

# THE GENESIS OF PEGMATITES

## II. QUANTITATIVE ANALYSIS OF LITHIUM-BEARING PEGMATITE, MORA COUNTY, NEW MEXICO

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### ABSTRACT

The Pidlite dike, one of several lithium-bearing pegmatite bodies in the Precambrian terrane of the Sangre de Cristo Range, lies in southwestern Mora County, New Mexico. Its major part, which is well exposed in surface and underground mine workings, has the form of a discoidal lens whose longest axis is essentially vertical. The dike consists of seven readily distinguishable types of pegmatite, four of which form typical zones that have a concentric arrangement. The other three rock types form units that are similar to the zones in shape and disposition, but are distinguished by their content of minerals that appear to have been developed by replacement of earlier pegmatite minerals.

The outer zones are granitoid aggregates of quartz, albite, perthite, and muscovite, and are relatively thin and continuous. The inner zones, which are lenticular to pod-like, are much coarser grained and consist mainly of quartz and perthite. The other three units show greater textural irregularity, and are characterized by an abundance of highly sodic albite, lepidolite, and white to pink muscovite. Additional minerals in the dike include amblygonite, apatite, beryl, betafite, bismuth, bismutite, columbite-tantalite, cyrtolite, fluorite, gahnite, hatchettolite, loellingite, magnetite, microlite, monazite, pyrite, spessartite, spodumene, topaz, and tourmaline (varieties elbaite and schorl).

The mineralogic and chemical composition of the Pidlite pegmatite was determined quantitatively by means of dimensional measurements of the zones and other units, megametrical analyses of their mineral content, and chemical and optical analyses of representative samples of the major minerals. The calculated bulk composition of the dike is remarkably similar to that of at least two other lepidolite-bearing pegmatites in the southwestern United States, and is not much different from that of Daly's average granite.

The amount of mineral replacement in the dike was estimated by means of detailed measurements of recognizable pseudomorphs and distribution of residual masses of earlier minerals. These data indicate that the dike, if formed mainly by crystallization from a pegmatite magma, must have been at least 75 per cent consolidated prior to the major stage of mineral replacement. The net amount of material transfer involved in the replacements need not have been very great, and can be accounted for quantitatively in terms of reactions between earlier-formed minerals and residual fluids derived from sources within the dike.

On the basis of their distribution, as well as their structural, textural, and compositional relations, the zones in the Pidlite dike are thought to have been developed by fractional crystallization of a pegmatite magma under essentially closed-system conditions. The younger minerals appear to have been developed in part through replacement of earlier-formed zonal material by residual fluid, and in larger part by direct crystallization from the fluid, beginning mainly at a time when this highly reactive residuum constituted 15 per cent to 25 per cent of the dike. Conditions may well have approached those of a closed system until consolidation of the pegmatite was virtually complete.

The possibility of late-stage replacement under open-system conditions, involving more dilute solutions derived from sources outside the dike, cannot be ruled out entirely. All the evidence at hand, however, suggests that the lepidolite and other late-stage minerals are products of replacement by, and direct crystallization from, residual fluid that was generated wholly within the dike.

#### INTRODUCTION

The widespread development of some pegmatite minerals by corrosion and replacement of other pegmatite minerals has been noted and described by hundreds of competent investigators, and plainly is a characteristic feature of pegmatites in general. However, the quantitative significance of such replacement varies considerably from one body of pegmatite to another, and in most of them the process appears to have played only a minor part in the formation of the minerals that can be observed. Other pegmatite bodies, and particularly those of highly complex mineralogy, show impressive evidence of mineral replacement on larger scales, and have provoked much discussion as to the nature and source of the fluids that were involved.

Most investigators recognize two major kinds of pegmatite bodies—those formed mainly by replacement of non-pegmatitic country rock, and those formed wholly or in part by crystallization from a mechanically injected fluid, or magma. Commonly included in the latter group are pegmatite bodies that are internally zoned, i.e., that comprise lithologically distinctive units that are more or less concentrically disposed within a given pegmatite body and reflect, at least to some degree, its general shape and structure. A magmatic stage in the formation of these and many other pegmatites ordinarily is adduced on the basis of structural relations between pegmatite and country rock, as well as structural, textural, and compositional relations within each pegmatite body. Most of the critical features have been summarized and discussed by Kemp

(1924), Johannsen (1932, pp. 74–84), Landes (1933, pp. 41–56), Cameron, *et al.* (1949, pp. 97–106), Flawn (1951, pp. 180–190), and many others.

Replacement phenomena within pegmatite bodies of magmatic origin, though readily identified in most occurrences, commonly are interpreted in different ways by different observers. In particular, opinions differ widely concerning the nature and amount of material that was replaced, the stage or stages during which replacement was active, and the effects of the replacement on the composition of the system as a whole. These factors are of prime importance in any attempt to establish the source of the replacing solutions, or to determine whether or not the replacement proceeded under open-system conditions. Unfortunately, however, they rarely have been assessed quantitatively or in detail. In discussing the origin of replacement material in pegmatites, for example, Cameron, *et al.* (1949, p. 106) remark that “it is worthwhile to remember that we have little data on what changes, if any, in the bulk composition of whole pegmatites have been effected during replacement. Most of the data and observations available apply only to limited portions of pegmatite bodies, and information regarding the more completely exposed pegmatites is mostly qualitative, not quantitative.”

Anyone who attempts to determine the bulk chemical or mineralogical composition of entire pegmatite bodies soon recognizes the serious difficulties imposed by the characteristic variations in their texture and structure. Most bodies are so coarsely and irregularly crystallized that ordinary methods of sampling do not yield acceptable results, and few bodies are well enough exposed in three dimensions to permit meaningful determinations by any method of sampling. Discouraging as these factors may be, however, the great need for more complete and quantitative data on pegmatite composition remains as a stimulus to investigators, whether they are interested primarily in the commercial aspects of certain pegmatite minerals or solely in theoretical questions of pegmatite genesis.

This paper presents a brief description of mineralogically complex pegmatites from northern New Mexico, as well as the results of quantitative analysis of one small pegmatite body that is particularly well exposed. The field work on which the paper is based was done during 1946 and 1947, and both it and supplementary laboratory studies were supported by a research grant from the California Institute of Technology. The investigations were facilitated considerably by E. P. Chapman and John A. Wood of the Hayden Mining Company, who permitted access to mine workings and provided a useful map of the principal pegmatite dike. Valuable assistance in the mapping of the pegmatite bodies was given by Don M. George, Jr., Lauren A. Wright, and Arthur Mont-

gomery. The writer also is indebted to Rudolf von Huene, who built the measuring device that was used for megametric analysis of the pegmatite in the field, to Mrs. Charlotte Bjornsson, who drafted two of the illustrations for this paper, and to Mrs. Florence Wiltse, who aided in preparation of the manuscript.

#### THE PEGMATITE AREA

Numerous masses of lithium-bearing pegmatite are exposed high on the east slope of the Sangre de Cristo Range near and along the south edge of western Mora County, New Mexico. Most of them lie at distances of 4 to 7 miles west and northwest of Lower Rociada, a village that in turn is 24 miles by road northwest of Las Vegas. The southern part of the pegmatite area can be reached by road and trail from Lower Rociada via Sparks Creek and Maestas Creek, and the northern part is served by a steep road that extends northwestward up Sparks Creek, and thence westward into the higher country south of the creek. This road ends at the Pidlite lithia mine, approximately  $5\frac{1}{2}$  miles from Lower Rociada.

The pegmatite area is elongate, and trends in a northerly direction for a distance of at least 2 miles across rough, heavily timbered country in which altitudes range from 8200 to about 9800 feet. It appears to be underlain chiefly by Precambrian metamorphic rocks that are concealed in many places by a thick mantle of soil and vegetation. These rocks include medium- to coarse-grained amphibolite and amphibole schist, biotite-bearing schist and gneiss, and coarse-grained quartz-muscovite gneiss, in all of which a very steeply dipping planar structure trends northeast to east. Beginning a short distance west of the pegmatite area, generally less than a mile, the Precambrian rocks are overlain by sandy to shaly limestone of Pennsylvanian age.

The pegmatite bodies occur as irregular dikes and discordant lenses that trend northerly and appear to have prevailing steep dips. They range in breadth from a few inches to 22 feet, and few exceed 150 feet in maximum dimension. As exposed in low outcrops and several small prospect openings, they are mainly medium- to very coarse-grained aggregates of quartz, perthite, and albite, with subordinate muscovite and lepidolite. The principal accessory constituents are apatite, beryl, spessartite, tantalum-niobium minerals, and topaz. Spodumene and amblygonite are present in some of the pegmatite bodies. Tourmaline, though rare in the pegmatites, is abundant in the immediately adjacent country rock.

Most of the pegmatite bodies are distinctly zoned. Typically they comprise outer zones with granitoid texture, and irregular, pod-like inner



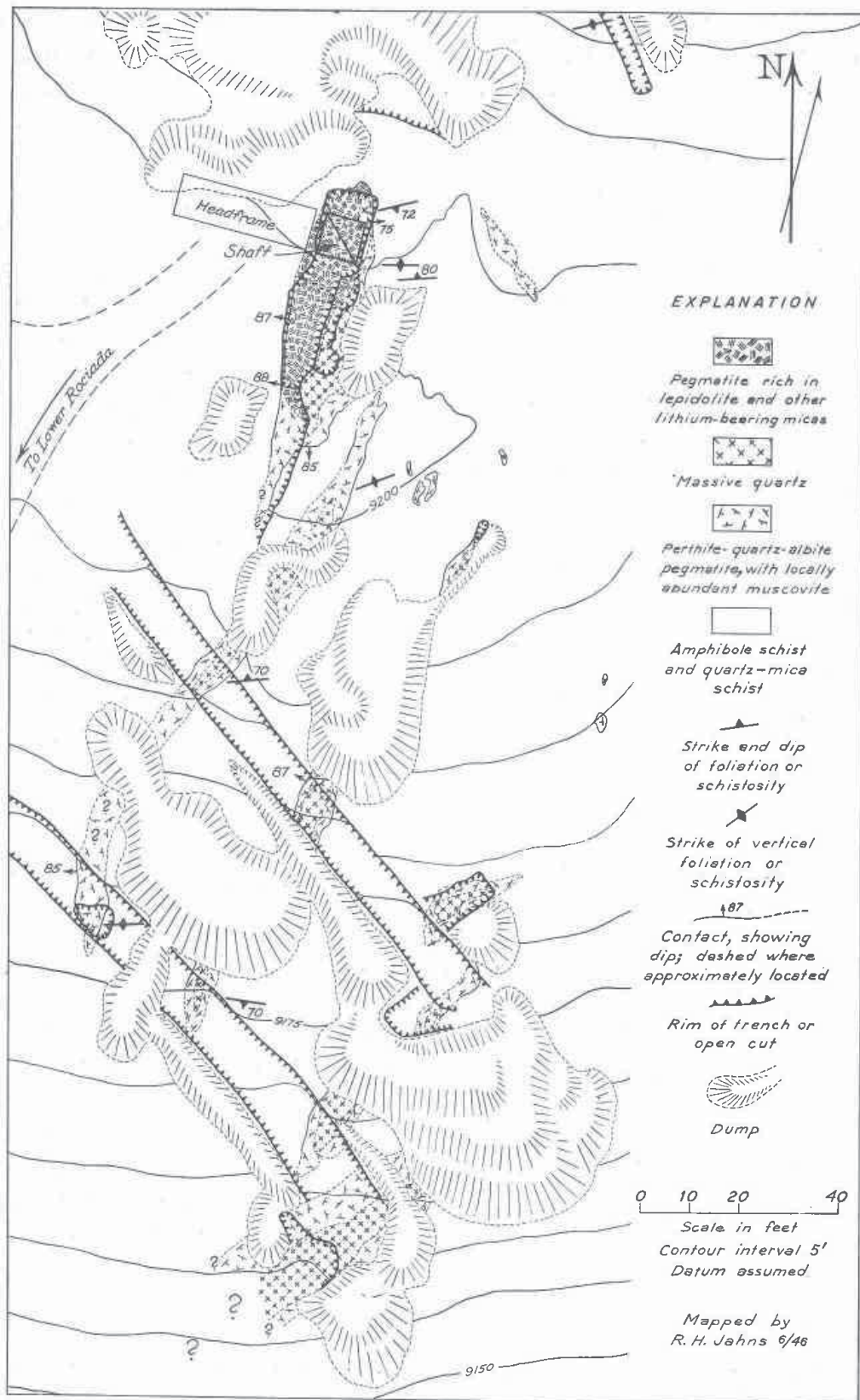


FIG. 1. Geologic map of the Pidlite mine area, Mora County, New Mexico.

zones in which very coarse-grained, anhedral quartz and large, euhedral crystals of perthite are most conspicuous. In addition, some of them also contain aggregates of quartz, cleavelandite, lepidolite, and muscovite that form veinlets, stockworks, and larger, lens-like masses with poorly defined margins.

#### DESCRIPTION OF THE PIDLITE PEGMATITE

##### *General features*

The Pidlite pegmatite lies at the crest of a prominent ridge between the headwaters of Sparks and Maestas creeks. It is a nearly vertical dike about 75 feet long and 18 feet in maximum exposed breadth, and was first prospected for lithium minerals at least two decades ago. It was stripped by means of a bulldozer in November 1945 largely on the basis of several inconspicuous showings of lepidolite-rich pegmatite, and was mined by open-cut methods early in the following year. Underground operations, conducted during 1946 and 1947 by the Hayden Mining Company, led to development of a 55-foot shaft and appended drifts in the northern part of the dike (Fig. 1). Small quantities of microlite and a modest tonnage of lepidolite constitute the commercial output from the deposit.

The locality was visited briefly by the writer in July 1943, and was studied and mapped in June 1946, April 1947, and July 1947, when mining operations yielded successively larger and more complete exposures of the pegmatite. It also was visited in 1948 by Page and McKinley (1950, p. 21), who prepared a sketch map of the dike, and in 1951 by Heinrich (1953, pp. 31–32), who devoted particular attention to the micas in the pegmatite.

The dike strikes north-northeast, and in most places is very sharply bounded from the adjacent country rock (Fig. 2), here mainly a fine-grained amphibole schist. It tapers abruptly southward, as shown in Figure 1, to form a 20-foot "tail" that is only 2 feet to 4 feet thick. About 10 feet of schist separates this thin part of the dike from the northeastern part of a second, nearly parallel dike that is 130 feet long and 3 feet to 10 feet thick. Farther southeast are at least four other subparallel, pinching-and-swelling dikes, which are exposed mainly in test pits and two exploratory trenches (Fig. 1). All these dikes in the mine area dip very steeply, and are arranged en echelon to form a north-trending pegmatite belt that is about 100 feet wide.

##### *Structure*

Excepting its relatively thin "tail," the Pidlite dike has the form of a discoidal lens whose major axes are essentially horizontal and vertical,





FIG. 2. View of main open cut, Pidlite mine, looking northeast. Note sharp contact between pegmatite and country rock in wall of cut immediately to left of the sacked lepidolite. Man is standing on contact between rib-like mass of quartz (at left) and perthite-quartz-albite pegmatite (at right).

respectively. As traced downward from its outcrop, it has a slight but prevailing hade to the east-southeast, and this is accentuated by a pronounced bend in both walls about 35 feet beneath the surface (Fig. 3). A second, much sharper jog in the opposite direction at the 55-foot level reflects a 10-foot to 12-foot displacement along a gently dipping fault. The north edge of the lens is fluted, and has a very steep northward plunge. The fluting is broadly expressed at and near the surface as three rounded bulges, and at greater depths it appears as more elongate projections (Fig. 3). The south edge of the lens, at the base of the "tail" of the dike, has a similar shape but appears to plunge less steeply northward and to become somewhat less well defined with depth.

The dike consists of seven readily distinguishable types of pegmatite, four of which form typical zones (Cameron *et al.*, 1949, pp. 13–24). As shown in Figure 4–I, these zones have a broadly concentric arrangement, and hence reflect the general shape of the pegmatite body. The other three rock types, which are most extensively developed in the northern and western parts of the dike, form units that are similar to the zones in

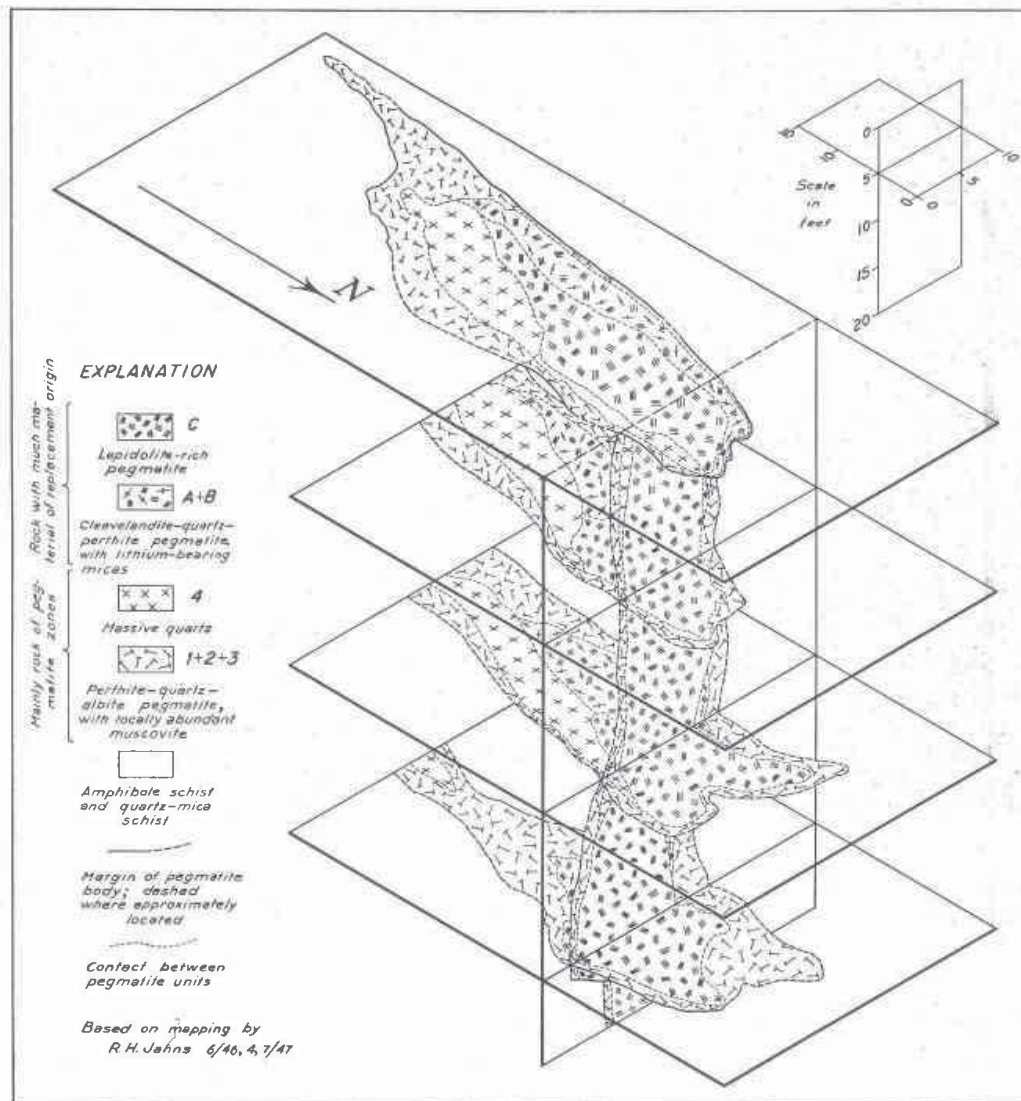


FIG. 3. Isometric plate diagram of the Pidlite pegmatite body, showing distribution of major units in the dike.

shape and disposition, but are distinguished by their content of minerals that appear to have been developed by replacement of earlier pegmatite minerals. It is with the origin of these units that much of this paper is concerned.

The surface distribution of all the pegmatite units is indicated in Figure 4-I. Their distribution in three dimensions is shown in more generalized form by the diagram in Figure 3, and they are further generalized on the map of the mine area (Fig. 1).

The outer zones of the dike are relatively thin and continuous, and thus form envelopes around the lenticular to pod-like inner units. The inner units are present only in the thick part of the dike, where they form



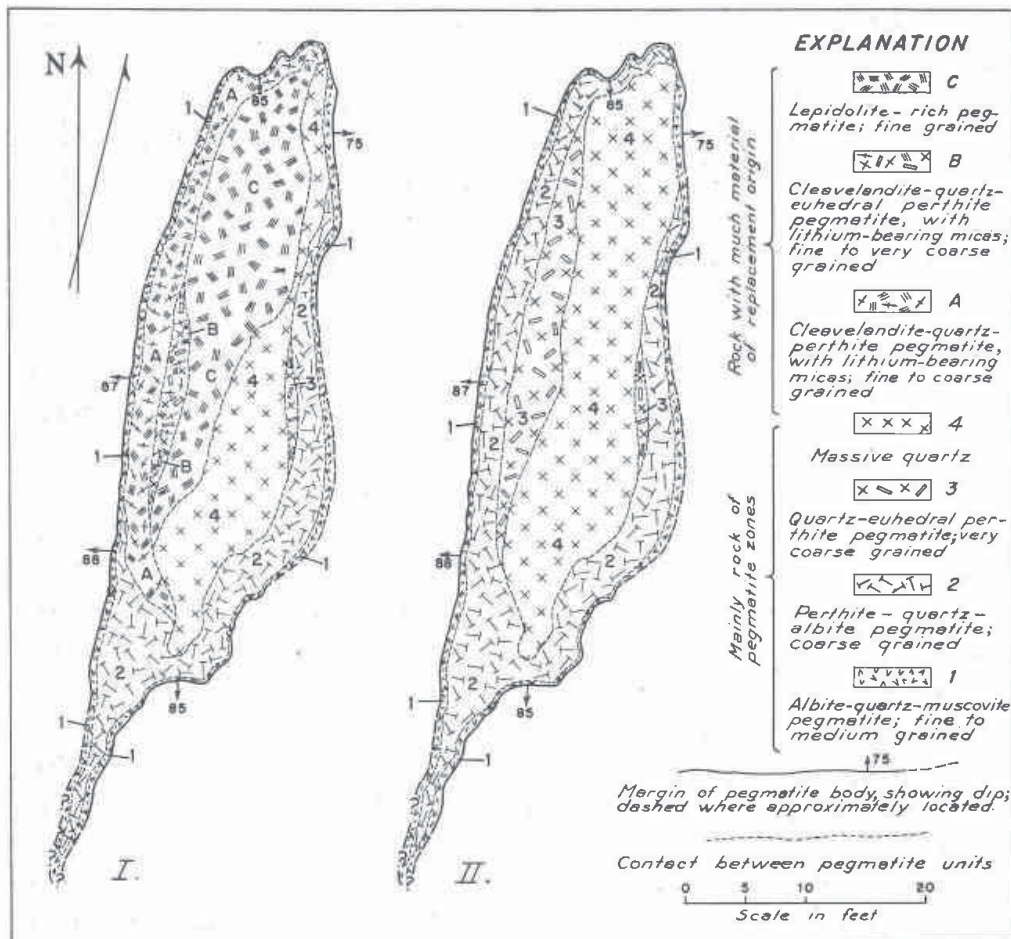


FIG. 4. Surface plan of Pidilite dike, showing distribution of pegmatite units. I. Distribution of units as they now exist. II. Possible distribution of zones, had there been no development of the composite units.

more than half of its outcrop breadth. As they are traced downward beneath the outcrop, their major horizontal axes decrease in length, evidently in response to the slight downward convergence of the ends of the main, thick part of the dike (Fig. 3).

### Zones

The border zone of the dike (unit I in Fig. 4) is a fine- to medium-grained selvage, 3 inches to 2 feet thick. It consists of calcic to median albite, quartz, and muscovite, with minor perthite and accessory apatite, beryl, fluorite, spessartite, and schorl. The immediately adjacent wall zone (unit 2, Fig. 4), which is about 2 feet in average thickness, is a coarse-grained, granitoid aggregate of perthite, quartz, and median albite, with minor muscovite and a suite of accessory minerals similar to that of the border zone. It also contains irregular masses of quartz and

fine-grained greenish muscovite, as well as scattered veinlets and fist-sized pods of cleavelandite and pink muscovite.

An intermediate zone of very coarse-grained quartz-euhedral perthite pegmatite (unit 3, Fig. 4) forms a thin lens on the east side of the dike. It contains accessory beryl and spessartite, and is cut by numerous veinlets and irregular aggregates of coarse-grained cleavelandite and muscovite. This zone is grouped with the border zone and the wall zone in the diagram of Figure 3.

The most conspicuous zone in the dike consists chiefly of very coarse-grained, anhedral quartz (unit 4, Fig. 4), and crops out as a bulbous to rib-like mass that is sharply bounded from the adjacent more feldspathic pegmatite (Figs. 2, 5). Some apophyses of quartz extend outward from this unit into the earlier-formed zones that flank it.

In the outer parts of the fourth zone are scattered crystals of perthite, and in its inner parts are a few prisms of topaz and numerous lath-shaped crystals of spodumene. At least three zones could be distinguished and mapped on the basis of the presence or absence of these other minerals, but for simplicity they are grouped together as one quartz-rich unit. Cleavelandite, muscovite, and lepidolite occur in the quartz as irregular bunches and lenses, and as stockworks of fracture-controlled veinlets. Locally these late-stage minerals constitute as much as one-third of the rock.

The other dikes in the mine area show similar zonal structure, except that in many places the border and wall zones constitute the entire thickness of exposed pegmatite. The cores of these dikes consist mainly of massive quartz, and occur as lens-like segments 2 inches to 10 feet thick and 15 inches to about 50 feet long (Fig. 1). Locally they are flanked by thin, discontinuous intermediate zones of quartz-euhedral perthite pegmatite.

#### *Composite units*

The other three units of the dike plainly are composite, in the sense that they contain two well defined generations of minerals. One of these units (A, Fig. 4), a thin, curving mass near the west wall of the dike, is a fine- to coarse-grained aggregate of cleavelandite, quartz, perthite, median albite, lepidolite, and white to pink muscovite. The micas and cleavelandite vein and corrode the other minerals, and appear to have been developed largely at their expense. This unit grades southward into the granitoid wall zone described above, and contains the same suite of accessory minerals as the wall zone.

A second, much smaller composite unit (B, Fig. 4), is analogous to the quartz-euhedral perthite zone on the opposite side of the dike, but is

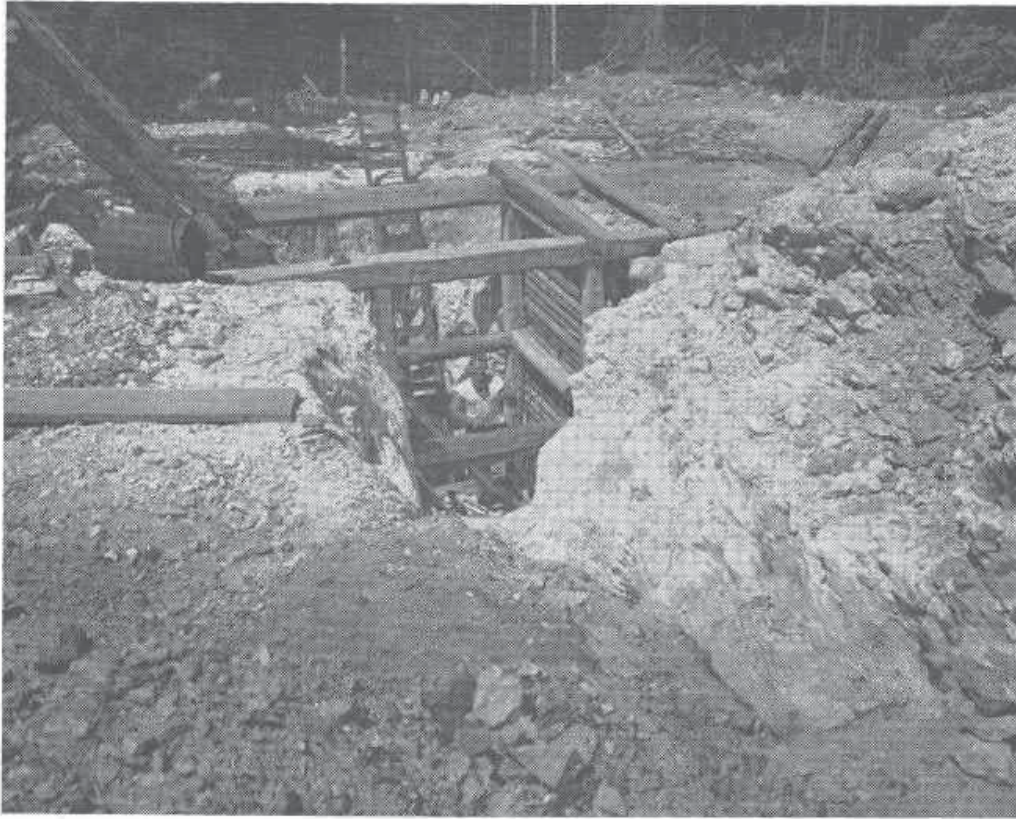


FIG. 5. View of shaft and part of main open cut, Pidlite mine, looking northeast. The openings are in lepidolite-rich pegmatite. Massive quartz with blocky fracture is exposed high on wall of cut at right.

characterized by abundant albite, muscovite, and lepidolite that transect and corrode the earlier crystals of quartz and potash feldspar. All stages in the replacement of perthite by sodic albite can be observed, and numerous pseudomorphs of cleavelandite and of fine-grained, sugary albite after perthite are present. The micas appear to have replaced quartz along fractures and crystal boundaries, and pseudomorphs of muscovite and lepidolite after topaz and spodumene also can be recognized.

The third composite unit (C, Fig. 4) consists mainly of lepidolite. As shown in Figures 3, 4, and 5, it is a bulbous, centrally disposed mass that is thickest in the northern part of the dike. It grades westward and northward into the composite units described immediately above, and eastward and southward into the zone that is rich in massive quartz. In its outer parts are conspicuous evidences of replacement of quartz, potash feldspar, spodumene, and topaz by sodic albite and micas, but its inner parts, which are composed almost wholly of fine-grained lepidolite (Fig. 6) with minor albite and tantalum-niobium minerals, show no such evidences of replacement. As pointed out later on, the total *amount* of de-



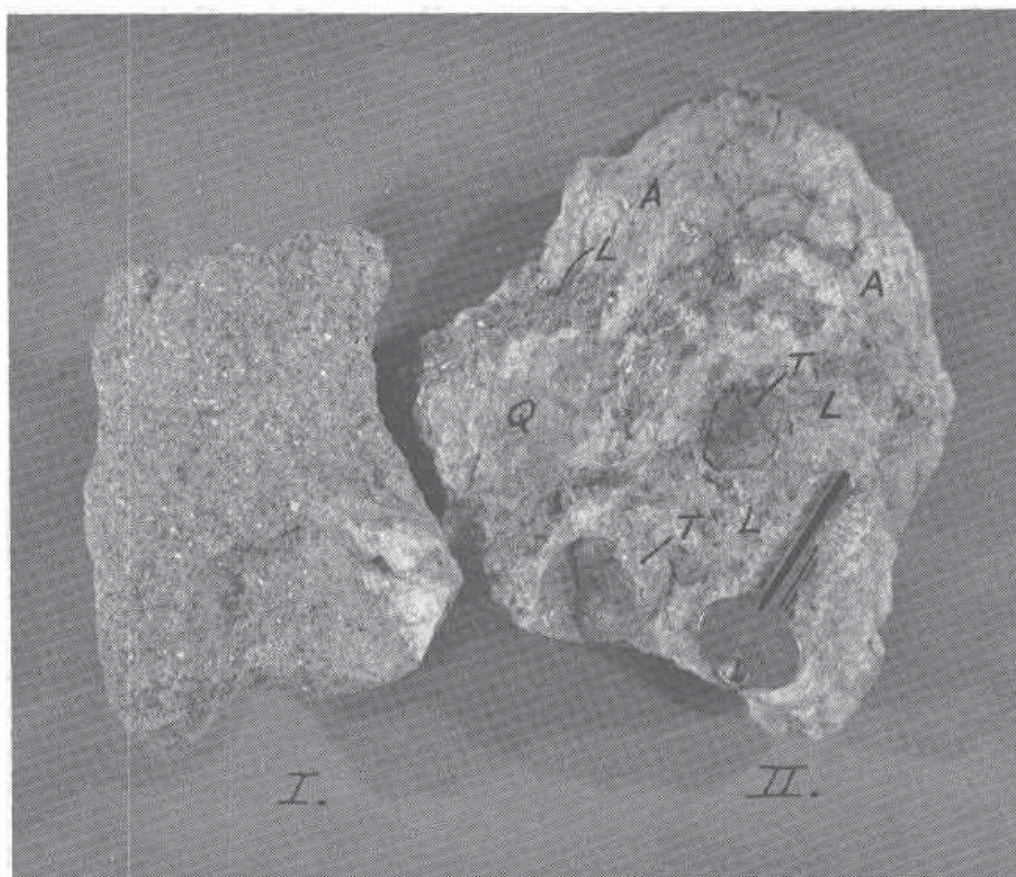


FIG. 6. Lepidolite-bearing pegmatite, Pidlite dike. I. Fine-grained lepidolite from inner part of unit C. II. Crystals of topaz (T) and residual mass of quartz (Q) in aggregate of lepidolite (L) and sodic albite (A), in rock from outer part of unit C.

monstrable replacement in this unit is not as great as one might estimate from a casual inspection of the rock, in which *qualitative* evidence for corrosion and replacement is both impressive and widespread.

No similar large composite units are definable within the other dikes of the mine area. Cleavelandite, lepidolite, and pink muscovite do occur, however, as irregular veinlets and pods in parts of several quartz-rich core segments, where they resemble units A and B of the main dike. None of these is large enough to be represented separately on the map in Figure 1.

### *Mineralogy*

The Pidlite dike contains an assemblage of minerals strikingly similar to those of the Harding pegmatites (Jahns, 1951, pp. 52–53) farther north in New Mexico, the Brown Derby pegmatites (Eckel, 1933; Landes, 1935, p. 333; Hanley *et al.*, 1950, pp. 68–74), in Gunnison County, Colorado, the Stewart pegmatite (Jahns and Wright, 1951, pp. 30–42, 57–61),

in San Diego County, California, and to those of several other lithium-bearing pegmatites in the United States. These masses of rock are essentially granitic in composition, and consist chiefly of perthite, quartz, and sodic plagioclase. All of those specifically mentioned contain abundant lepidolite, and all but the Brown Derby pegmatites contain spodumene and small quantities of lithium-bearing phosphate minerals, as well. The similarities of their accessory-mineral suites, as indicated in Table 1, testify to a consistent occurrence of beryllium, bismuth, boron, columbium (niobium) and tantalum, fluorine, manganese, and rare-earth elements.

TABLE 1. ACCESSORY MINERALS OF THE PIDLITE PEGMATITE AND OTHER LITHIUM-BEARING PEGMATITES IN THE SOUTHWESTERN STATES

Mineral	Pidlite pegmatite, Mora County, New Mexico	Harding pegmatite, Taos County, New Mexico	Brown Derby pegmatite, Gunnison County, Colorado <sup>a</sup>	Stewart pegmatite, San Diego County, California <sup>b</sup>
Apatite	x	x	x	x
Beryl	x	x	x	x
Betafite	x	—	x	—
Beyerite	—	x	—	x
Bismite	—	x	—	x
Bismuth	x	x	—	x
Bismuthinite	—	x	—	x
Bismutite	x	x	—	x
Chalcocite	—	x	—	x
Columbite-tantalite	x	x	x	x
Cyrtolite	x	—	—	—
Elbaite	x	—	x	x
Fluorite	x	x	x	—
Gahnite	x	x	x	x
Hatchettolite	x	x	x	—
Lithiophilite	—	x	—	x
Loellingite	x	x	—	x
Magnetite	x	x	x	x
Microlite	x	x	x	x
Monazite	x	x	x	x
Pyrite	x	x	—	x
Schorl	x	x	x	x
Spessartite	x	x	x	x
Topaz	x	x	x	—
Zinnwaldite	—	—	x	x

<sup>a</sup> List furnished by J. B. Hanley, U. S. Geological Survey.

<sup>b</sup> Jahns, R. H., and Wright, L. A., 1951, pp. 30-42.

The major minerals of the Pidlite dike, as traced from its borders inward to its center, show many of the variations that are characteristic for zoned pegmatites in general. The perthite, for example, becomes progressively coarser, and ranges in color from medium tan and flesh through pale buff to gray. The contained lamellae of albite also become coarser, as well as increasingly sodic, toward the center of the dike. The characteristic plagioclase of the border zone is gray albite in the  $Ab_{90-95}$  range, whereas that of the wall zone is whiter and has the composition  $Ab_{94-97}$ . The albite of the inner pegmatite units is extremely sodic, and occurs both as lustrous, white, sugary aggregates and as sheaves and clusters of white to dark pearly gray cleavelandite. Most of the cleavelandite blades are 1 inch to  $6\frac{1}{2}$  inches long, and typically are curved and bent. The coarsest crystals are mottled white to medium bluish gray.

Spodumene, which occurs mainly with quartz in the central part of the dike, forms chunky prismatic crystals one-half inch to 14 inches in maximum dimension. These are white to greenish gray, and have a dull to waxy luster. Most are partly altered to very fine-grained albite, micas, and clay minerals, and resemble the altered crystals described, for example, from lithium-bearing pegmatite in Colorado (Hanley *et al.*, 1950, p. 13), Arizona (Jahns, 1953), southern California (Jahns and Wright, 1951, pp. 36-37), and the Black Hills region of South Dakota (Schwartz and Leonard, 1926). In addition, some of the crystals are veined and partly replaced by coarser-grained aggregates of white to pink muscovite and lithium-bearing micas; where replacement has been complete, the mica pseudomorphs retain the crystal outlines and even traces of the prismatic cleavage of the original spodumene.

Topaz occurs as white to gray prisms that are characteristically rhombic in cross section (Fig. 6-II). Most are cigar shaped, and are 1 inch to 5 inches long. The crystals are somewhat rounded, and are sheathed with flaky to waxy aggregates of white and pale pink muscovite and paragonite. In addition, many of them are rimmed, veined, and otherwise partly replaced by micas of varying coarseness (Fig. 7). The fresh topaz has the following optical properties:  $\alpha=1.616$ ,  $\beta=1.618$ ,  $\gamma=1.625$ , all  $\pm 0.002$ ;  $2V$  approximately  $60^\circ$ . These data suggest the presence of 10 to 15 mol. per cent of the hydroxyl-bearing member in the formula for this material (Winchell and Winchell, 1951).

Beryl is present in nearly all the pegmatite units. It forms white to gray anhedral crystals in the outer zones, very pale pinkish, nearly equant subhedral crystals in the inner zones, and rare white, tabular euhedral crystals in the lepidolite-rich units. None of the observed crystals is greater than 3 inches in maximum dimension, and most are less than an inch. The  $\omega$  index of refraction of this mineral ranges from 1.583



for some crystals in the border zone to 1.595 for several of those in the central units. This indicates a relatively high content of alkali elements (Schaller, oral communication), particularly cesium and sodium, in all of the beryl, as well as a progressive increase in the proportions of these elements as the mineral is traced from the margins of the dike inward to its center. This consistent trend in alkali content seems to be a widespread characteristic of the beryl in zoned pegmatite bodies (see, for example, Cameron *et al.*, 1949, pp. 69, 99; Fersman, 1931; Heinrich, 1952; Jahns and Wright, 1951, pp. 37–38; Jahns and Adams, 1953; Landes, 1925, p. 374), and constitutes a strong argument for crystallization of this mineral from a magma during successive development of the zones in a given pegmatite body.

The most widespread accessory constituents of the outer pegmatite zones are pale to bluish gray apatite, colorless to gray fluorite, lustrous red spessartite, and minor schorl in small prisms and needles. Tiny crystals of cyrtolite are present as inclusions in scattered small books of biotite, which are present only at the borders of the dike. White to pale bluish amblygonite occurs sparingly with spodumene and topaz in the inner part of the quartz-rich zone. Associated accessory constituents, present mainly in the massive quartz, include apatite, beryl, bismuth minerals, columbite-tantalite, gahnite, spessartite, and sulfides. These minerals, together with betafite, fluorite, and monazite, also occur in the wall zone, where they represent an association very similar to that reported from the Brown Derby pegmatites in Colorado (Page, 1950, p. 30).

Three generations of micas can be recognized in the Pidllite dike. Pale yellowish green and green muscovite is a minor constituent of the pegmatite zones, and is most abundant in the outer part of the dike, where it forms foils and thin plates  $\frac{1}{16}$  inch to about 3 inches in diameter. It is associated with a little biotite in the border zone. A younger generation of mica is represented by lepidolite, which is widely distributed, as already noted, and is particularly abundant in the central parts of the dike. Most of it forms dense aggregates of small, thick, crystals (Fig. 6), which range in color from pinkish gray through lilac and pale lavender to pale purple. Other crystals are much coarser, and thin plates 2 inches to 5 inches in diameter form fringes around rosettes of cleavelandite blades in the outer composite units of the dike.

Similar coarse books form a relatively high proportion of the lepidolite in the other dikes of the mine area, in which they are closely associated with albite, and especially with the cleavelandite variety. The lepidolite commonly veins and corrodes the albite in detail, and on a larger scale replaces other, earlier minerals in the pegmatite.

The youngest micas in the main dike are white to pale pink muscovite

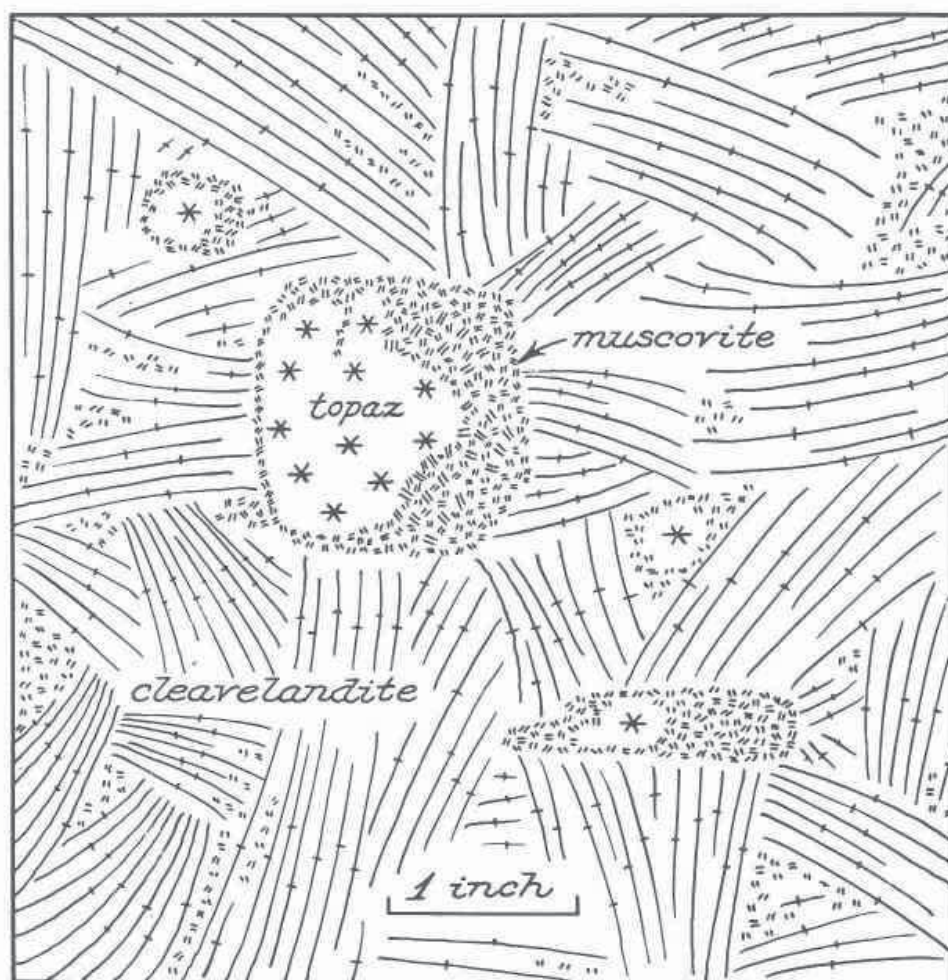


FIG. 7. Peripheral replacement of topaz crystals by pink muscovite, outer part of Unit C, Pidlite dike.

and paragonite, which form waxy to finely crystalline aggregates that are most abundant in the pegmatite immediately adjacent to the lepidolite-rich unit (C, Figs. 3, 4). As pointed out by Heinrich and Levinson (1953, pp. 31–32), these aggregates are interstitial to blades of cleavelandite as elongate or irregular pods, generally an inch or less across. They also form irregular veinlets in aggregates of lepidolite and sugary albite, and in individual crystals of apatite, beryl, quartz, potash feldspar, and other earlier minerals. In addition, they form jackets around crystals of elbaite, spodumene, and topaz (Fig. 7). Some of these jackets contain individual flakes  $\frac{1}{8}$  inch to  $\frac{1}{2}$  inch in diameter, and resemble the aggregates of pink muscovite that replace spodumene in the Harding pegmatite (Heinrich and Levinson, 1953, pp. 29–31 and Plate I; Jahns, 1951, p. 53).

A few rough, opaque prisms of pale green to pink elbaite,  $\frac{1}{4}$  inch to 2 inches long, are scattered through some of the quartz-albite-lepidolite

pegmatite in the inner part of the dike. This tourmaline also forms small, distinctly flattened inclusions in some of the coarsest crystals of lepidolite. A little deep purple fluorite, in anhedral crystals  $\frac{1}{2}$  inch or less in maximum dimension, occurs with albite in the largest masses of lepidolite. Associated with it are small tabular crystals of monazite and columbite-tantalite.

Microlite is scattered through the lepidolite-rich unit in the northern part of the dike, and several concentrations of this and other tantalum-columbium minerals were encountered in the mine workings at about the 30-foot level. The microlite forms microscopic grains and honey-yellow to pale yellowish brown octahedral crystals  $\frac{1}{32}$  inch to  $\frac{3}{8}$  inch in diameter. Many of the crystals are zoned, with pale centers and dark-colored rims. Nearly all of the microlite has a specific gravity greater than 6.00 and an index of refraction above 2.00, as determined by immersion in selenium melts, and evidently is characterized by a high tantalum-niobium ratio.

Hatchettolite, the uranian microlite, also is present in the aggregates of lepidolite, where it forms small, roughly faced crystals with waxy to brightly resinous luster. They are dark mahogany brown to black, and are surrounded by haloes of discoloration in the enclosing lepidolite. In general appearance they resemble the hatchettolite of the Harding pegmatites and the uranian microlite of the Brown Derby pegmatites (Hanley *et al.*, 1950, pp. 72-73).

#### QUANTITATIVE ANALYSIS OF THE PIDLITE PEGMATITE

##### *General methods*

The mineralogic and chemical composition of the Pidlite pegmatite was determined quantitatively by a simple, though indirect, method. The difficulties of collecting representative composite or bulk samples of all the pegmatite units (or a single sample of the dike as a whole) for microscopic or chemical analysis were regarded as prohibitive, and hence the determinations were based instead upon three general types of data:

1. Dimensional measurements of pegmatite units, obtained directly in the field and indirectly from 23 detailed plans and sections of the pegmatite body.
2. Proportions of major minerals in each pegmatite unit, determined by measurements along closely spaced linear traverses.
3. Average composition of individual mineral species, obtained directly by chemical analyses of representative material and indirectly by means of optical data.

Mapping of the dike at the surface was done with plane table and telescopic alidade at a scale of 10 feet = 1 inch, and supplementary control



was set in by means of tape-triangulation and by tape-measured offsets from previously established lines. Additional direct measurements with a yardstick were used wherever needed to define irregularities in the contacts between pegmatite units, or between pegmatite and country rock. Similar techniques were used in the preparation of the subsurface plans and cross sections, except that a simple sight alidade was used with the plane table.

Areas of all pegmatite units were determined on each plan and section by means of a transparent measuring grid ruled in twentieths of an inch. The areas were converted to volumes by the so-called cross-section method, first by using successive plans as sections of the dike and then

TABLE 2. VOLUMES AND TONNAGES OF PEGMATITE UNITS IN THE PIDLITE DIKE

Unit	Volume (cubic feet)			Amount (short tons)
	Determined from suc- cessive plans of dike	Determined from suc- cessive cross- sections of dike	Average	
Zones				
1+2+3	16,172	16,138	16,155	1,353.1
Zone 4	7,568	7,552	7,560	633.1
Composite units				
A+B	3,834	3,852	3,843	321.9
Composite unit				
C	9,301	9,419	9,360	783.9
Total dike to 55-foot level (by summation)	36,875	36,961	36,918	3,092.0
Total dike to 55-foot level (by direct measurement)	37,007	36,919	36,963	3,095.7

by using successive cross-sections as the sections. The results were found to be in close agreement (Table 2). Calculations were based on the end-area formula:

$$V = 1/2H(A_1 + 2A_2 + 2A_3 + \dots + 2A_{n-1} + A_n),$$

where  $V$  is the volume of the solid,  $H$  is the distance between the parallel sections that form its ends, and  $A_1, A_2, A_3$ , etc. are the areas of equally spaced parallel sections of the solid. The more general prismoidal formula was used as a check, and yielded very similar results. All volumes were

converted to masses on the basis of a density factor of 11.94 cubic feet per ton of pegmatite.

Modal analyses of the pegmatite units were made megametricaly by the Wentworth method. Measurements of mineral intercepts were made in the field along linear traverses spaced one foot apart, and two sets of these traverses, at right angles to each other, covered each exposure of pegmatite. The respective intercepts were converted to volume proportions of minerals, and then to weight proportions. Most of the measuring was done with a 5-inch wheel mounted on the end of a rod. As the wheel was rolled along a given line on a rock exposure, its revolutions were recorded by means of an attached counter. A second counter, which could be engaged or disengaged by means of a clutch, was used to record the intercepts of a given mineral. The traverse was repeated for each of the other minerals exposed along the line. Direct measurements with a steel tape were made on a few irregular walls in the underground workings, where the mechanical device was limited in its usefulness.

Data on average composition of the muscovite, lepidolite, paragonite, and spodumene were obtained from chemical analyses of one or more composite samples of each species. The proportions of alkalis in the feldspars were estimated on the basis of partial chemical analyses of five composite samples. Perthites from two analyzed samples were examined in thin section, and the proportions of intergrown albite, as determined micrometrically, were found to be compatible with the proportions of  $K_2O$  and  $Na_2O$  indicated by the chemical analyses. Further micrometric work was done to check the proportions of perthitic albite in fourteen other samples, in order to broaden the basis for estimating the average composition of perthite in the dike.

### *Modal analyses*

Two major simplifications in the modal analyses of the dike and its component parts were made in order to save time without sacrificing accuracy or essential detail. First, although areas of all the pegmatite units were determined in the surface exposures and in several subsurface exposures of the dike, some of these units were grouped together, as shown in Figure 3, for the final calculation of modes. The border zone, wall zone, and quartz-euhedral perthite intermediate zone (Zones 1, 2, and 3) were considered together, as were two of the composite units (A and B). Second, none of the minor accessory minerals in the pegmatite was considered in the measurements, which were confined to quartz, perthite, calcic to median albite, cleavelandite and other highly sodic albite, muscovite and minor paragonite, lepidolite, spodumene, and topaz.

Table 2 shows the respective volumes and tonnages of the units that

were measured. These represent the part of the dike that lies between the surface and a level 55 feet beneath the collar of the shaft. The chief source of error in the figures is the possible occurrence of major irregularities in the subsurface disposition of the units at points where no exposures are provided by mine workings. Owing to this factor, it seemed unwise to attempt more elaborate methods for estimating the volumes. In the words of Jackson and Knaebel (1932, p. 117), "Somewhat intricate calculations involving higher mathematics have sometimes been advocated for making tonnage estimates, but since the basic data usually are not exact and often speculative it is questionable whether such refinements in calculation are warranted." Another source of error, plainly of much lesser import, is the application of a single conversion factor for calculating tonnage from the volumes of units that differ from one another in composition.

The linear-traverse method of analysis under the microscope has been so thoroughly discussed in the geologic literature (Chayes, 1946, 1949, 1951; Lincoln and Reitz, 1913; Thomson, 1930) that its megametric analogue, used in the present investigation, needs no elucidation here. The chief source of error in the mineral measurements almost certainly is one of sampling, and stems in large part from incomplete exposure of the dike in three dimensions, and from the markedly uneven distribution of certain mineral constituents in the rock. The proportion of exposed pegmatite, however, was unusually large, and fortunately the exposures

TABLE 3. MODES OF PEGMATITE UNITS IN THE PIDLITE DIKE

Mineral	Zones 1+2+3		Zone 4		Composite Units A+B		Composite Unit C	
	Proportion	Amount (short tons)	Proportion	Amount (short tons)	Proportion	Amount (short tons)	Proportion	Amount (short tons)
Quartz	29.8	403.2	87.3	552.7	19.5	62.8	9.6	75.2
Perthite	42.2	571.0	2.3	14.5	15.3	49.3	3.4	26.7
Albite: calcic to median	22.6	305.8	—	—	—	—	—	—
Albite: highly sodic	— <sup>a</sup>	—	5.0	31.7	38.1	122.6	21.5	168.5
Muscovite and minor paragonite	5.4	73.1	2.7	17.1	14.7	47.3	4.8	37.6
Lepidolite	Tr.	—	1.1	7.0	12.2	39.3	60.4	473.5
Spodumene	—	—	1.6	10.1	Tr.	—	Tr.	—
Topaz	—	—	Tr.	—	0.2	0.6	0.3	2.4
Total	100.0	1,353.1	100.0	633.1	100.0	321.9	100.0	783.9
Total traverse length (feet)	4,840.7		2,077.0		1,464.4		3,916.2	

<sup>a</sup> Cleavelandite and other highly sodic albite are present, but were grouped together with median albite in measurements of these zones.



were most nearly complete in those units with the coarsest and most irregularly distributed minerals.

The modes of the pegmatite units are recorded in Table 3. The total length of traverses in each unit was sufficiently great to insure a reasonably small analytical, or precision, error, and comparison of different sets of traverses within each unit indicated only a modest scattering in the proportions of individual minerals. No attempt was made to apply shape-factor corrections, as the only major minerals with markedly platy or elongate habit occur principally as aggregates of diversely oriented crystals.

The data in Tables 2 and 3 were used to calculate the mode of the entire mass of pegmatite between the surface and the 55-foot level, and the results appear in Table 4. Although a large proportion of the dike was available for study, it cannot be denied that significant error might well attend any assumption that the composition of its exposed parts is the same as its true bulk composition, either mineralogically or chemically. Unfortunately, there is no satisfactory means for determining the amount or composition of the pegmatite that lies beneath the deepest mine workings, or of the pegmatite that has been eroded from points above the present outcrop. On the basis of comparisons with numerous other, more fully exposed pegmatites with zonal structure and pod-like form, however, it might be assumed that the distribution of rock units along the vertical axis of the Pidlite dike is not fundamentally different from that along its major horizontal axis. If this assumption is correct, the mode of the entire dike cannot differ greatly from that recorded in Table 4, particularly with respect to quartz and feldspars. The proportion

TABLE 4. MODE OF THE PIDLITE DIKE

Mineral	Units in which mineral occurs in more than trace amounts	Amount (short tons)	Proportion
Quartz	All	1,093.9	35.4
Perthite	All	661.5	21.4
Albite: calcic to median	1+2+3	305.8	9.9
Albite: highly sodic	4+A+B+C	322.8	10.4
Muscovite and minor paragonite	All	175.1	5.7
Lepidolite	4+A+B+C	519.8	16.8
Spodumene	4	10.1	0.3
Topaz	A+B+C	3.0	0.1
Total		3,092.0	100.0

TABLE 5. COMPOSITION OF MAJOR MINERALS IN THE PIDLITE DIKE

	Quartz	Perthite <sup>a</sup>	Albite <sup>b</sup> (calcic to median)	Albite <sup>c</sup> (highly sodic)	Musco- vite <sup>d</sup> (and minor parag- onite)	Lepido- lite <sup>e</sup>	Spodu- mene <sup>f</sup>	Topaz <sup>g</sup>
SiO <sub>2</sub>	100.0	65.0	67.1	68.3	45.4	50.8	53.5	32.7
Al <sub>2</sub> O <sub>3</sub>	—	18.8	20.5	19.7	37.7	26.6	29.9	55.5
CaO	—	0.3	1.2	0.3	0.1	—	1.2	—
Na <sub>2</sub> O	—	2.0	10.7	11.4	2.5	2.7	4.3	—
K <sub>2</sub> O	—	13.9	0.5	0.3	9.8	10.5	3.4	—
Li <sub>2</sub> O	—	—	—	—	—	4.3	4.6	—
H <sub>2</sub> O	—	—	—	—	4.5	2.0	3.1	1.2
F	—	—	—	—	—	5.4	—	18.2
Total	100.0	100.0	100.0	100.0	100.0	100.0 <sup>b</sup>	100.0	100.0 <sup>i</sup>

<sup>a</sup> Based on average composition of 16.5 per cent pure albite, 1.5 per cent pure anorthite, and 82.0 per cent pure microcline, as estimated from two partial chemical analyses and optical data.

<sup>b</sup> Based on average composition of 91.0 per cent pure albite, 6.0 per cent pure anorthite, and 3.0 per cent pure microcline, as estimated from two partial chemical analyses and optical data.

<sup>c</sup> Based on average composition of 97.0 per cent pure albite, 1.5 per cent pure anorthite, and 1.5 per cent pure microcline, as estimated from a partial chemical analysis and optical data.

<sup>d</sup> Weighted average of two chemical analyses.

<sup>e</sup> Weighted average of four chemical analyses.

<sup>f</sup> Based on two partial chemical analyses of altered crystals, one partial analysis of a fresh crystal, and modal determinations of the ratio of fresh to altered material in the dike.

<sup>g</sup> Based on composition of 12 mol. per cent of  $[\text{Al}(\text{OH})_2\text{SiO}_4]$  and 88 mol. per cent of  $(\text{AlF})_2\text{SiO}_4$ , as estimated from optical data.

<sup>h</sup> Includes—2.3 correction for O equivalent to F.

<sup>i</sup> Includes—7.6 correction for O equivalent to F.

of lepidolite, however, would be appreciably smaller, and perhaps would amount to 12 or 13 per cent.

### *Chemical composition*

The composition of each major mineral in the dike is shown in Table 5, and the sources of the data are summarized in the footnotes. The figures should be regarded as approximate, even though an attempt was made to reduce sampling errors through the use of composite samples and by petrographic examination of specimens obtained from all parts of the dike. Where chemical analyses were available for different varieties of a

TABLE 6. BULK COMPOSITION OF THE PIDLITE DIKE, COMPARED WITH OTHER LITHIUM-BEARING PEGMATITE BODIES AND WITH GRANITES

	Pidlite dike, Mora County, New Mexico <sup>a</sup>	Main Harding dike, Taos County, New Mexico <sup>b</sup>	Main bulge of Stewart dike, San Diego County, California <sup>a</sup>	Granite of all geologic periods, average of 546 chemical analyses <sup>c</sup>	"Alka-line" granite, average of 12 chemical analyses <sup>c</sup>	Pre-cambrian granites of Colorado and New Mexico, average of 23 chemical analyses
SiO <sub>2</sub>	74.5	75.43	74.9	70.18	73.30	74.81
Al <sub>2</sub> O <sub>3</sub>	14.8	14.66	14.9	14.47	12.33	13.30
CaO <sup>d</sup>	0.2	0.23	0.1	2.87	0.72	0.75
Na <sub>2</sub> O	3.3	4.13	3.6	3.48	4.55	3.44
K <sub>2</sub> O	5.4	3.01	5.2	4.11	4.20	5.42
Li <sub>2</sub> O	0.7	0.76	0.7	— <sup>e</sup>	— <sup>e</sup>	Tr.
H <sub>2</sub> O	0.6 <sup>f</sup>	0.43 <sup>g</sup>	0.4 <sup>f</sup>	0.84 <sup>g</sup>	0.86 <sup>g</sup>	0.73 <sup>g</sup>
F	0.9	0.55	0.4	— <sup>e</sup>	— <sup>e</sup>	0.19
XO <sup>h</sup>	n.d.	0.88	n.d.	4.05	4.04	1.37
	100.4	100.08	100.2	100.00	100.00	100.01
Correction for O equivalent to F	0.4	0.23	0.2	—	—	0.1
<b>Total</b>	100.4	99.85	100.0	100.00	100.00	100.00

<sup>a</sup> Analysis calculated from the mode. Accessory minerals and minor chemical constituents are neglected.

<sup>b</sup> Chemical analysis of composite sample from cores of 39 diamond-drill holes in thickest part of the dike. Eileen H. Oslund and Samuel S. Goldich, analysts; Li<sub>2</sub>O determined by R. B. Ellestad.

<sup>c</sup> Quoted from Daly, R. A., 1933. *Igneous rocks and the depths of the earth*, pp. 9–10, McGraw-Hill Book Company, Inc., New York.

<sup>d</sup> Includes small amounts of MgO.

<sup>e</sup> Not included in calculations.

<sup>f</sup> Represents OH in micas, topaz, and altered spodumene.

<sup>g</sup> Includes H<sub>2</sub>O+ and H<sub>2</sub>O—.

<sup>h</sup> Includes Fe<sub>2</sub>O<sub>3</sub>, FeO, MnO, CO<sub>2</sub>, TiO<sub>2</sub>, and P<sub>2</sub>O<sub>5</sub>, wherever respectively determined.

given mineral—as, for example, green and pink muscovite—their averages were weighted in accordance with the respective abundance of each variety in the pegmatite. The data thus are thought to constitute a reasonably satisfactory basis for calculating the bulk composition of the exposed pegmatite, and it seems evident that further refinements not only would necessitate many additional analyses, but probably would be



limited in value by the degree to which the available exposures reflect the true composition of the pegmatite units.

The bulk composition of the Pidlite dike, as calculated from the data in Tables 4 and 5, is given in Table 6, which also shows analyses of the lepidolite-rich parts of the main Harding dike, about 30 miles to the northwest, and the Stewart dike, in southern California. The similarities in composition are evident. It should be noted that the analyses of the Pidlite and Stewart dikes were obtained by means of modal determinations, whereas that of the Harding was obtained chemically from one very large composite sample.

The composition of the Pidlite pegmatite does not differ greatly from that of Daly's average granite (Table 6), although the granite does contain considerably more total iron (included in XO, Table 6) and calcium. Daly's average, however, includes calcalkaline rocks, as well as some rocks that many geologists would regard as more nearly granodioritic than strictly granitic. The composition of the pegmatite even more closely resembles that of Daly's average "alkaline" granite, as well as that of average granite from the Precambrian terranes of Colorado and New Mexico, as calculated by the writer from 23 published analyses. The most notable differences in the constituents listed in Table 6 reflect a distinct concentration of lithium and fluorine in the pegmatites, and a higher proportion of mafic minerals in the granites.

It is not the purpose of this paper to discuss the implication of the figures in the table, but it seems worth while to emphasize the essentially normal granitic composition, in terms of all major constituents, of three pegmatites that are not likely to appear "normal" to the casual observer in the field. In particular, large masses of quartz in these and many other pegmatite bodies give an understandably exaggerated impression of the SiO<sub>2</sub> content of such bodies, and the occurrence of large crystals or crystalline aggregates of the less common minerals often gives a similar impression. Further, there has been a tendency among a few geologists to consider the genesis of pegmatites, and especially of zoned pegmatites, solely in terms of the composition of individual minerals or of restricted mineral groups. This approach can be misleading, especially if it is used as a measure of the composition of presumed fluids from which the minerals were formed. It would seem to be much more desirable first to approach the problem in terms of the composition of pegmatite zones and other units, as well as the bulk composition of entire pegmatite bodies.

#### ANALYSIS OF THE REPLACEMENT FEATURES

##### *The general problem*

Despite a few firmly expressed opinions to the contrary (for example,

Barth, 1952; Higazy, 1949), pegmatite zones commonly are regarded as products of fractional crystallization from a magma, or melt, with incomplete reaction between successive crops of crystals and rest-liquid (for example, Cameron *et al.*, 1949, pp. 79–106; Flawn, 1951, pp. 183–190; Jahns and Wright, 1951, pp. 44–45). This thesis has impressed many investigators as the most satisfactory means for explaining the structure, texture, and mineralogy of zones, as well as the chemical trends and age relations within and between such pegmatite units.

Nearly all zoned pegmatite bodies exhibit widespread evidences of replacement, and many contain masses of rock that appear to have been formed, wholly or in large part, at the expense of earlier pegmatite minerals. Such masses, or units, have been termed replacement bodies by Cameron, *et al.* (1949, pp. 84–85), who attempt to restrict the term to those units “formed by replacement at a stage following the complete crystallization of the parts of the pegmatite body affected by replacement.” They point out, however, that such units are not always readily distinguished from those in which replacement took place prior to complete consolidation.

Replacement of one mineral by another can occur at various stages during crystallization of the pegmatite magma under conditions approaching those of a closed system. Widespread reaction between crystals and rest-liquid, especially during the early stages, can be characterized as magmatic or late-magmatic, depending, perhaps, upon the extent to which the initial pegmatite magma itself reflects differentiation from a “normal” granitic magma. During a later stage, when residual liquid has been largely concentrated in the central part of the pegmatite body and in pores and other openings in its almost wholly crystallized outer parts, the effects of replacement can be characterized as post-magmatic (Chayes 1950, p. 36), high-temperature hydrothermal (Shand, 1944, p. 350), or simply as deuteric. The effects of replacement during this stage are gradational from those of the earlier stages, except that hydroxyl-bearing silicates commonly are more abundant and the effects of replacement tend to be much more localized.

As the more volatile constituents in the residual liquid are increasingly concentrated by crystallization of minerals that do not contain these constituents, or contain them only in small proportions, a second fluid phase may separate, either as a liquid saturated with alkali salts (Shand, 1944, p. 348) or as a vapor. This second phase can react with previously formed crystals, and, if it leaves the residual fluid as a vapor that condenses elsewhere in the pegmatite body, the condensate can be highly reactive (Bowen, 1933, pp. 124–125). Mineral replacements accomplished by this second phase, which is relatively rich in water and other volatile constituents, ordinarily are referred to as hydrothermal. The reacting fluid

commonly appears to have been controlled in its distribution by fractures in the earlier-formed rock, and it is largely to masses of pegmatite formed by this type of fracture-controlled replacement that Page (1950, pp. 15–23), for example, restricts the term replacement body.

Alternative mechanisms for explaining the replacement features in pegmatites bespeak open-system conditions, and commonly involve the introduction of hydrothermal fluids from sources outside the pegmatite bodies. According to one possible mechanism, solid pegmatite first is formed by a magmatic process, and then, as described by Schaller (1926, p. 59), is acted upon hydrothermally in an open system, with “much material moving, coming in, and going out.” An alternative mechanism, advocated in various forms by Andersen (1931), Quirke and Kremers (1943), and others, involves deposition of successive layers of pegmatite from solutions traveling along a channelway. The deposition is accompanied, under these open-system conditions, by various mineral replacements. Still other investigators make no specific suggestion as to the immediate source of the replacing fluids, although it is clear that they recognize two stages in the development of certain pegmatite bodies. Björlykke (1937, p. 244), for example, notes that some granitic pegmatites in southern Norway “were subsequently influenced by solutions and gases following cracks in the already congealed magmatic pegmatite, thus forming deposits of hydrothermal-pneumatolytic origin. . . .”

As pointed out by Cameron, *et al.* (1949, p. 105), the development of some replacement bodies can be correlated with development of an inner zone in the same pegmatite body, and the source of the material thereby established. Consistencies in distribution, age relations, and trends in mineralogy and composition of replacement units in many pegmatite bodies have impressed some investigators as evidences of closed-system, or restricted-system, conditions during development of these pegmatites. Further, many replacement units occur as apophyses that extend outward from the central, or youngest, parts of the containing pegmatite body, suggesting development from a source within the body, perhaps under deuteric conditions.

A major question often is raised concerning the amounts of material involved in replacement reactions within a given pegmatite body. If the replacement minerals are small in amount, as compared with the earlier-formed magmatic pegmatite, it seems reasonable to regard them as the products of residual solutions accumulated during final consolidation of the pegmatite body. On the other hand, numerous investigators have pointed out (Cameron *et al.*, 1949, p. 106) that “where the volume of replacement material is great in proportion to the total volume of pegmatite . . . an appeal to solutions from outside the pegmatite becomes more attractive.” Unfortunately, however, little is known about the quantita-



tive relations of replacement, and especially about the net gains and losses of elements during replacement, in the very pegmatite bodies that contain the most conspicuous evidences of this process.

Evidences of replacement are so well developed in the Pidlite dike that no observer would deny the widespread occurrence of replacement minerals, especially in the units that contain large proportions of cleavelandite, lepidolite, and pink to white muscovite. The quantitative relations in these composite units, however, are considerably less obvious. An attempt was made to evaluate them by means of detailed measurements, in the hope that they might be useful in connection with the problems discussed above.

#### *Quantitative relations*

The texture and mineralogy of the outer composite unit (A) of the Pidlite dike indicate that it comprises minerals of the wall zone (Zone 2) and minerals formed mainly by replacement of typical wall-zone constituents. Similarly, the middle composite unit (B) evidently was developed by widespread partial replacement of a segment of the quartz-euhedral perthite intermediate zone (Zone 3) and a marginal part of the massive-quartz zone (Zone 4). The lepidolite-rich composite unit (C) clearly was developed in part from the massive-quartz zone and in small part from the quartz-euhedral perthite zone, but much of its inner portion, though composed of late-stage minerals, shows no evidences of a replacement origin. Figure 4-II indicates what the zonal structure of the dike might have been, had there been no development of the composite units. By analogy with other zoned pegmatites in which no lepidolite-rich units are present, the central zone probably would have consisted mainly of very coarse-grained, anhedral quartz.

All exposures of the composite units were studied in detail, in order to determine the minimum amounts of earlier minerals that were present before partial replacement by later minerals. The original outlines of earlier crystals, now wholly or in part replaced by albite and micas, were restored as accurately as possible, chiefly on the basis of recognizable pseudomorphs and the distribution of residual masses of the earlier material (Fig. 8). These outlines were sketched in with crayon on the exposed surfaces of rock, and the total proportion of material whose existence prior to replacement could be thus demonstrated was determined megametrically by means of linear traverses. By this means, it was found that the rock in units A and B must have been at least 95 per cent solid prior to corrosion and replacement by albite and micas, and the rock in unit C must have been at least 22 per cent solid prior to attack of its early-formed constituents. It should be noted that these are minimum esti-

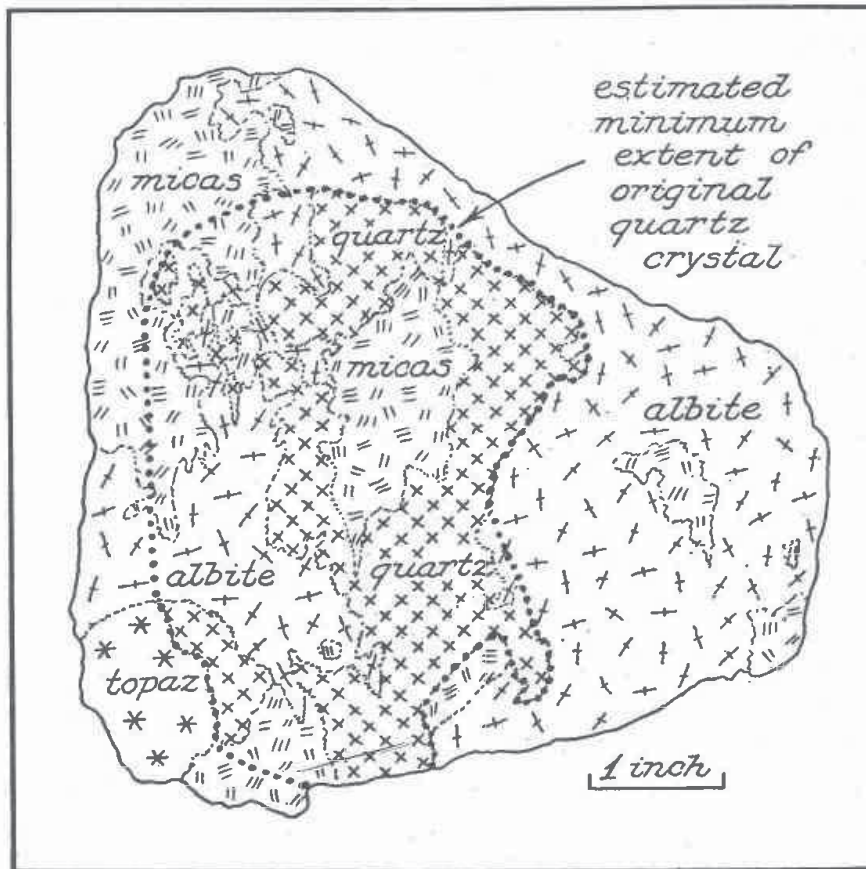


FIG. 8. Specimen of complex pegmatite from outer part of unit C, Pidilite dike, showing general method used to estimate the amount of quartz removed through replacement by albite and micas.

mates, and that much additional solid material may have been removed completely during development of the composite units, without leaving recognizable evidence of its former presence.

Analysis of mineral distribution in the composite units, as determined by study of the exposures in the field, indicates that the rock of units A+B was derived from a volume of material whose composition can be represented as follows:

	<i>Per cent</i>	<i>Short tons</i>	
Material X, which yielded Units A+B =	Zone 2	63.5	204.4
	Zone 3	20.0	64.4
	Zone 4	11.5	37.0
	Not accounted for (=fluid?)	5.0	16.1
		100.0	321.9

Similarly, unit C appears to have been derived from earlier material of the following composition:

	<i>Per cent</i>	<i>Short tons</i>	
Material Y, which yielded Unit C =	Zone 3	1.0	7.8
	Zone 4	21.0	164.6
	Not accounted for (=fluid?)	78.0	611.5
		100.0	783.9

No change of weight is assumed in comparing units A, B, and C with their antecedents, materials X and Y. The compositions of X and Y, converted in part to proportions and amounts of contained minerals, are as follows:

<i>Material X</i>			<i>Material Y</i>		
	<i>Per cent</i>	<i>Short tons</i>		<i>Per cent</i>	<i>Short tons</i>
Quartz	42.5	136.8	Quartz	20.8	162.6
Perthite	41.6	133.9	Perthite	0.7	5.5
Albite (calcic to median)	9.0	29.0	Spodumene	0.5	4.3
Muscovite	1.4	4.5	Not accounted for	78.0	611.5
Spodumene	0.5	1.6	(=fluid?)		
Not accounted for (=fluid?)	5.0	16.1			
	100.0	321.9		100.0	783.9

The processes involved in converting material X to units A and B and converting material Y to unit C, considered together in quantitative



terms, resulted in net losses of 161.4 tons of quartz, 63.4 tons of perthite, 29.0 tons of calcic to median albite, and 5.9 tons of spodumene, together with disappearance of pegmatite fluid or fluids and possibly of additional solid material for whose existence there is no present evidence. Attending these losses were net gains of 291.1 tons of sodic albite, 80.4 tons of muscovite, 512.8 tons of lepidolite, and 3.0 tons of topaz. These figures of course apply only to the composite units, and the relatively minor replacement features within the units mapped as true zones (Figs. 3, 4) are neglected in this approximate analysis.

The net losses noted above represent minerals that were eliminated, as such, through replacement by younger minerals, but not all of the younger minerals in the composite units need have been formed by replacement. Indeed, the net gain of 3 tons of topaz does not appear to represent replacement at all, as this mineral is an early-stage constituent of the composite units, and is partly replaced by the lepidolite and cleavelandite. It is younger, however, than most of the mineral constituents of materials X and Y. With regard to the lepidolite, if as much as half of the large central mass of this mineral were formed by replacement, substantial quantities of the earlier minerals must have disappeared without a trace.

TABLE 7. MINIMUM GAINS AND LOSSES OF OXIDES IN DEVELOPMENT OF COMPOSITE UNITS A, B, AND C FROM THEIR IMMEDIATE ANTECEDENTS, MATERIALS X AND Y

	Gain (From development of minerals by replacement and by direct crystallization from fluids) (Short tons)	Loss (From removal of solid material from X and Y by reaction and replacement) (Short tons)	Loss (Representing contri- butions from other parts of X and Y: fluid material and/or other replaced solid material) (Short tons)
SiO <sub>2</sub>	496.8	225.2	271.6
Al <sub>2</sub> O <sub>3</sub>	225.7	19.6	206.1
CaO	1.0	0.6	0.4
Na <sub>2</sub> O	49.0	4.6	44.4
K <sub>2</sub> O	62.6	9.2	53.4
Li <sub>2</sub> O	22.1	0.3	21.8
H <sub>2</sub> O	13.9	0.2	13.7
F	27.8	0.0	27.8
	898.9	259.7	639.2 <sup>a</sup>

<sup>a</sup> Discrepancy between this sum and 627.6, the sum of the "not-accounted-for" portions of Materials X and Y, represents the correction for O equivalent to F.

The net amount of material transfer involved in the mineral replacements was of course considerably less than the losses and additions of mineral species as such. The  $K_2O$  liberated during the albitization of potash feldspar, for example, was available for development of muscovite and lepidolite, and the  $Li_2O$  derived from spodumene was available for the development of lepidolite. The minimum gains and losses of oxide constituents are shown in Table 7, the right-hand column of which represents the bulk composition of the materials needed for net conversion of demonstrably solid parts of materials X and Y to the composite units A, B, and C.

The composition of these materials is expressed as proportions of oxide constituents in Table 8. This would be an approximation of the actual composition of fluids plus any earlier-formed solids, if the entire process of transfer took place under essentially closed-system conditions. On the other hand, if open-system conditions prevailed, much material probably would have been added to the system, and appropriate amounts of material would have escaped; in this case the figures in Table 8 would represent the effective composition of the materials that actually took part in final development of the composite units.

TABLE 8. COMPOSITION OF FLUID AND/OR SOLID MATERIAL NEEDED FOR NET CONVERSION OF THE DEMONSTRABLY SOLID PARTS OF MATERIALS X AND Y TO THE COMPOSITE UNITS A, B, AND C

SiO <sub>2</sub>	43.3
Al <sub>2</sub> O <sub>3</sub>	32.8
CaO	0.1
Na <sub>2</sub> O	7.1
K <sub>2</sub> O	8.5
Li <sub>2</sub> O	3.5
H <sub>2</sub> O	2.2
F	4.4
	101.9
Correction for O equivalent to F	1.9
	100.0

### *Discussion and conclusions*

Whether or not the composite units were formed under open-system conditions, it is interesting to compare the net composition of the very late-stage materials with the bulk composition of the dike (Tables 6 and 8). The dike as a whole is markedly richer in SiO<sub>2</sub>, but poorer in almost all other constituents. It should also be noted, however, that the con-

centrations of  $\text{Li}_2\text{O}$ ,  $\text{H}_2\text{O}$ , and F in the late-stage fluids (and solids, if present) need not have been as great as one might expect from casual observation of the inner units of the dike.

It has been emphasized that, although evidences of mineral replacement are widespread in the dike, the *amount* of demonstrable replacement material is relatively small as compared with the bulk of the pegmatite. Even in the lepidolite-rich composite unit, it cannot be proved that more than 22 per cent of the present space was occupied by solid material prior to the attack of this material by replacing fluids. For purposes of discussion, however, let it be assumed that as much as 85 per cent of this space actually was occupied by crystallized pegmatite prior to replacement, and that the replacement thus was much more extensive than is indicated by any evidence now available. The solid material probably would have consisted mainly of quartz and some potash feldspar and spodumene, as previously noted, and hence probably would have contained at least 630 tons of  $\text{SiO}_2$ . Inasmuch as the entire unit, as now exposed, contains only about 465 tons of  $\text{SiO}_2$ , at least 165 tons necessarily would have been expelled preferentially from the space now occupied by this rock.

There is little evidence for such wholesale expulsion of silica at a late stage in the development of the Pidlite dike. Indeed, the late-stage replacement in its outer parts, much of which seems best attributed, on structural grounds, to fluids that were ejected from its innermost parts, testifies to a large-scale introduction of Al, Na,  $\text{H}_2\text{O}$ , and F, but not of silica. The mineral replacements noted on earlier pages plainly involved reductions, rather than increases, in the proportion of  $\text{SiO}_2$  during development of the final products.

It might be argued, to be sure, that silica was expelled from the dike as a whole, and was fixed in silicate minerals within the surrounding country rock. This may well have happened on a small scale. Granting that much larger quantities could be disposed of in this way without effecting marked changes in the rock, no evidence of such major transfer could be found, despite the most careful search. A few veinlets of quartz do occur in the wallrock, but their total volume in the mine area is trivial. The only noteworthy change in the rock adjacent to the pegmatite body is the conversion of hornblende to biotite, and this almost certainly involves no increase in silica; moreover, it appears to be associated with the earlier, rather than the later, stages in the history of the dike. It can only be concluded that if large amounts of  $\text{SiO}_2$  were introduced into the country rock during development of the composite pegmatite units, their effects on the rock were too subtle to be recognized by ordinary examination in the field or under the microscope.



The quantitative analyses of pegmatite units and of replacement features in the dike indicate that all the observed relations can be accounted for if the zones were developed by fractional crystallization of a pegmatite magma, and if the composite units were developed in part by replacement of earlier-formed zonal material and in larger part by direct crystallization from residual fluid or fluids, especially if the period of major replacement began when 15 per cent to 25 per cent of the dike still was fluid. The general conditions would approach those of a closed system, with emphasis on transfer of materials within the pegmatite body during the latest stages of its development, rather than on introduction of some materials from sources outside the pegmatite body, accompanied by the escape of others into the enclosing country rock. That the dike actually did develop in this way is suggested by the textural, structural, compositional, and age relations of the different units, as well as by their disposition within the dike.

There is no positive evidence to indicate that the central part of the dike, now occupied mainly by lepidolite, was composed largely of solid material prior to development of lepidolite and other minerals by replacement of still earlier minerals. If it were, it would be difficult to account for the implied removal of  $\text{SiO}_2$  in large quantities by fluids whose sources lay wholly within the dike. The ratio of expelled silica to fluids available for carrying this silica would be very high, and the effects of deposition from such concentrated solutions should be evident within or adjacent to the dike.

More dilute solutions presumably could have removed the silica and distributed it through large volumes of country rock, but the source of such solutions necessarily would lie outside the margin of the dike, owing to the large amounts of fluid material required. This in turn bespeaks open-system conditions during the end stages of the pegmatite formation, for which there is little evidence in the Pidlite dike. It seems best, therefore, to regard development of the lepidolite as involving both replacement of earlier minerals and direct crystallization from residual pegmatite fluid.

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