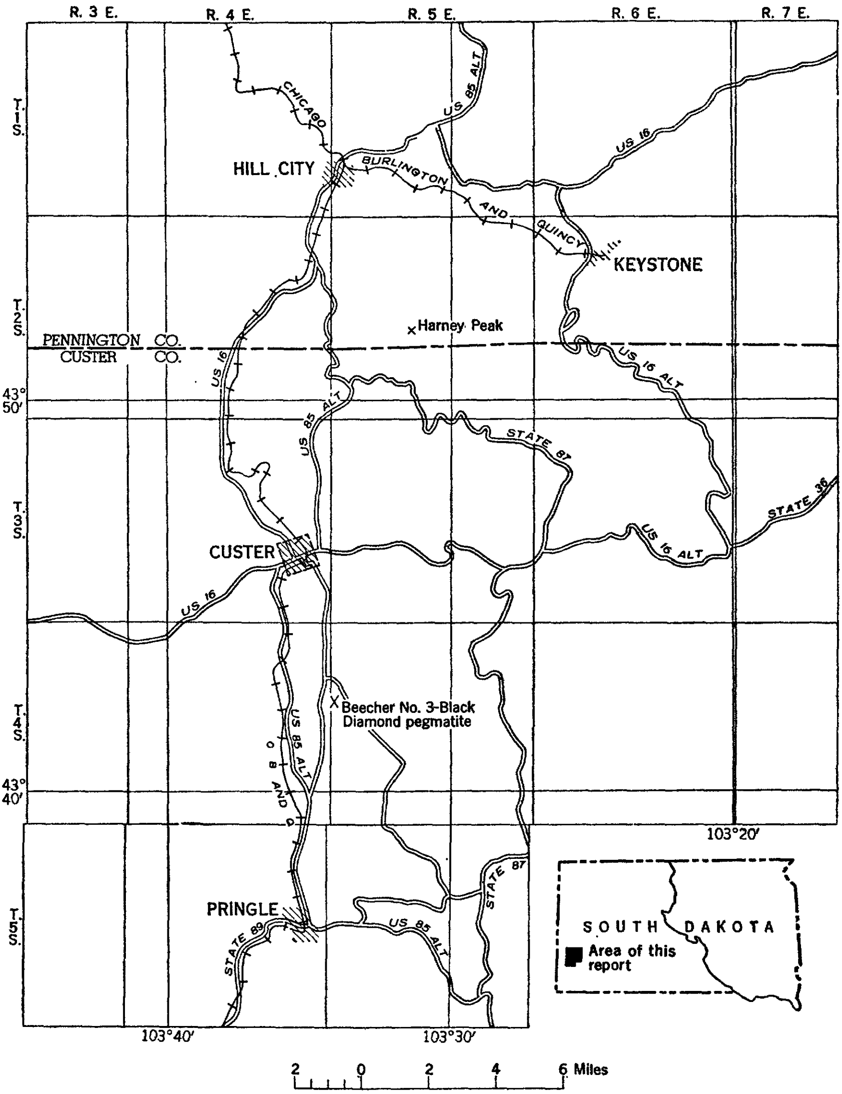

FIGURE 21.—Index map showing location of Beecher No. 3-Black Diamond pegmatite, Custer County, S. Dak.

of pegmatite minerals in the southern Black Hills. The exposed beryl was so heavily stained that it had not previously been recognized. During subsequent prospecting and mining, 342 tons of beryl concentrates was produced. The results of geologic investigation and mapping of this deposit suggest that it contains large reserves of beryl and possibly also of lithium minerals.

The pegmatite is in sec. 13, T. 4 S., R. 4 E. and sec. 18, R. 5 E. The part in sec. 13 is on the Widensee ranch homestead. The Black Diamond claim covers most of the pegmatite in sec. 18; the Beecher No. 3 claim, also in sec. 18, covers the south end of the pegmatite and includes the principal exposed beryl deposit.

The pegmatite was mapped by telescopic-alidade and planetable methods in the fall of 1952 and spring of 1953 by the author, with the assistance of Robert Lawthers and R. E. Roadifer.

Permission was given by George V. and George C. Bland to publish data on production from the Beecher No. 3 claim and information concerning their mining operations, and by Fremont F. Clarke of the Lithium Corp. of America for permission to publish production data on the Black Diamond claim.

HISTORY

The Black Diamond claim was located on January 4, 1922, by Edgar and Frank Sutherland; and Spencer, Floyd, and W. R. Bond. The small prospect pits in the central and southern parts of the pegmatite mass (pl. 17) were probably opened shortly thereafter in exploration primarily for spodumene, and no further prospecting was done on this pegmatite until 1949. Beryl was abundant in the old pit between sections *I–I′* and *J–J′* (pl. 17), but either was not recognized or was neglected because beryl had little value at that time. In 1950 the Black Diamond claim was purchased by the Lithium Corporation of America, largely because part of the claim extends over the south end of the Beecher No. 2 pegmatite, which has a high spodumene content.

In 1949 G. V. and G. C. Bland filed the Beecher No. 3 claim. Shortly thereafter they excavated the easternmost opencut (shown in section *K–K′*, pl. 17) and enlarged previous cuts. They apparently did some work in a short drift on the south end of the pegmatite (pl. 17), but this drift may have been started at an earlier date. After the discovery of beryl in 1952, the Blands excavated the opencut shown in cross sections *M–M′* and *L–L′* (pl. 17). The mine was operated continuously during the second half of 1952 and all of 1953, but operations were curtailed in 1954, and in 1955 they were virtually ended. The curtailment of mining was brought about partly because of the increased depth of the opencut, and partly because of difficulty in keeping the grade of the beryl concentrates above 8 percent BeO, the minimum required for sale to the U.S. General Services Administration purchasing depot in Custer, S. Dak.

After the pegmatite was mapped in 1953, the northward-trending limb of the main opencut, shown in section *L–L′*, was extended northward and deepened to a point about 5,455 feet above sea level. The small pit near the middle of the pegmatite and 10 feet south of section *I–I'* was enlarged until it was nearly 65 feet long from north to south. Although these later workings were not mapped in detail, exposures in them were utilized for the projection of the geology in the cross sections.

MINING AND PRODUCTION

Production from the Beecher No. 3-Black Diamond pegmatite has consisted chiefly of beryl. Additional products consist of approximately 800 tons of rock containing 60 to 80 percent scrap mica, and 15 tons of spodumene concentrates assaying approximately 5 percent Li_2O. All was produced by handpicking and cobbing rock from the opencuts.

The production of beryl is as follows:

Year	*Tons*	BeO (*percent, weighted average*)
1952	92	7.4
1953	218	7.7
1954	31	----------
1955	1.5	----------
Total	342.5	

The relatively low percentage of beryllium oxide in the beryl concentrates is largely due to the difficulty of cobbing the beryl free from other minerals.

The importance of the Beecher No. 3-Black Diamond pegmatite as a producer of beryl is illustrated by the fact that Page and others (1953) list only one body of pegmatite in the Black Hills, the Peerless, that has produced more beryl. The Bob Ingersoll mine has produced more, but production came from two bodies of pegmatite. Outside of the Black Hills not more than two other pegmatite mines in the United States have yielded a greater quantity of beryl.

GEOLOGIC SETTING

The general geology of the region has been described by Newton and Jenney (1880) and by Darton and Paige (1925). The Black Hills is an oval area of peaks, hills, and ridges formed by dissection of an elongate domal uplift. The uplift is approximately 125 miles long in a north-northwesterly direction and 60 miles wide. Erosion has exposed a core of Precambrian metamorphic and igneous rocks surrounded by sedimentary rocks of Paleozoic and later age. The doming probably occurred in Tertiary time.

The Precambrian rocks of the southern Black Hills include many bodies of granitic and pegmatitic rocks, which are the dominant rocks in an area of about 40 square miles surrounding Harney Peak (fig 21). These granitic rocks around Harney Peak are rich in tourmaline and mica, and small bodies of pegmatite in these rocks contain beryl and a few lithium-bearing minerals. Pegmatite bodies in general gradually decrease in abundance away from the area of largely granitic and pegmatitic rocks, but they are commonly as abundant as 100 per square mile in outlying areas, and locally there are as many at 300 per square mile.

The metamorphic rocks are chiefly quartz-mica schist, but they also include quartzite, amphibolite, lime-silicate gneiss, and garnetiferous schist. Staurolite, andalusite, and sillimanite are common in the higher grade metamorphic schist.

Most of the pegmatite masses are mineralogically relatively simple and do not contain commercial concentrations of industrial minerals. They are composed mainly of plagioclase (commonly albite, rarely oligoclase), quartz, and perthite. All contain muscovite as an accessory mineral, and most contain one or more of the minerals tourmaline, apatite, garnet, biotite, and beryl.

The few pegmatite bodies that are zoned contain all the mineral deposits of economic importance. Many of the zoned pegmatites in the Black Hills have been described by Page and others (1953). Among them are the Beecher Lode and Beecher No. 2 pegmatites, a few hundred yards north and east of the Beecher No. 3-Black Diamond pegmatite. These are rich in lithium minerals, and the Beecher Lode has also been an important source of beryl and columbite-tantalite.

PETROLOGY

COUNTRY ROCK

Most of the country rock in contact with the Beecher No. 3-Black Diamond pegmatite is quartz-mica schist, but that on the extreme southeast corner of the pegmatite is amphibole schist.

The quartz-mica schist is medium grained, light gray on fresh fractures, and commonly stained brown in outcrop. Muscovite and biotite, nearly equal in abundance, constitute as much as 60 percent of the rock, and quartz from 40 to 60 percent. The common accessory minerals are plagioclase, garnet, tourmaline, and apatite. Schist adjacent to the pegmatite contact may contain more than 50 percent tourmaline, but the tourmaline content decreases greatly a few feet from the contact. About 200 feet west of the pegmatite are exposures of intensely folded schist containing sillimanite, andalusite, and staurolite.

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The amphibole schist is in contact with the pegmatite on the southeast (pl. 17). Float indicates that the schist extends northward parallel to the pegmatite outcrop for its entire length but somewhat east of the pegmatite proper. This schist is a dark-green to brownish-black fine- to medium-grained rock. Its weathered outcrops are coated with limonite and partly encrusted with chalcedony. About 20 percent of the rock consists of thin layers and lenses of quartzite ranging in thickness from a fraction of an inch to several inches. The material between these is about 60 percent grunerite and 30 percent common hornblende; the γ (gamma) index of refraction of the grunerite averages 1.705 and that of the hornblende 1.69. A specimen from near the contact of the Beecher Lode pegmatite consists almost entirely of ferroanthophyllite ($\gamma=1.698\pm.003$). The common accessory minerals are magnetite, garnet, and apatite. Regional mapping of nearby areas suggests that this amphibole schist with quartzite layers is a metamorphosed iron-formation.

A few quartz veins 2 to 4 feet thick are exposed west of the north end of the pegmatite (pl. 17). These veins have a northerly strike, are nearly vertical, and consist mainly of white quartz with some dark-brown tourmaline near the edges. Quartz veins a few hundred feet west of the mapped area contain sillimanite and andalusite.

PEGMATITE

The Beecher No. 3-Black Diamond pegmatite is exposed in an area that extends from north to south for 1,750 feet (pl. 17). The northern exposures are on the crest of a ridge, and the southern exposures are on the west slope.

The pegmatite crops out in a single, wide, virtually continuous exposure, which is in general paralleled by discontinuous, narrow exposures locally joining the main pegmatite mass. These exposures are part of a pipelike body that plunges 4° S. Locally the plunge is much steeper, and reversals of plunge are common. The upper, exposed part is very irregular and consists of a series of doubly plunging rolls parallel to the long dimension of the pegmatite. The resulting map pattern is complex, and many roof pendants or schist screens appear to divide the pegmatite into two or more separate intrusive bodies. Actually the southern part of the mass consists of two segments, the larger one on the west and the smaller one on the east (section *I–I′* and *M–M′*).

In the natural exposures of the pegmatite, which are generally heavily stained with limonite, the constituents are hard to identify. Staining and alteration persist as far down as the bottoms of the deepest opencuts, and are especially noticeable where the rock is jointed and sheared.

Seven different kinds of rock were recognized in mapping the pegmatite. Five of these form zones in the sense defined by Cameron and others (1949, p. 14); the other two fill fractures that may extend outward from unexposed inner zones. The zones, from the contact inward, are (1) quartz-muscovite-albite pegmatite (border zone), (2) albite-quartz-muscovite pegmatite (wall zone), (3) quartz-albite-muscovite-perthite-beryl pegmatite, (4) perthite-quartz-albite pegmatite, and (5) perthite-quartz pegmatite. Some of the fracture fillings consist of quartz-spodumene pegmatite and others of quartz pegmatite. Zone 3 is discontinuous, but all the others are continuous.

Mineralogy of pegmatite zones and fracture-filling units

Minerals	Zone 1 (border zone)	Zone 2 (wall zone)	Zone 3	Zone 4	Zone 5	Fracture fillings	
						Quartz-spodumene	Quartz
Albite:							
Abundance ---------percent--	15	40	32	17	Trace	3	----------
Average grain size--------in--	.05	.8	1.0	.5	0.5	1.0	----------
Minimum index of cleavage fragments	----------	1.529	1.529	1.529	----------	1.528	----------
Anorthite content [1]-percent--	----------	3-4	3-4	3-4	----------	0-1	----------
Perthite:							
Abundance ---------percent--	----------	4	10	45	80	3	Trace
Average grain size--------in--	----------	3	8	8	18	4	2
Quartz:							
Abundance ---------percent--	50	39	38	35	18	60	98
Average grain size--------in--	.05	.7	1.0	1.0	2.0	1.5	Massive
Muscovite:							
Abundance ---------percent--	30	15	10-15	2	Trace	4	Trace
Average grain size--------in--	.1	1.0	1.5	1.0	.5	.8	.5
Beryl:							
Abundance ---------percent--	([2])	.5 [3]	6	Trace	----------	Trace	.5
Average grain size--------in--	----------	1.0	4.0	4.0	----------	.5	1.0
ω (omega) index ------------	----------	1.584	1.586	----------	----------	1.586-1.588	1.587
Tourmaline:							
Abundance ---------percent--	2	2	1	Trace	Trace	----------	----------
Average grain size--------in--	.05	1.0	1.5	1.0	1.0	----------	----------
Apatite:							
Abundance ---------percent--	Trace	Trace	Trace	----------	----------	----------	----------
Average grain size--------in--	.03	.2	.1	----------	----------	----------	----------
Spodumene:							
Abundance ---------percent--	----------	----------	----------	----------	Trace	30	----------
Average grain size--------in--	----------	----------	----------	----------	10	6	----------

[1] Determination of anorthite content is based on curves by Winchell (1951, fig. 173, p. 200). The absolute value of the anorthite content of the albite may be in error. However, the small differences in the refractive indices between outer zones and albite from fracture fillings are easily reproducible.
[2] Not observed but probably present.
[3] Not observed in southeast segment of pegmatite.

Muscovite is abundant in the outer zones of the pegmatite but its abundance rapidly decreases inward. Albite also decreases in abundance, but less rapidly than muscovite. Perthite, on the other hand, becomes more abundant inward. Quartz is a major constituent of all zones and is virtually the sole constituent of the latest fracture fillings. Lithium minerals have been found only in fracture fillings and in parts of zone 5, and beryl is abundant only in zone 3. The grain size of all the minerals generally increases toward the center of the mass. These changes in mineralogy are tabulated in the table on page 543.

ZONE 1 (BORDER ZONE)

Zone 1, or the border zone, consists of quartz-muscovite-albite pegmatite. As this zone is only a fraction of an inch to 3 inches thick, most of its exposures are too narrow to be shown on the map, but there are a few larger exposures on dip slopes along the west side of the pegmatite mass and on low plunging rolls along its crest (pl. 17). The zone is present, however, along all the contacts with the country rock.

Zone 1 is composed of variable amounts of quartz, albite, and muscovite, with accessory tourmaline, apatite, and microcline. Quartz is ordinarily the most abundant mineral, constituting as much as 75 percent of the rock. Muscovite, which makes up 10 to 50 percent of the rock, forms crystals less than 0.2 inch in diameter. Albite forms as much as 30 percent of the rock in some places but is almost absent in others. The quartz and albite grains are commonly anhedral and have an average diameter of less than 0.1 inch.

ZONE 2 (WALL ZONE)

Zone 2, the wall zone, which consists of albite-quartz-muscovite pegmatite, occurs close to all observed contacts. Its average thickness is only about 2½ feet, and its maximum thickness 4 feet, yet it forms wide outcrops on dip slopes along the gently plunging top of the pegmatite (see section *E–E′*, pl. 17). Zone 2 is unusually thick near the middle of section *K–K′* (pl. 17) where the two segments of the pegmatite coalesce.

The mineral composition of zone 2 is variable; it averages about 40 percent albite, 40 percent quartz, 15 percent muscovite, and 4 percent perthite, with accessory tourmaline, apatite, and beryl. Outcrops rich in quartz may contain as much as 30 percent muscovite and from 0 to 30 percent perthite. Beryl was not found in this zone in the eastern segment of the pegmatite exposed south of section *K–K′*.

The albite grains are subhedral and grayish white; they are partly sericitized in sheared areas. Their average diameter is about 0.8 inch, although individual crystals as much as 2 inches in diameter occur in the coarser grained inner part of the zone, which is exposed in the large opencut near the south end of the pegmatite. The minimum index of refraction for cleavage fragments of the albite in four samples from the wall zone ranged from 1.529 to 1.530; this indicates a composition of An_3 to An_4 (Winchell, 1951, fig. 173, p. 280).

The quartz is white to gray and forms anhedral grains about 0.7 inch in average diameter. The gray quartz is concentrated along shear zones. Its gray color is due to very small opaque inclusions, apparently tiny flakes of hematite; where these inclusions are very abundant the quartz is nearly black. Very thin stringers and veins of secondary quartz and chalcedony cut the primary quartz and all the other minerals.

The muscovite forms thin silvery-white to pale-yellow books about 1 inch in average diameter. Many of these are warped and broken and contain inclusions of tourmaline and albite. The perthite, which is flesh colored, forms crystals as much as 12 inches in diameter, but the average is about 3 inches.

The accessory minerals have a great range in size, appearance, and distribution. Black tourmaline is commonly disseminated throughout the zone. Apatite forms small greenish crystals about 0.2 inch in diameter. Beryl forms subhedral to euhedral grayish-white to cream-colored crystals 0.3 inch to 2 inches in diameter. Its ω (omega) index of refraction averages 1.584. The beryl commonly encloses grains of quartz, plagioclase, muscovite, and tourmaline.

ZONE 3

Zone 3, which consists of quartz-albite-muscovite-perthite-beryl pegmatite, occurs only along the east side of the western segment of the pegmatite body and even there it is locally absent. It is well exposed in the southern part of this segment, but except in one small area in the northern part it is missing or is so small that it was not recognized. In the southern part of the pegmatite the zone extends downward to the bottom of the main opencut and appears to be an integral part of the western segment only. Mining done after the map was made shows that the zone continues at least to the 5,455-foot level (approximately as shown in sections *J–J′* and *K–K′*, pl. 17). Its thickness ranges from 0 to 5 feet. Some of the mapped exposures, however, are much wider, either because the zone there has a gentle dip or because it is repeated in rolls.

In its overall mineral composition, zone 3 differs from zone 2 chiefly in containing more perthite and beryl. Its average perthite content is about 10 percent. In some places perthite is entirely absent, but elsewhere it constitutes as much as 40 percent of the zone; its abundance generally increases inward. Muscovite is about as abundant as in zone 2; albite and quartz are slightly less abundant. In the deeper parts of the opencut excavated after the map was prepared there is much less muscovite than above; at that depth the zone consists mainly of albite, quartz, perthite, and beryl, with black tourmaline as the only common accessory mineral. Beryl there constitutes 5 to 10 percent of the rock.

This zone is coarser in texture than zone 2. In the largest opencut the muscovite books are as much as 18 inches in diameter and average about 3 inches. This cut shows some albite crystals 1 foot long and perthite crystals 2 feet in diameter. The beryl crystals there average about 6 inches in diameter, although several crystals 2 feet in diameter have been found. The beryl crystals commonly occur in aggregates, some of which contain more than a ton of beryl. The miners call this beryl "massive," though crystal faces can be found in it by close inspection.

The beryl is cream white to light gray on fresh fractures, but it is hard to identify in weathered rock, where almost all the crystals are heavily stained with limonite and are cut by stringers of limonite and hematite. Most of the beryl in the larger crystals in this zone has an omega index of refraction of about 1.586. "Shell" crystals of beryl (Page and others, 1953, p. 47) contain inclusions of one or more of the minerals quartz, albite, muscovite, and tourmaline. One such crystal contains a core of quartz, albite, and muscovite, surrounded by a layer of beryl, which is succeeded by a crudely hexagonal layer of quartz, albite, and muscovite, and finally by an outer layer of beryl. The beryl in the outer shell had an ω (omega) index of 1.586, and that in the inner shell an ω (omega) index of 1.582. This decrease in index of refraction toward the center of the crystal agrees with the findings of J. W. Adams (1953, p. 51) for beryl from other pegmatites in the Black Hills.

The quartz and albite have the same appearance in zone 3 as in the outer zones. The range of albite composition is also the same as in zone 2.

The minerals of this zone in the largest opencut are heavily iron stained along northward-trending fractures, which contain late veinlets and stringers of chalcedony. The albite is somewhat altered and the muscovite books are broken.

ZONE 4

Zone 4, which consists of perthite-quartz-albite pegmatite, is almost continuously exposed throughout the length of the pegmatite. Its thickness ranges from 9 to about 20 feet and averages about 12 feet. It probably lenses out at shallow depth, however, and has a hood-shaped cross section (sections *I–I′*, *J–J′*, and *K–K′*, pl. 17). Since zone 3 is absent over much of the pegmatite, zone 4 is commonly in direct contact with zone 2. This contact is gradational; it is characterized by an inward decrease in muscovite and beryl content and an increase of the perthite content.

The chief minerals of zone 4 are perthite, quartz, and albite, and the accessory minerals are muscovite, tourmaline, and beryl. Perthite is by far the most abundant mineral, making up about 45 to 50 percent of the rock. The perthite crystals, which are subhedral, average about 8 inches in diameter, but some are nearly 3 feet in diameter. The perthite is flesh colored when fresh, but is generally stained with limonite and hematite along joints, shears, cleavage cracks, and crystal boundaries. Some crystals about halfway from the north end of the pegmatite are intergrown with quartz. Elsewhere, quartz is abundant as grains interstitial to the larger perthite crystals and is rare as small blebs and veinlike masses within the perthite. The quartz is mostly white, but in shear zones it is gray.

The albite is similar in composition to that in zones 2 and 3 but is generally not so coarse grained. It forms about 15 or 20 percent of the zone as a whole, and as much as 40 percent of some parts of it.

Beryl is rare in zone 4; it occurs only in the outer part of the zone, at places where adjacent zones contain beryl. It is similar to the beryl in zone 3 but is coarser grained.

In the southeast segment the rock in zone 4 is finer grained than it is in the main segment of the pegmatite—much of it consists of grains less than an inch in diameter. Plagioclase and muscovite are more abundant here than elsewhere.

ZONE 5

The innermost lithologic unit of this composite mass of pegmatite is called zone 5. It is exposed at the surface mainly in small scattered areas near the south end of the pegmatite ridge, but mining in the largest opencut, done partly after the mapping was completed, shows that it extends downward at least 30 feet from the surface. In the main opencut, zone 5 is locally in contact with zone 3 where zone 4 has pinched out with depth (see secs. *I–I′ through K–K′*, pl. 17). In most of its exposures the rock contains about 80 percent perthite and 15 percent quartz; albite is only an accessory mineral, along with muscovite. Locally, spodumene is an accessory mineral of the zone. In some places the perthite content is greater than 90 percent. The perthite is similar to that of zone 4, but occurs in larger crystals, some as much as 5 feet in diameter. It is commonly iron stained and cut by hematite veins. The quartz and accessory minerals are interstitial to the perthite crystals.

In some places, however, spodumene is a conspicuous mineral of rock that is mapped at part of zone 5. A few crystals of spodumene as much as 3 feet long and 3 inches thick are exposed in this zone on the west side of the main opencut. These crystals are slightly more abundant near the lower part of the cut. Little of this spodumene is fresh and hard; most of the crystals are altered to a soft claylike material. Much of it is in aggregates which give a general impression of having replaced the other minerals, but the altered condition of the spodumene crystals, and the general limonite staining of the rock, make it difficult to interpret the relations.

Fresh, hard spodumene crystals as much as 6 feet long have been found, however, at approximately the 5,560-foot level, between sections *K–K′* and *J–J′*, (pl. 17), in rock that was exposed by mining after the map was completed. This is apparently part of an inner spodumene-bearing zone which may have an outline similar to the possible concealed inner zones shown in the sections in plate 17. Water in the deepened opencut prevented detailed examination of this spodumene-rich pegmatite, but the spodumene is probably associated with perthite and quartz.

Zone 5 is concealed over most of the central and northern parts of the pegmatite, except perhaps around a small quartz fracture filling just north of section *B–B′* (pl. 17). The rock in this exposure, however, may be an integral part of the fracture filling and an offshoot from zone 5 at depth.

FRACTURE FILLINGS

Fracture fillings of quartz-spodumene and quartz pegmatite are exposed at several places along the outcrop. They are thin dikelike bodies which generally cross the structure of the enclosing zones and are equivalent to fracture fillings as defined by Cameron and others (1949, p. 14). Most of the quartz-spodumene fracture fillings that have been mapped are well exposed on the wall of the opencuts in the southern part of the pegmatite mass. They occur in both the east and west segments of the pegmatite. Quartz-spodumene pegmatite, presumably part of fracture fillings, also occurs in three small prospect pits to the north. These fracture fillings are generally 1 to 4 feet thick. Most of them cut across zonal boundaries, though some are locally parallel to those boundaries. Their contacts are ordinarily sharp, but in places they are gradational where they cross spodumene-bearing parts of zone 5.

Most of the spodumene-bearing fracture fillings strike north to N. 11° W., and dip 15°–90° E., but one in the easternmost opencut strikes nearly east and dips 32° N. Some of these fracture fillings intersect one another in the large cuts, but they all appear to be of about the same age.

The quartz-spodumene pegmatite of these fracture fillings is about 60 percent quartz and 30 percent spodumene, although locally the spodumene content may exceed 50 percent. About 10 percent of it consists of perthite, albite, and muscovite. The fracture fillings are commonly zoned; muscovite and albite are concentrated along the edges and quartz and spodumene in the middle. A fracture filling may thin so much along the strike that the quartz-spodumene core pinches out, leaving only the borders of quartz, muscovite, and albite. Small crystals of beryl occur very sparsely in the mica-rich parts of the fracture fillings. The ω (omega) index of refraction of the beryl ranges from 1.586 to 1.588. Albite from three of these fracture fillings was found to range in composition from An_0 to An_1.

These fracture fillings may be offshoots from unexposed inner zones of spodumene-bearing pegmatite.

Four fracture fillings about 1½ feet thick and composed of nearly pure quartz were mapped in the northern part of the pegmatite mass (pl. 17); smaller ones which occur elsewhere were not mapped. The quartz-filled fissures strike north and dip 75° or more east; one of them, however, has a vertical offshoot that strikes east. The contacts with the enclosing pegmatite are for the most part sharp, but locally they are somewhat gradational.

A very small amount of muscovite and perthite occurs along the outer edges of the massive quartz in these fracture fillings, and cream-white beryl crystals 1 inch to 3 inches in diameter are commonly associated with the muscovite. Two beryl crystals from the northernmost fracture fillings had an ω (omega) index of 1.587 ± 0.002. The beryl is commonly more nearly euhedral than that in zones 2 and 3.

STRUCTURE

The crest of the Beecher No. 3 pegmatite plunges, on the average, about 4° S. Its keel is not exposed, but if it is at a relatively shallow depth and about parallel to the crest, the pegmatite mass has the form of a nearly horizontal pipe, the southern part of which consists of two separate segments.

The irregular outline of the pegmatite (pl. 17) is caused by numerous rolls on its top, whose plunge is about parallel to that of the mass as a whole. These relations are shown in plate 18.

The general strike of the pegmatite outcrop mass trends northward, but the contacts locally deviate as much as 25° from this trend. The general dip of the mass is about vertical. The flanks of the many rolls along the top of the pegmatite show varying dips, but these cannot be projected in depth. The contacts along the northern part of the pegmatite generally dip steeply westward, nearly parallel to the bedding of the country rock. The contacts between zones in the southern part of the pegmatite dip steeply inward or are vertical, and so, presumably, do the outer contacts of the pegmatite, though they are not well exposed in this area.

The ends of the pegmatite mass plunge outward. The keel is not exposed, and its depth is uncertain, even though recent mining has penetrated the southern part of the mass to a depth of at least 70 feet. Farther north the present exposures are all near the crest of the pegmatite, and it is possible, though not probable, that the bottom of the pegmatite is at a much shallower depth than that suggested by the sections.

The southern part of the pegmatite consists of two segments separated in part by zone 2 and in part by zone 3 (secs. *I–I′* through *M–M′*, pl. 17). In sections *I–I′* and *J–J′*, the two segments are separated at the surface by a screen of schist. In sections *K–K′*, *L–L′*, and *M–M′*, zone 2 of one segment merges with zone 2 of the other. This zone extends to depths as much as 40 feet below the upper contact of the pegmatite in section *K–K′*, and zone 3, found only in the western segment, extends even farther downward. This zonal structure whereby outer zones appear to penetrate inner zones could have resulted from the replacement of a thin screen of schist between two segments of a single pegmatite body. It is more likely, because of the lack of evidence for this replacement and because of small differences in mineralogy of the segments, that they were formed by multiple intrusion at slightly different times. Many other pegmatite bodies in nearby areas were formed by multiple intrusions. Page and others (1953, p. 111–112) have described structures giving evidence of such origin in the Edison pegmatite, at Keystone, S. Dak.

The structure of the top of the pegmatite is characterized by many rolls in the contact as shown by the distribution of the zones and contacts (pls. 17 and 18). The axes of the six largest rolls, only, are shown on the map (pl. 17), but many more small ones are shown by the map pattern and by the restored contacts in the sections, especially sections *G–G′* and *H–H′*. Because of partial erosion of the doubly plunging troughs of these rolls many small bodies of schist are surrounded by pegmatite. (Mining done after the geologic sections were prepared proved that two such bodies in sections *J–J′* and *K–K′* (pl. 17) are shown in essentially the correct form.)

The plunge of the main structure of the pegmatite is best understood by following the detailed changes of plunge in the major and minor rolls along the pegmatite outcrop (pls. 17 and 18). The plunge of the axes of these rolls can only rarely be determined accurately, but it can be approximated because zone 2 is thin and essentially at the pegmatite contact. The extreme north end of the pegmatite plunges 40° N. 15° E., but 10 feet to the south the plunge flattens to 14°, and about 40 feet farther south it plunges southward, thus forming a structural high. From section *A–A′* to section *C–C′*, the general plunge is gentle and almost due south, but there is a high just south of section *A–A′*. Minor doubly plunging crests and troughs occur near section *D–D′*, but in general that section is on a high. Near section *E–E′* the plunge of the top of the pegmatite is nearly 30° S. 5° W. A little farther south the westernmost limb or roll of the pegmatite plunges northward. From a point halfway between sections *E–E′* and *F–F′* to section *G–G′*, this roll plunges 5°–11° S. South of section *E–E′* the crest of the main part of the pegmatite is nearly horizontal and may locally plunge a few degrees northward; the direction of plunge changes from S. 5° W. to S. 20° E., and then back southward. Near section *G–G′* there are many small doubly plunging rolls. Just north of section *H–H′* the main crest of the pegmatite plunges as much as 27° S. 10° W., and there is thus a high between sections *H–H′* and *G–G′*. This is succeeded by a structural low between sections *H–H′* and *I–I′*. North of section *I–I′* the plunge is north to N. 15° W. Just north of section *J–J′* the plunge is again southward; it apparently steepens farther to the south at the end of exposed pegmatite. At the extreme south end of the pegmatite the direction of plunge changes from about S. 20° E. to nearly due south. There are many doubly plunging rolls near section *K–K′* and *I–I′*.

The three easternmost rolls near the south end of the pegmatite outcrop (pl. 17) are in the east segment. Two of these rolls merge near section *I–I′*, so that farther north there are probably only two major rolls. On the map (pl. 17) these rolls are projected only a short distance northward, to the place where the eastern segment of the pegmatite appears to pinch out. Farther northward, two rolls appear in a like structural position, but near section *D–D′* they are part of a single mass that shows no evidence of having been formed by coalescence.

If the elevations of the many structural highs along the top of the pegmatite were projected onto a vertical north-south plane, they would all fall close to a line that plunges 4° S. This is believed to be the average plunge of the crest of the pegmatite.

The Beecher Lode and Beecher No. 2 pegmatites, on adjacent claims, are also pipelike masses plunging gently southward on the whole but showing local reversals of plunge. Schist exposed a few hundred feet west of the Black Diamond claim has doubly plunging folds that are very similar in form to the rolls in these pegmatites.

The Dyke No. 2 pegmatite, a few hundred feet south of the mapped area and across a small valley, crops out exactly in line with the Beecher No. 3-Black Diamond pegmatite, and it likewise trends northward. Its north end plunges beneath the valley and the south end plunges southward. The mineralogy of the two pegmatites is similar except that beryl is not an important constituent of the Dyke No. 2 pegmatite. The two masses may well be connected. Diamond drilling on the Dyke No. 2 pegmatite has proved that it extends to depths of more than 100 feet, and it appears likely that the Beecher No. 3-Black Diamond pegmatite extends to at least that depth.

ORIGIN

Much has been written about the origin of pegmatites, especially zoned pegmatites, which have been variously ascribed to aqueous, metamorphic, and igneous agencies. Jahns (1955, p. 1058–1066) has recently summarized the principal theories of origin. Cameron and others (1949, p. 98–105) concluded that zoned pegmatites crystallized from the walls inward, and that zones were developed by fractional crystallization of magma rich in volatile matter and by incomplete reaction of crystallized material with the rest liquid in an essentially closed system. Page and others (1953, p. 17–24) proposed the same mode of origin for zoned pegmatites in the Black Hills and suggested that the source of the pegmatitic magma was the granite around Harney Peak. They believed that the magma was sufficiently viscous to deform the wallrocks. Higazy (1949, p. 555–581) concluded from a study of the perthite in the Black Hills pegmatite that those rocks were formed by metasomatic replacement of schist. In a recent article, Ramberg (1956, p. 185–213) states that the zoned pegmatites in West Greenland were formed by a combintion of metamorphic and metasomatic agencies, and that certain zoned pegmatites in many other parts of the world originated in the same manner.

The lack of evidence of much replacement of the country rock indicates that the Beecher No. 3-Black Diamond pegmatite is an intrusive rock rather than a product of metasomatism. No perceptible alteration of the country rock can be ascribed to the pegmatite except for the addition of tourmaline for a few inches outward from the pegmatite contact. The structural evidence, if correctly interpreted, that the pegmatite is a multiple intrusion indicates that at least part of one segment had crystallized before the other segment was emplaced. It cannot be determined which segment is earlier. The similarities of the two segments, however, show that they have a common source.

The rolls on the upper contact of the pegmatite resemble the doubly plunging minor folds in the nearby country rocks. Such folds have been recognized as much as 300 feet from the pegmatite, and it is unlikely that they were formed so far away by the force of intrusion of the pegmatite. More probably they were preexisting structures, some of which controlled the emplacement of the pegmatite (Cameron and others, 1949, p. 9–11; Page and others, 1953, p. 8–9; Staatz and Trites, 1955, p. 12–18). Some of the small doubly plunging folds have deformed the metamorphic minerals sillimanite, andalusite, and staurolite, indicating that the late folding and the subsequent emplacement of the pegmatite followed the peak of the metamorphism. The late folding and intrusion of the pegmatite body could have been almost contemporaneous.

The Beecher No. 3-Black Diamond pegmatite is similar to other zoned pegmatites in the Black Hills. The sequence of zones, the structure, and the mineralogy are all in accord with evidence cited by Page and others (1953, p. 17–24) to show that these pegmatites formed by crystallization of a volatile-rich magma. The crystallization occurred in a restricted system where some volatile matter may have been lost but where no new material was added.

The composition of the Beecher No. 3-Black Diamond pegmatite as a whole approaches that of some granitic rocks, but the muscovite content is unusually high, especially in the outer zones, and tourmaline is abundant. The pegmatite also differs from typical granite in containing beryl and spodumene, but although these minerals are locally abundant, their total amount in the entire mass is small.

The composition of zones and fracture fillings in the Beecher No. 3-Black Diamond pegmatite indicates a gradual change in the crystallizing components from sodium- to potassium- to possibly lithium-rich materials. Albite is most abundant in the outer zones, and perthite in intermediate zones. The younger fracture fillings are enriched in silica. This sequence is very similar to that in the Etta pegmatite, in which an albite-rich outer zone is succeeded by a perthite-rich zone, a spodumene-rich zone, and a quartz core (Page and others, 1953, p. 118).

The refractive indices of beryl and albite indicate that the composition of these minerals differed slightly at different stages of crystallization. The composition of albite is An_{3-4} in zones 2 to 4 and An_{0-1} in fracture fillings. The absolute value of the anorthite content of the albite may be slightly in error, but the differences in indices are identifiable between samples of the outer zones and the fracture fillings. The beryl has an ω (omega) index of 1.582 to 1.586 in zones 2 and 3 and 1.586 to 1.588 in the fracture fillings. Beryl with a higher refractive index contains more alkalies (Winchell, 1951, p. 464). and therefore the older beryl contains more beryllium oxide and less of the alkalies that the younger beryl. In fact, the inner, and older, parts of large beryl crystals have lower refractive indices than the outer parts, and must therefore contain less of the alkalies.

An alternative explanation of the origin of zoned pegmatites is the metasomatic origin advocated by Ramberg (1956, p. 210–211). He believes that pegmatitic material migrates to an area of low pressure and that the differing relative mobility and availability of the various constituents cause segregation into zones. The process takes place in the solid state and there is never any large reservoir of uncrystallized material.

If the pegmatites in the Black Hills are of metasomatic origin, there should be a relation between the composition of a given pegmatite mass and that of its wallrocks, but no such relation is evident from a study of the Beecher No. 3-Black Diamond pegmatite body and other pegmatites nearby. Within 500 feet of that body there are 17 others, all but 3 of which are zoned and contain beryl. Two of these are the very large Beecher Lode and Beecher No. 2, both rich in spodumene. Although the area that contains those 18 pegmatites is relatively small, it extends across a stratigraphic interval containing widely different varieties of amphibole schist and quartz-mica schist; and yet there is no apparent relation between the composition of the pegmatite bodies and the composition of their wallrocks. Furthermore, the country rocks show no appreciable changes in composition near the pegmatite bodies or along the strike of those bodies, as they should if they had supplied the material to form the pegmatites by metasomatism. The country rocks have been traced for several miles north and south through areas of apparently the same metamorphic conditions, and although many homogeneous pegmatites have been mapped in those areas, no zoned pegmatites or lithium-bearing pegmatites were found. According to Ramberg's metasomatic theory, those country rocks apparently would be as favorable for the development of zoned pegmatites in one place as in another. It seems likely, therefore, that the zoned pegmatites are abundant in the Beecher area because that area was underlain by fluids of favorable composition. According to this view these zoned pegmatites differ slightly in composition because they were intruded at somewhat different times, when different amounts of the various chemical constituents were available at the source.

During the formation of a zoned pegmatite that was really of metasomatic origin, one would expect zones 1 and 2, the border and wall zones, to grow continuously in area to accommodate the ever-increasing size of the pegmatite body. Fracture fillings might be extremely abundant. There should, then, be mineralogic or structural evidence that the outer parts of the wall zone are younger than its inner parts, and that the zone as a whole is younger that the inner zones. Such evidence has not been found. The mineralogy and texture of the wall zone suggest that the zone crystallized as a single unit, from the contact inward, at substantially the same time throughout the mass. Moreover, the fracture fillings in this and other zoned pegmatites of the Black Hills are similar in composition to the inner zones, indicating that the inner zones formed later than the outer zones.

It thus may be concluded that the Beecher No. 3-Black Diamond pegmatite was intruded as a body of volatile-rich magma, which then crystallized in a restricted space. Zones were formed by progressive crystallization and differentiation of this magma. The later differentiates were enriched in potassium and lithium, and quartz pegmatite was probably the last rock to form. The Beecher No. 3-Black Diamond pegmatite and the several very similar zoned pegmatites nearby were probably derived from a common source but intruded at slightly different times. This group of zoned pegmatites, like others throughout the southern Black Hills, is probably related genetically to the granite of Harney Peak, which is mineralogically very similar to the pegmatites and has in places a pegmatitic texture.

MINERALS OF ECONOMIC IMPORTANCE

BERYL

Beryl, which has been the chief economically important product of the Beecher No. 3 mine, has been mined almost entirely from zone 3 of the pegmatite mass. Small quantities, however, have been recovered from zone 2 and from the edge of quartz-spodumene fracture fillings, and perhaps from zone 4.

Visual estimates of the percentage of beryl in the zones are unreliable because of the extreme iron staining of the rock, but fairly close estimates can be reached from records of production. At the time the map was made, 170 tons of concentrates containing about 8 percent BeO had been produced from approximately 1,500 tons of rock from zone 3; and after the mapping, 172 tons with approximately the same beryllium oxide content was produced from 2,300 tons of rock from the same zone. The percentage of beryl-bearing rock containing 8 percent BeO, calculated from these figures, is:

$$\frac{\text{342 tons of concentrates}}{\text{3,800 tons of rock from zone 3}} = 9.0 \text{ percent}$$

The indices of refraction show that the pure beryl from this zone contains about 12.5 percent BeO. Therefore, the amount and percentage of pure beryl is:

$$\text{Tonnage of pure beryl in the rock} = \frac{0.08 \times 342}{0.125} = 219$$

$$\text{Percentage of pure beryl in rock} = \frac{219}{3{,}800} = 5.8$$

Microscopic impurities may decrease the beryllium oxide percentage in the beryl to about 11 percent. Furthermore, some beryl, possibly 10 percent, was lost during mining. If these two factors are taken into consideration, the rock contained about 7 to 8 percent beryl that was megascopically, though not microscopically, pure.

Areas of 50 to 80 square feet in zone 3 have been estimated to contain as much as 30 percent beryl, but other areas of equal size contain none. The beryl content of the zone as a whole probably is not much greater than 6 percent.

The beryl-rich zone 3 has been recognized chiefly in the southern part of the pegmatite. Before mining, it was exposed here and there near the axis of the pegmatite outcrop from its south end to a point about 130 feet north of section *I–I′* (pl. 17). Throughout this distance it is localized along a single roll in the top of the western segment of the pegmatite. The discontinuous surface exposures proved to be part of a continuous zone that is at least 430 feet long. At the extreme south end of the pegmatite body the zone pinches out at a depth of about 10 feet. Northward, however, the zone extends down to an increasingly greater depth parallel to the contact between the two segments of the pegmatite. By 1956 the main opencut had been extended to the vicinity of section *J–J′* (pl. 17), and the beryl-rich zone had been exposed down to about the 5,450-foot level, as shown in sections *K–K′* and *J–J′*. It probably extends northward as shown in section *I–I′*, for according to G. V. Bland the bottom of the zone appears to be plunging gently northward.

The beryl-rich zone forms an arched tubular body having a long, steeply dipping limb on the east side, as shown in section *J–J′* (pl. 17). Its average thickness is about 3 feet. In places, however, it has been mined across a horizontal width of nearly 8 feet, probably where the zone locally has a low dip. In section *I–I′* the wide surface exposure of the zone is caused by the low dip along a roll in the upper contact of the pegmatite.

The beryl-rich zone has also been recognized just south of section *C–C′*, where it is inferred to be a hood-shaped body in a roll near the top of the pegmatite—apparently the same roll along which the zone is localized in the southern part of the pegmatite. According to this interpretation of the structure the main beryl deposit plunges northward beneath the surface between section *I–I′* and *H–H′*, pinches out down the plunge, and does not reappear when this roll reverses plunge and crops out near section *H–H′*. Between sections *H–H′* and *E–E′*

(pl. 17), exposures of the inner contact of the wall zone along this roll are scarce but the zone may be present locally. Exploration is needed to investigate this possibility.

Beryl also occurs in zone 2, but is there so fine-grained that most of it cannot be recovered economically by hand cobbing; it occurs only in scattered patches and may be absent over many square feet of exposures. This zone, which was estimated visually to contain about 0.5 percent beryl, has an average thickness of about 2.5 feet. Even so, the beryl reserves are large if the pegmatite extends, as it probably does, to a depth of 100 to 150 feet in zone 2.

Fracture fillings generally contain small quantities of beryl about as fine grained as that in zone 2, but it probably constitutes only 0.5 percent, or less, of the fillings. However, the inner zones of the pegmatite, from which the fillings are possibly offshoots, may contain significant quantities of beryl.

LITHIUM MINERALS

Spodumene, the only exposed lithium mineral in the pegmatite, was found only in fracture fillings and in zone 5 during the mapping in 1952–53. Recently, however, previously concealed spodumene-rich pegmatite was exposed by mining. This is believed to be part of a largely concealed zone whose approximate cross sectional outline is indicated in sections *I–I′*, *J–J′*, and *K–K′* (pl. 17).

Spodumene constitutes about 30 percent of the quartz-spodumene fracture fillings, in which the spodumene crystals average about 10 inches in length and 2 inches in diameter. Most of these crystals are largely altered to a soft claylike material, except in a fracture filling exposed in the prospect pit between sections *H–H′* and *I–I′*, where hard, unaltered spodumene has been found. Some of the few scattered crystals, which are altered and are found in zone 3, are as much as 3 feet long and 3 inches thick.

The 15 tons of spodumene concentrates sold was handpicked from the larger fracture-fillings and possibly from the spodumene-bearing zone 5. The concentrates were found by assay to contain only about 5 percent Li_2O, whereas fresh spodumene from other Black Hills deposits commonly contains 6 percent or more.

Spodumene crystals more than 5 feet long are exposed in the recent workings at deeper levels, and even larger crystals are likely to be found. Although the spodumene-rich rock could not be examined in detail, it appeared to contain 15 or 20 percent of easily visible spodumene crystals, probably associated with perthite and quartz. G. V. Bland reports that this spodumene is relatively unaltered.

These discoveries may indicate that the deeper parts of the pegmatite body not only contain large deposits of spodumene but also amblygonite or lepidolite. The presence of scattered spodumene-bearing fracture fillings along much of the length of the pegmatite suggests that spodumene-bearing rock may extend continuously throughout the length of the pegmatite. Although some of the spodumene in the fracture fillings is altered, that found at greater depth may well be fresh and have a higher content of lithium oxide. Page and others (1953, p. 58) point out that although the spodumene in the outer parts of zones in pegmatite is mostly "rotten" and altered, fresh spodumene is commonly found in the inner parts of the zones.

The size of the now largely concealed spodumene-bearing zone or zones depends on the thickness of the pegmatite at depth, the thickness of the outer zones, and the possible presence of an inner barren core of quartz. Since none of these conditions are known, any satisfactory estimate of the size of concealed spodumene deposits must await deeper exploration, which appears to be well warranted by these recent discoveries.

MICA

Muscovite is concentrated in zones 2 and 3 and in the marginal parts of many fracture fillings. It is most abundant in the upper part of zone 3, along the roll near the upper contact of the pegmatite. This part of the zone averages about 15 percent muscovite and locally contains as much as 25 percent, but deeper parts contain less. The books of muscovite in this zone have an average diameter of about 3 inches, but some are as much as 12 inches in diameter. Sheet mica, however, is very scarce or entirely absent, and as the mica is heavily weathered and iron stained, as well as ruled, warped, and tied, it is suitable only for scrap mica. Much of it is so intergrown with other minerals that the mixture is sold as rock containing 50 to 80 percent scrap mica.

The wall zone contains about 15 percent muscovite. The books are generally smaller than in the first intermediate zone and are not easily recoverable. The mica has the same defects as that in zone 3 and is suitable only for scrap mica. Because of their large volume, the wall zone and zone 3 contain a large reserve of scrap mica.

FELDSPAR

Microcline perthite is an essential constituent of zones 4 and 5, and is also a minor constituent of zone 3. It forms about 80 percent of zone 5, and 45 to 50 percent of zone 4. Crystals are large and easily recoverable by hand sorting. The perthite crystals average 18 inches in diameter in zone 5 and about 8 inches in zone 4. Crystals as much as 5 feet in diameter are common in inner parts of zone 5.

Unfortunately most of the perthite is too heavily iron stained to be marketed in its present condition. However, large reserves of easily recoverable feldspar are available and could be used if the iron content could be reduced by beneficiation.

OTHER MINERALS

Columbite-tantalite is the only other mineral of economic importance commonly occurring in pegmatites of this type in the Black Hills. It has not yet been found in the Beecher No. 3-Black Diamond pegmatite, but the Beecher Lode pegmatite, 450 feet to the east, has produced more columbite-tantalite than any other pegmatite in the Black Hills. It is therefore likely that deposits of this mineral will ultimately be found in the Beecher No. 3-Black Diamond pegmatite.

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