BUREAU OF ECONOMIC GEOLOGY
The University of Texas
Austin 12, Texas

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PEGMATITES OF THE VAN HORN MOUNTAINS, TEXAS.[1]

PETER T. FLAWN.

ABSTRACT.

Zoned and unzoned perthite-quartz-plagioclase-muscovite pegmatites in the form of tabular bodies, irregular bodies with tabular branches, irregular masses, elongate lenses, *lit-par-lit* zones, and small augen and stringers are distributed throughout the Precambrian metasedimentary rocks of the Mica Mine area, Van Horn Mountains, Texas. Zoned bodies have a core of perthite and quartz and a plagioclase-quartz-perthite-muscovite wall zone. The pegmatites contain numerous schist inclusions, and some show evidence of contamination by biotite schist and amphibolite.

Intimate penetration of the host rock by pegmatite fluids was accomplished by a combination of dilation and digestion. Dilation was effected by injection pressure and (to an unknown degree) orogenic stresses. Crystallization of a solution containing a large excess of potash took place in a closed or restricted system where a delicate balance of solubility factors was maintained for long periods or in a solution of low viscosity, thus facilitating growth of large crystals about a limited number of centers. Zoning and textural relationships are accounted for under these conditions. The importance of horizon and mode of emplacement in the formation of pegmatite textures and shapes is emphasized. A review of the granitization, palingenesis or anatexis, open-system (or aqueous), and magmatic theories of pegmatite origin shows that the features of Mica Mine pegmatites are best explained by the magmatic theory.

The Mica Mine area has possibilities of exploitation for feldspar and scrap mica.

INTRODUCTION.

PRECAMBRIAN metasedimentary rocks intruded by pegmatites are exposed in the Mica Mine area of the Van Horn Mountains (Fig. 1). The area is about 15 miles south-southwest of Van Horn, Texas, and is reached by a county road that turns south from U. S. highway No. 80 within the western limits of Van Horn.

The pegmatites of the Mica Mine area are mentioned in the reports of Von Streeruwitz (26, 27),[2] Baker (4), and Redfield (21), but no systematic investigation of the area was made prior to the present study. In a project by the U. S. Bureau of Mines (11) during World War II an investigation was made of the sheet (strategic) mica deposits of the Mica Mine. The project was confined to exploration, analysis, and metallurgical testing in conjunction with the operations of the Texas Mica and Feldspar Company.

The present study is a project of the Bureau of Economic Geology of The University of Texas.[3] The field work was done during 1949 and 1950. The

[1] This paper is part of a dissertation submitted to Yale University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
[2] Numbers in parentheses refer to Bibliography at end of paper.
[3] Published by permission of the Director, Bureau of Economic Geology, University of Texas.

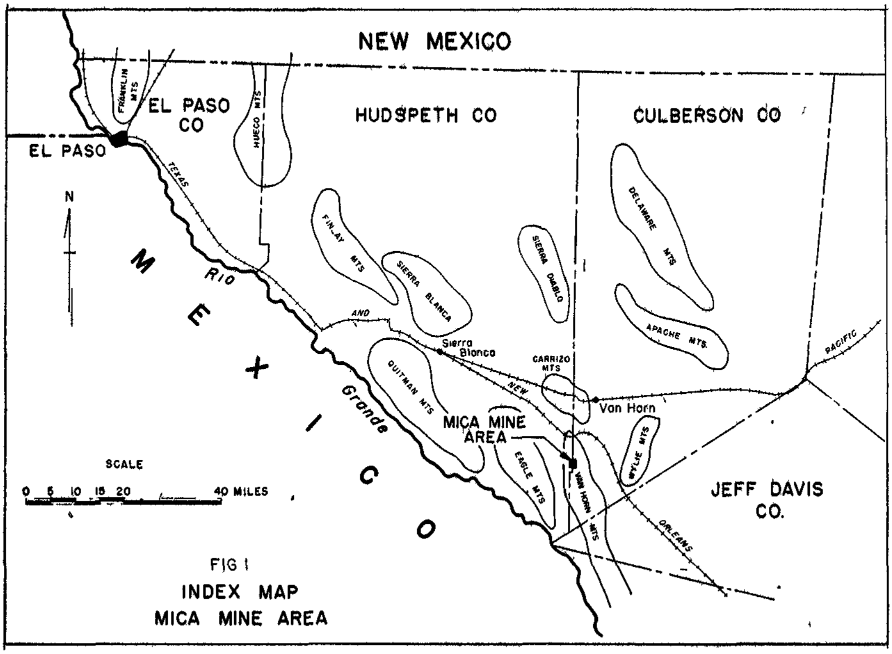


FIG 1
INDEX MAP
MICA MINE AREA

entire area was mapped by plane table and telescopic alidade on a scale of 200 feet to the inch (Fig. 2). The area around the Mica Mine No. 1 (Fig. 14), from which most of the sheet mica produced to date was recovered, was mapped on a scale of 40 feet to the inch.

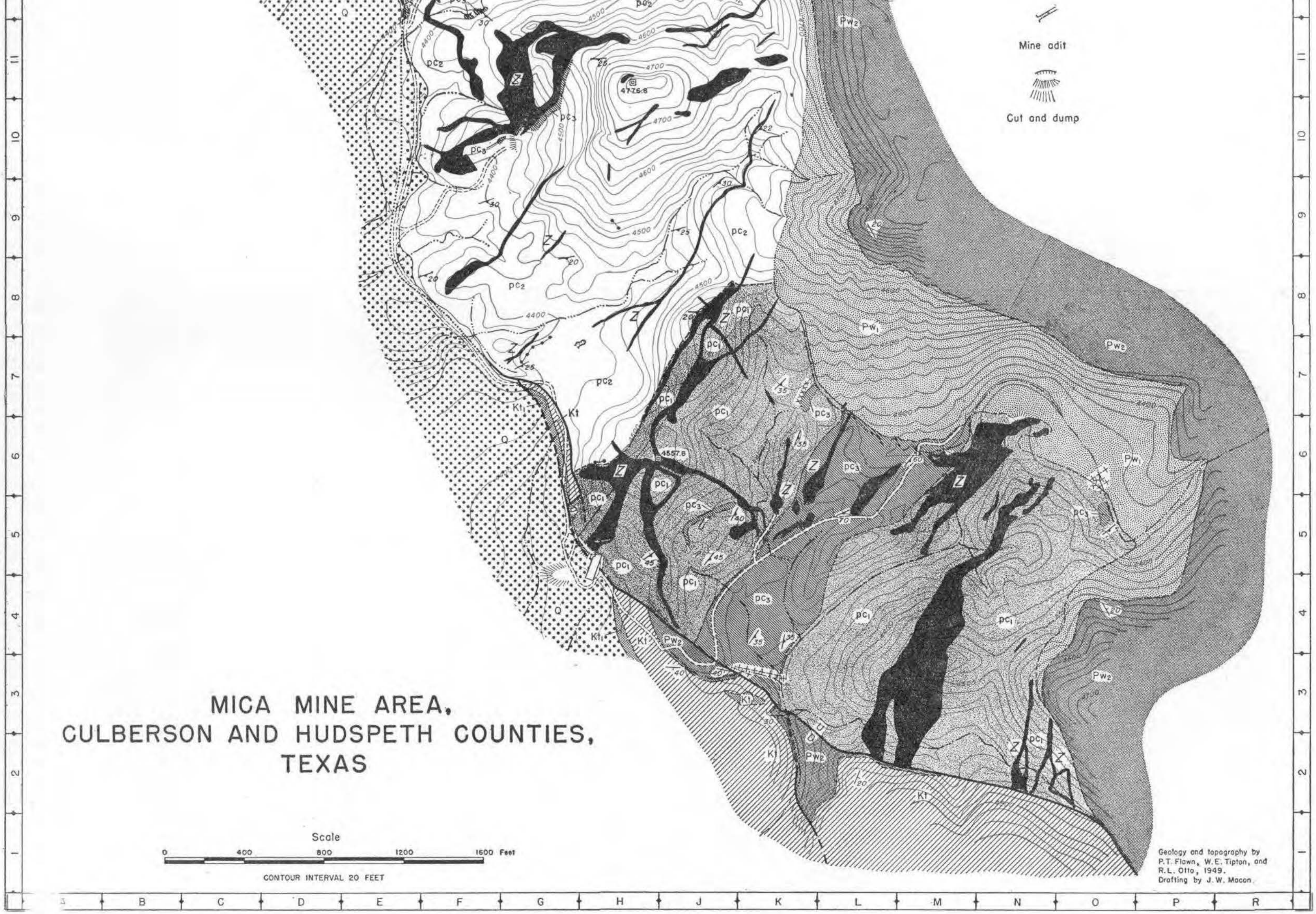
The writer wishes to thank Dr. J. T. Lonsdale and Dr. V. E. Barnes of the Bureau of Economic Geology, Dr. S. E. Clabaugh of The University of Texas, Dr. Adolph Knopf of Yale University, and Dr. L. R. Page of the U. S. Geological Survey, for helpful criticism and advice.

GENERAL GEOLOGY.

The Precambrian rocks of the Mica Mine area are exposed beneath unconformably overlying Permian (Wolfcamp) rocks in a horst that forms the northwest spur of the Van Horn Mountains. The Precambrian and Permian rocks are upthrown relative to Cretaceous rocks (Fig. 2).

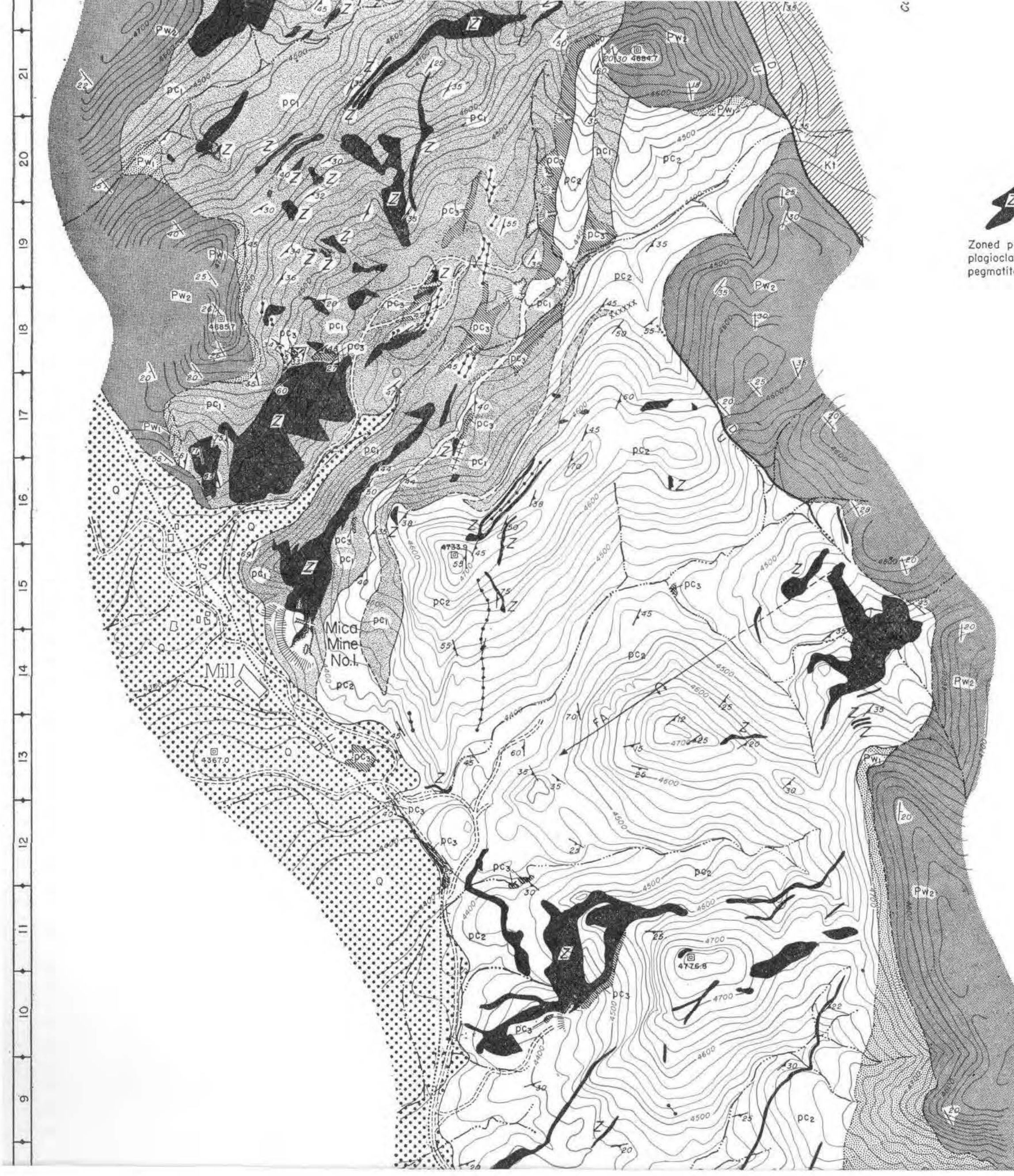
Precambrian Rocks.

The Precambrian rocks of the Mica Mine area consist of a thick sequence of feldspathic quartzites and muscovite schists containing thin beds and lenses of biotite schist and amphibolite. The metasedimentary rocks can be grouped into three units: (1) feldspathic muscovite schists and muscovitic quartzites, biotitic in part; (2) feldspathic quartzites and micaceous feldspathic quartzites; and (3) biotite schists and amphibolites. The only difference between the first two units is the mica content. The schists contain quartzite beds of varied



Mine adit
Cut and dump
MICA MINE AREA,
CULBERSON AND HUDSPETH COUNTIES,
TEXAS
Scale
0 400 800 1200 1600 Feet
CONTOUR INTERVAL 20 FEET
Geology and topography by
P.T. Flawn, W.E. Tipton, and
R.L. Otto, 1949.
Drafting by J.W. Macon

FIG. 2



POST-PERMIAN

+++++ Trachyte dikes

xxxxxxx Diabase dikes

PRE-PERMIAN

Quartz and biotite-quartz veins

Zoned perthite-quartz-plagioclase-muscovite pegmatite

Unzoned (unizoned) perthite-quartz-plagioclase-muscovite pegmatite

Contact of lithologic units, dotted where concealed, dashed where inferred

Fault
Dotted where concealed, dashed where inferred
D = downthrown side
U = upthrown side

Strike and dip of bedding

Strike and dip of foliation

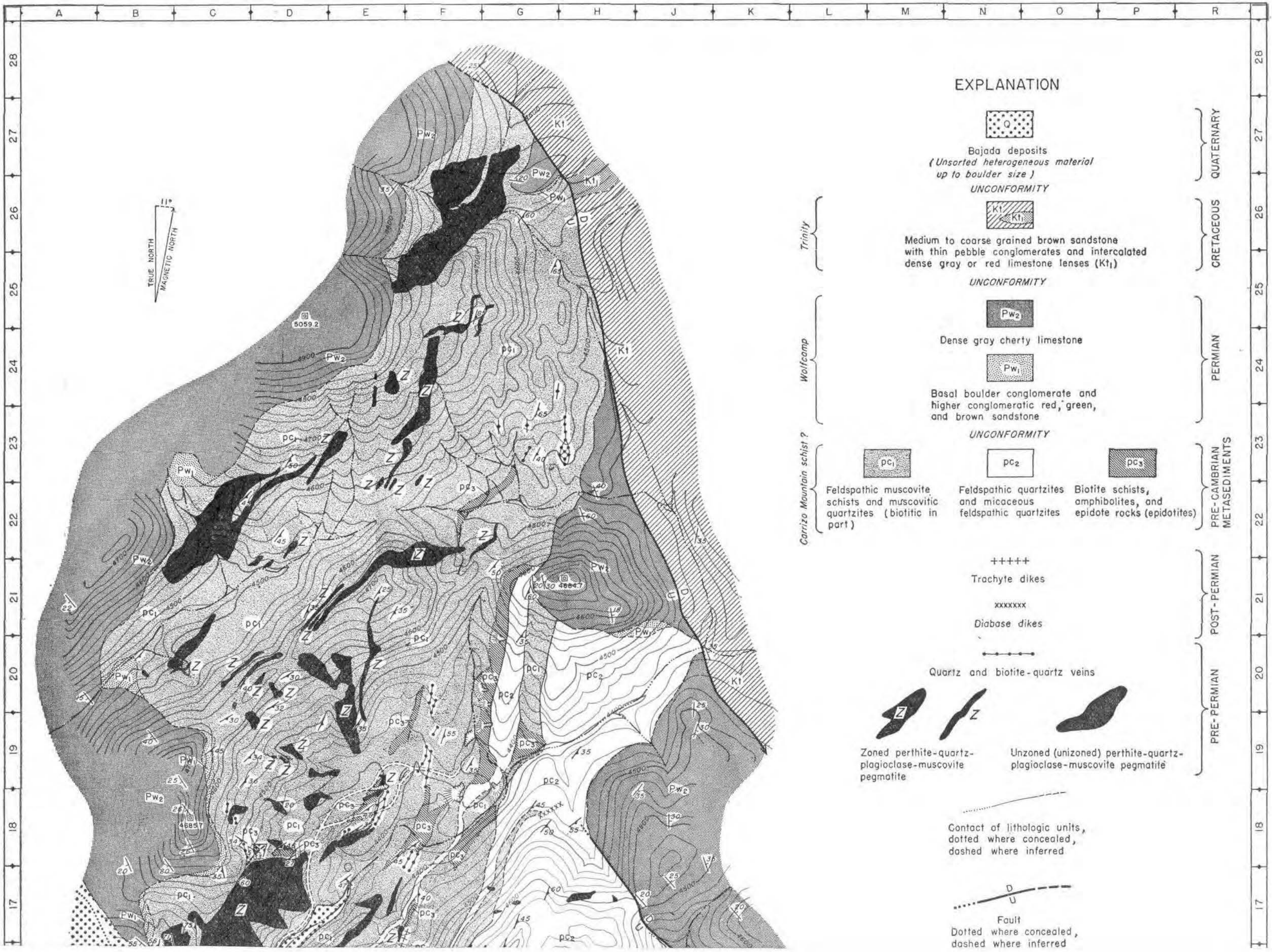
Strike of vertical foliation

Plunge of overturned fold axis

Triangulation stations
(Control = Gulf Oil Corp. level station U25.463, 1299.92 meters)

Mine adit

Cut and dump


EXPLANATION
Q
Bajada deposits
(Unsorted heterogeneous material up to boulder size)
UNCONFORMITY
QUATERNARY
Trinity
Kt Kt1
Medium to coarse grained brown sandstone with thin pebble conglomerates and intercalated dense gray or red limestone lenses (Kt1)
CRETACEOUS
UNCONFORMITY
Wolfcamp
Pw2
Dense gray cherty limestone
Pw1
Basal boulder conglomerate and higher conglomeratic red, green, and brown sandstone
PERMIAN
UNCONFORMITY
Carrizo Mountain schist ?
pc1
Feldspathic muscovite schists and muscovitic quartzites (biotitic in part)
pc2
Feldspathic quartzites and micaceous feldspathic quartzites
pc3
Biotite schists, amphibolites, and epidote rocks (epidotites)
PRE-CAMBRIAN METASEDIMENTS
+++++
Trachyte dikes
xxxxxxx
Diabase dikes
POST-PERMIAN
Quartz and biotite-quartz veins
Zoned perthite-quartz-plagioclase-muscovite pegmatite
Unzoned (unizoned) perthite-quartz-plagioclase-muscovite pegmatite
PRE-PERMIAN
Contact of lithologic units, dotted where concealed, dashed where inferred
Fault
Dotted where concealed, dashed where inferred
TRUE NORTH
MAGNETIC NORTH
11°
5059.2
4884.7
4885.7

thickness and the quartzites contain schistose members. Biotite schist and amphibolite make up less than 10 percent of the sequence.

Structure.

The rocks of the Mica Mine area show a more or less uniform strike and dip without any of the contortion common in Precambrian metasediments. The major structure is an asymmetric fold, the axis of which is shown in Figure 2. Small open folds and local distortions connected with pegmatites are in evidence. The general restriction of the quartz veins to a north-south linear zone indicates an old locus of fissuring.

The foliation shown by symbols on Figure 2 is a bedding-plane foliation. It is expressed by orientation of mica parallel to the planes of contact of major and minor litholigic units, that is, the original stratification of the rocks. In the massive quartzite beds the foliation is difficult to determine megascopically, but in thin section the mica is invariably oriented. In the amphibolites the amphibole may or may not show a lineation. Commonly a mat of non-lineated hornblende needles occurs in the plane of the foliation, giving the rock a gneissic appearance. Locally the more micaceous rocks may show a rucking or even small folds of some inches in diameter.

Petrography of the Quartzite-Muscovite Schist Sequence.

The Quartzites.—Feldspathic metaquartzites with variable content of muscovite and biotite occur throughout the metasedimentary series. They occur as thin beds (up to 3 feet) within the schistose sections and as massive beds (up to 30 feet), separated by thin layers of schist, in the quartzite sections. Quartzites make up 30 to 40 percent of the exposed Precambrian rocks.

TABLE 1.

ESTIMATED MODES (PERCENT BY VOLUME) OF REPRESENTATIVE ROCKS OF THE QUARTZITE-MUSCOVITE SCHIST SEQUENCE.

	I	II	III	IV	V*
Quartz	70	50	64	60	46.2
Microcline	9	37	15	10	31.4
Plagioclase	15	5	15	5	9.7
Muscovite	5	6	—	25	12.7
Biotite	—	2	5	—	—
Magnetite or ilmenite	1	—	1	—	—
Zircon	tr	tr	tr	tr	tr
Totals	100	100	100	100	100.0

* Mode calculated by Rosiwal analysis.

I, Muscovitic feldspathic quartzite; average grain size 0.1 to 0.2 mm (maximum grain size 4 mm).
II, Biotitic-muscovitic feldspathic quartzite; average grain size 0.2 to 0.4 mm.
III, Biotitic feldspathic quartzite; average grain size 0.2 mm.
IV, Muscovite schist; average grain size 0.5 mm.
V, Muscovitic feldspathic quartzite (slightly schistose); grain size 0.2 mm.

TABLE 2.

CHEMICAL ANALYSES OF PEGMATITE AND COUNTRY ROCK, MICA MINE AREA (R. M. WHEELER, ANALYST).

	I	II	III	IV
SiO_2	78.15	77.12	78.37	79.00
Al_2O_3	11.09	13.69	12.57	11.38
Fe_2O_3	1.41*	0.80*	1.52*	0.68*
FeO	nd	nd	nd	nd
MgO	0.25	1.45	0.97	0.25
CaO	0.42	0.37	0.35	0.80
Na_2O	1.64	1.91	1.85	2.45
K_2O	5.56	3.00	3.35	3.45
H_2O-	nd	nd	nd	nd
H_2O+	nd	nd	nd	nd
Ignition loss	0.95	1.38	1.56	1.08
TiO_2	0.11	0.13	0.17	0.14
P_2O_5	0.02	0.02	0.01	—
MnO	0.01	0.02	0.03	nd
CO_2	nd	nd	nd	nd
BaO	nd	nd	nd	nd
Totals	99.61	99.89	100.77	99.23

* Total iron reported as Fe_2O_3.
nd = not determined.

I, Feldspathic (microcline) quartzite, Mica Mine area.
II, Biotitic muscovite schist, Mica Mine area.
III, Muscovite schist, Mica Mine area.
IV, Representative pegmatite, Mica Mine area (30 percent pink microcline perthite, 40 percent white plagioclase, An_7, 20 percent quartz, 10 percent muscovite).

On the weathered surface the rocks are dark brown. A fresh face shows a pink to buff color. The rock is a hard vitreous quartzite in which individual quartz grains can easily be distinguished. The orientation of the mica flakes and the long axes of some of the larger quartz grains impart a planar tendency that is not definite enough to be called gneissic. Sporadic large grains of quartz and feldspar are visible.

In thin section the rock shows the typical granoblastic fabric of meta-quartzite—a mosaic of quartz (with mild undulatory extinction), microcline, and plagioclase, generally albite. The average grain size of the mosaic is 0.2 to 0.5 mm, with some grains reaching 3 to 5 mm. The mica plates show a preferred orientation, but no mineral segregation into bands, that is, development of a gneissic fabric, has taken place. Table 1 gives the modes of some representative quartzites. On the average the quartzites are composed of 80 to 95 percent quartz and feldspar. Microcline, characteristically twinned, may make up as much as 40 percent of the entire mineral composition of the rock (range 5 to 40 percent, average 20 to 30 percent). Plagioclase, which may or may not show polysynthetic twinning, has been observed to make up as much as 15 percent of the rock (range 2 to 15 percent, average 5 to 10 percent). The anorthite content of the plagioclase ranges from 5 to 20 percent, averaging about 10 percent. Most of the feldspar occurs as an integral part of the mosaic, but in a minor category some small rounded inclusions of feldspar are present within the quartz. This may indicate a tendency toward a “sieve” fabric. Recrystallization of a feldspathic quartz sandstone provides a satisfactory explanation of the origin of these rocks.

Mica, either muscovite or biotite, or both, is well oriented. The biotite is a green-brown variety, γ = 1.600–1.650, and shows a variable degree of alteration to bleached biotite, or bauerite.

Zircon, magnetite or ilmenite, leucoxene, and apatite are present as accessory minerals.

Muscovite Schist.—Feldspathic muscovite schists, commonly biotitic, make up to 50 to 60 percent of the entire Precambrian section. They form a glittering white outcrop of rather soft rock that crumbles into a micaceous sand under the hammer. These rocks possess characteristic schistosity and foliation.

Thin section shows parallel plates of mica in a granoblastic aggregate of quartz and feldspar. The quartz shows a mild undulatory extinction. Excepting the higher content of mica, this rock is in every way similar to the quartzites just discussed. The muscovite content is rarely over 30 percent and averages 15 to 25 percent. Microcline, plagioclase (albite and albite-oligoclase), magnetite or ilmenite, and zircon are also present. The average grain size of the mosaic is 0.2 to 0.5 mm with the mica laths averaging 1 by 0.2 mm. Table 1, IV, gives the mode of a representative muscovite schist.

Chemical analyses of quartzo-feldspathic rocks are given in Table 2.

Petrography of the Amphibolite-Biotite Schist Sequence.

Intercalated with the quartzites and muscovite schists are small lenses and beds of biotite schist, amphibolite, and epidote rock or epidotite.

Biotite Schists.—The biotite-bearing rocks of the Mica Mine area have a varied mineralogy. They seem to represent a transition between the potash-rich muscovite-microcline-quartz rocks on the one hand and the potash-deficient hornblende-plagioclase rocks on the other. Not uncommonly an amphibolite bed of some 5 to 10 feet in thickness is separated from the muscovite schists by several feet of biotite schist or biotite-albite schist. A rock containing biotite, amphibole, and plagioclase frequently occurs as a transition unit between biotite schists and amphibolites composed solely of hornblende and plagioclase. Thus the biotite rocks fall into two classes: (a) normal biotite-quartz schists and (b) biotite-amphibole-plagioclase rocks.

The biotite-quartz schists in beds up to 15 feet thick form a glittering black outcrop in the Mica Mine area. Biotite plates several millimeters in diameter, red-stained quartz, and a white feldspar are visible in the hand specimen. Commonly a rucking is present, with the amplitude of the tiny fold on the order of several millimeters.

Thin section shows parallel plates of biotite in a mosaic of quartz and albite. There is a marked variation in size among the grains of the mosaic (0.5 mm is a fair average). The rock is composed of about 40 to 60 percent quartz, 10 to 20 percent albite (microcline may be present), and 30 to 40 percent biotite. The biotite of this rock is an olive-brown variety (γ = 1.662 ± 0.002). One section shows 3 percent garnet restricted to a narrow zone parallel to the foliation. Apatite, sphene, leucoxene, magnetite or ilmenite, rutile, and carbonate occur in minor quantities.

The biotite of the biotite-plagioclase (with or without amphibole) schists reflects a potassic phase of the general amphibolite assemblage. Hornblende, anthophyllite, epidote, and sphene may accompany biotite in this phase. The hand specimen is a more massive rock than above. The biotite occurs in small flakes (1 mm or less) and makes up less of the total mineral assemblage.

Thin section shows a mosaic of albite-oligoclase averaging 0.5 mm in grain size and making up 50 to 75 percent of the rock. The plagioclase is more or less altered to sericite. Biotite, an olive-brown to red-brown variety (γ = 1.660 to 1.700), makes up 10 to 30 percent of the rock and again shows a parallel orientation. The biotite laths average 0.2 by 1 mm. Some specimens contain amphibole—blue-green hornblende or anthophyllite. The hornblende occurs in poikilitic crystals or subhedral prisms aligned with the biotite. The anthophyllite occurs in bladed or fan-shaped porphyroblasts up to 10 or 20 cm in length. Minor quartz, ilmenite or magnetite, sphene, leucoxene, apatite, and carbonate may be present. Platy ilmenite (associated with leucoxene) may occur in biotite cleavages.

Amphibolites.—Four main types of amphibolite can be distinguished: (a) amphibolite, (b) almandine amphibolite, (c) anthophyllite amphibolite, and (d) epidote amphibolite (grading into epidotite).

The normal amphibolite (a) is a massive green-black rock in which, on close inspection, minute prisms of hornblende are visible. These prisms may show a fair lineation or they may occur in a mat of non-lineated prisms parallel to the general foliation of the area and imparting a rude schistosity. The average length of the hornblende prisms is 1 to 3 mm. Local coarsenings are common. Hornblende may make up as much as 70 percent of the rock. Plagioclase is the only other major mineral.

Under the microscope this rock shows poikilitic hornblende prisms in a mosaic of untwinned plagioclase. The hornblende is a blue-green variety with $Z \wedge C = 16$ to 18 degrees, β = 1.665 to 1.672, and negative optic sign. These determinations, unless otherwise stated, hold true for blue-green hornblende of all amphibolite types. The hornblende averages 30 to 50 percent of the rock but may range as high as 70 percent. The plagioclase (oligoclase-andesine) has the same percentage range in amount as the hornblende (average, 30 to 50; maximum, 70). It invariably shows some degree of alteration to sericite. An inverse zoning, characteristic of the plagioclase of many metamorphic rocks, can be seen in most sections. Quartz is generally present in amounts less than 10 percent. Quartz-rich layers were observed in some thin sections, and in these layers the quartz content may be as high as 25 or 30 percent. The quartz is easily distinguished from the altered plagioclase. Magnetite or ilmenite (4 to 5 percent) and apatite (1 to 2 percent) are present. The average grain size of the mosaic is 0.2 to 0.4 mm. The hornblende prisms average 1 to 2 mm in length.

Almandine amphibolite (b) was observed in one outcrop (see 19.3-F.O, Fig. 2). Here the normal green-black amphibolite contains porphyroblasts of garnet averaging between 5 mm and 1 cm in diameter and making up 10 to 15 percent of the rock. They weather out in perfect dodecahedrons. The garnet is deep red and has a specific gravity of 4 14. The mass of the rock consists of 40 to 50 percent lineated prisms of blue-green hornblende in a mosaic of plagioclase (oligoclase-andesine). There is no distortion or bending of the hornblende prisms where they abut the garnet. Inclusions of magnetite in the garnet show a lineation at an angle to the lineation of the rock as a whole and may be evidence of rotation. The plagioclase makes up about 30 percent of the slide and is partly altered to sericite. Magnetite or ilmenite makes up 5 to 8 percent of the rock. Apatite, in rounded grains, may make up as much as 3 percent.

Anthophyllite amphibolite (c) is in contact with the almandine amphibolite and is different from the biotite-anthophyllite rock previously described. The hand specimen is a massive green-black rock with bladed porphyroblasts of anthophyllite, on the order of 1 by 15 mm, showing fair lineation. Thin section shows a mosaic (0.1 to 0.2 mm) of andesine containing oriented prisms of blue-green hornblende. The plagioclase and hornblende each make up about 40 percent of the slide. Large poikilitic porphyroblasts of anthophyllite constitute the remaining 20 percent of the rock. The anthophyllite blades, averaging about 1 cm in length, show no orientation and cut across the lineation of the hornblende.

In contact with the rock just described is another anthophyllite rock. It is composed of 50 percent andesine and 40 percent anthophyllite, with complete absence of hornblende.

Epidote-bearing amphibolites (d) are distributed through a more or less linear zone in the northern schist outcrop. With the appearance of a substantial epidote content the normal green-black amphibolite takes on a waxy green cast. Yellow-green streaks show up in the darker hornblende-bearing rocks, and these streaks may develop into layers of an aphanitic waxy yellow-green rock containing scattered magnetite crystals. These layers are discontinuous and about 1 to 2 inches thick. This rock conforms to the description of an epidotite (7).

The epidote amphibolite consists of a mosaic of quartz and oligoclase containing blue-green poikilitic hornblende prisms, grains, and granular masses of epidote and grains of sphene. There is some tendency for the hornblende and quartz to be concentrated in layers.

The rock is composed of 10 to 30 percent well-lineated prisms of blue-green hornblende, 10 to 50 percent plagioclase, and a variable amount of epidote and quartz. The oligoclase shows alteration to sericite. Quartz is in amounts less than 10 percent, although in one section it reaches as high as 30 percent. Epidote, distinctly yellow in thin section, ranges from 10 to 20 percent up to 60 to 70 percent, at which point the rock may be classed as an epidotite. The epidote is clearly a metamorphic mineral and occurs as small discrete grains (0.5 to 0.1 mm) and groups of grains. Sphene makes up 1 to 3 percent of the rock. Ilmenite is a common accessory and may make up as much as 5 percent of the total composition.

Aphanitic waxy yellow-green rocks occurring in streaks and layers within the epidote amphibolites are here called *epidotites.*

The epidotites of the Mica Mine area contain 80 to 90 percent granular epidote in grains 0.04 to 0.06 mm in diameter and 8 to 10 percent albite or albite-oligoclase, usually altered. Sphene makes up 2 to 4 percent of the rock. A dark-green hornblende may be present in amounts up to 5 percent. The fabric is crystalloblastic.

Quartz Veins.

Veins of white quartz containing variable amounts of biotite and hematite occur within the Mica Mine area. They are mostly restricted to a north-south zone (Fig. 2), indicating an old locus of fissuring. The location of minor quartz veins is in places controlled by the hanging or footwall of pegmatites, and the veins are, therefore, later than the pegmatites.

The veins are the product of high-temperature hydrothermal solutions carrying iron and silica. The reaction of these iron-bearing solutions with the potash and alumina of the wall rocks formed biotite, commonly in sheaf-like masses. Discontinuous and distorted masses of quartz and biotite conforming to the structure of the metamorphic rocks may be interpreted as the product of pre-metamorphic or syn-metamorphic hydrothermal solutions.

Permian Rocks.

Permian rocks rest on the Precambrian rocks of the Van Horn Mountains with marked angular unconformity. On the basis of lithologic character and megafauna the Permian section of the Mica Mine area is assigned to the Wolfcamp. Two lithologic units can be distinguished: (1) a conglomeratic sandstone and (2) a compact aphanitic gray cherty limestone.

The sandstone is extremely varied in thickness and the thickness is controlled by irregularities in the old Precambrian surface. On old Precambrian hills the limestone rests directly on Precambrian rocks while in low places on the old surface as much as 250 feet of sandstone is present. The rock is a fine-grained red and brown micaceous feldspathic sandstone containing sporadic pebbles of quartz, feldspar, and pegmatite. In the southern part of the Mica Mine area, 20 to 30 feet of boulder conglomerate is present at the base of this clastic unit. Boulders of schist, quartzite, and pegmatite reach diameters of 3 to 4 feet. The sandstone grades into the overlying limestone through a 20 to 30-foot zone of interbedded silty limestone and sandstone.

Comformably overlying the clastic unit is a compact aphanitic gray cherty limestone. This rock occurs in beds 6 inches to 6 feet thick and forms bold cliffs around the exposed Precambrian rocks. Diagnostic features are the abundance of brown chert in stringers, nodules, and irregular masses; crystalline calcite in veinlets and lining cavities; nodules of manganese dioxide in cavities; silicified echinoid spines and plates; and strong fetid smell on breaking.

Cretaceous Rocks.

Unconformably overlying the Permian limestone is a brown Cretaceous sandstone that marks the top of the Trinity. In the Mica Mine area this rock is generally in contact with the Permian only along faults. The rock is a medium to coarse-grained sandstone; well indurated (locally it is an orthoquartzite) and well sorted. It is composed mostly of quartz with a small amount of altered feldspar (less than 5 percent) and less than 1 percent magnetite. The grains are sub-round. Bands of chert and quartz pebbles and cross-bedding are common. Thin beds of silty limestone and limestone and chert pebble conglomerates occur within the sandstone. Masses of oyster shells occur locally in the limestone beds. This sandstone is overlain by the basal Fredericksburg Finlay limestone to the east of the Mica Mine area.

Igneous Rocks.

Trachyte and analcime-bearing diabase dikes occur in the Mica Mine area. From the field evidence these intrusions cannot be assigned to a definite age. The trachytes cut Permian rocks. On the basis of similarity to rocks described by Lonsdale (17) and Baker (4) the writer believes these dikes to be Tertiary (?).

PEGMATITES.

More than eighty pegmatite bodies at least 1 foot thick were mapped in the Mica Mine area. They are relatively resistant and form prominent topographic features. The pegmatites consist of an aggregate of microcline perthite, quartz, plagioclase (albite and oligoclase), muscovite, and tourmaline (schorlite). Biotite and spessartite garnet occur in a very few pegmatites. Internal zoning can be distinguished in about 30 percent of the pegmatites.

Pegmatite bodies occur in all parts of the metasedimentary series, but they are more abundant in the schistose rocks than in the massive quartzites. They range in size from stringers less than 1 inch thick to lens-like bodies as much as 150 feet thick. The shape of the pegmatites varies widely. They may be more or less tabular bodies, irregular bodies with tabular branches, irregular masses, elongate lenses, small augen, or thin stringers, either as separate bodies or as groups in *lit-par-lit* zones.

Relation to Host Rock.

Most of the pegmatites are tabular or lens-like bodies that conform to the foliation of the host rock. It is not uncommon for a body, that is for the most part conformable, locally to distort the foliation of the country rock. Rolls and minor undulations of the contact are common. Some pegmatites are concordant in part but have discordant forks or branches. A few small pegmatites are in fractures that cross-cut massive quartzite.

Relation to the Quartzite and Muscovite Schist.—The contact between the pegmatite bodies and the quartzites or muscovite schists is either a planar surface or a *lit-par-lit* zone 1 to 5 feet wide, depending on the presence and attitude of schistosity in the invaded rock. There is no alteration of the wall rock at the contact. A thin section across ¼-inch feldspar-quartz-muscovite pegmatite in a feldspathic muscovite schist shows that the pegmatite is a panallotriomorphic aggregate of quartz and feldspar with a high albite content, and the muscovite schist is a typical unaltered lepidoblastic quartz-microcline-muscovite rock. Along the contact the schist shows the beginnings of a sutured mosaic. A concentration of strained and bent muscovite plates along the plane of contact between pegmatite and schist indicates that the pegmatite was emplaced under stress. The presence of a sub-round zircon in the pegmatite (similar to those found in the schist) and a faint trace of mosaic structure in the pegmatite quartz may indicate that some of the pegmatite material was derived from the host rock by a process of digestion and recrystallization.

Relation to the Amphibolite and Biotite Schist.—Pegmatites in contact with amphibolite have a narrow zone, less than 6 inches wide, of biotite amphibolite at the contact. The biotite occurs in discrete laths in contact with hornblende and does not rim or interfinger with hornblende. Pegmatites in contact with biotite schist apparently have not altered their wall rocks.

The pegmatites in contact with biotite schist or amphibolite contain minerals that reflect the composition of the wall rock. Pegmatites in contact with amphibolite contain spessartite garnet, biotite, and plagioclase with an anorthite content that is approximately 10 percent higher than that of plagioclase in pegmatites in contact with muscovite schists and quartzites. The pegmatites in contact with biotite schist contain biotite and spessartite, but the plagioclase does not have a high anorthite content. In both types of pegmatites the spessartite and biotite have a spotty and uneven distribution. The presence of spessartite and biotite only in those pegmatites in contact with biotite schist and amphibolite is definite evidence of contamination.

Schist Inclusions.—Nearly all of the Mica Mine area pegmatites contain inclusions of country rock. These inclusions form partitions parallel to the contact of the pegmatite (and the foliation of the host) or irregular blocks. In the more schistose areas partitions are especially common. They exhibit all stages of digestion[4] and recrystallization and grade into rock that is essentially pegmatite. Only the finer grain size and the even texture of the digested rock enable the observer to distinguish it from pegmatite. On occasion a partition of schist thins and passes into a mica-rich streak. Small mica books commonly grow at right angles to the contact of schist and pegmatite.

A number of thin sections of inclusions in various stages of "pegmatization" were studied. The following points were noted:

(1) The straight-line grain boundaries of the former mosaic of the muscovite schist inclusions are changed to the very irregular contacts of a sutured mosaic (Figs. 3-5).
(2) Quartz is coarser grained and shows marked undulose extinction. Traces of former grain outlines may indicate a welding of the smaller quartz grains of the normal schist (Fig. 5).
(3) Bent muscovite crystals are common (Fig. 4).
(4) Plagioclase surrounds islands of quartz and microcline (Fig. 7), and quartz embays plagioclase and microcline (Figs. 6, 8).
(5) Simultaneous growth of minerals may result in a "sieve" fabric (Fig. 9).
(6) Veinlets of quartz, quartz and muscovite or sericite, or quartz and feldspar cut earlier minerals (Figs. 10, 11).

The minerals of the schist inclusions show strain and therefore have not completely recrystallized.

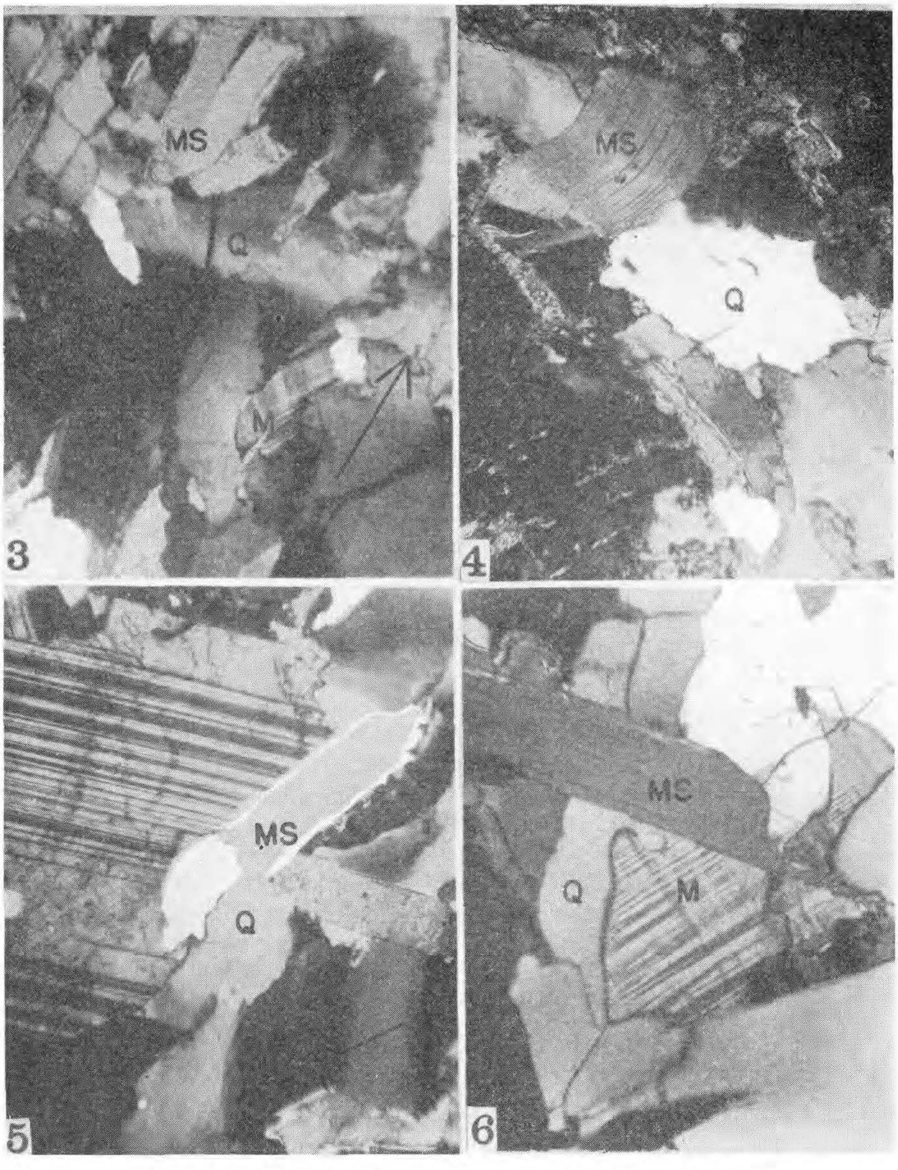
Internal Structure.[5]

More than one-third of the pegmatites mapped in the Mica Mine area are bizonal. A wall zone and a core, commonly discontinuous, form the two units of the zoned pegmatite.

Wall Zone.—The wall zone of all the pegmatites in the area consists of blocky subhedral crystals of microcline perthite (size range 1 to 8 inches long, average 3 to 4 inches long) in a fine-grained matrix with grains which range from 1/16 to 1 inch long and average 14 inch long. The blocky perthite averages 30 to 40 percent of the wall zone and ranges from 10 to 80 percent. The fine-grained matrix is composed of subhedral microcline perthite, plagioclase, quartz, and muscovite. In most pegmatites the larger part of the feldspar in the wall zone is plagioclase, although the relative proportions of the two feldspars, plagioclase and microcline perthite, vary widely. The wall zone averages about 60 percent microcline perthite and plagioclase. Muscovite, in small books, ranges from 2 to 10 percent and averages 5 percent of the zone. Quartz makes up the remainder. Chemical analysis of a representative sample of the wall zone is given in Table 2, IV. Some pegmatites contain intergrowths of quartz and muscovite up to 8 inches in diameter (called mica aggregate or "bull" mica

[4] *Digestion* is defined as replacement in an essentially closed system.

[5] The use of the term *zone* in this paper conforms to that of Cameron et al (5). A zone is a structural or lithologic unit that in general reflects the shape of the pegmatite body. It is distinguished from fracture fillings and replacement bodies and is considered to be a primary rather than a secondary feature of the pegmatite.



FIGS. 3–6. M, microcline; MS, muscovite; Q, quartz. × 70.

FIG. 3. Muscovite schist inclusion. Note sutured mosaic (arrow) and straining in quartz.

FIG. 4. Muscovite schist inclusion. Note sutured mosaic, bent muscovite, and strained quartz.

FIG. 5. Muscovite schist inclusion with pegmatite seams parallel to the foliation. Note former grain boundaries of quartz (arrow), and sericite rimming muscovite.

FIG. 6. Muscovite schist inclusion almost completely pegmatized. Note embayed and corroded microcline in the quartz.

in the trade). These intergrowths seem to be distributed for the most part within the inner part of the wall zone.

Core.—The core is a relatively narrow zone, commonly discontinuous, of coarse microcline perthite and massive white quartz. It is rarely over 2 or 3 feet thick. Microcline perthite crystals (range 4 inches to 3 feet long, average 6 to 10 inches long) make up 60 to 70 percent of the core. Included quartz, commonly in a rude graphic intergrowth, is found in some perthite crystals. In a few pegmatites muscovite books 3 to 4 inches in diameter may occur in or on the periphery of the core. Nearly all of these books are "wedged" and show "rulings" and "A" structure.

Sequence of Zones.—From the data gathered in various pegmatite districts, Cameron et al. (5) have formulated an ideal sequence of zones which are said to occur invariably in the same order with relation to each other. Some zones in this sequence may be absent and/or telescoped in different districts. Zones three and four (from the wall inward) in the ideal sequence are: (3) quartz-perthite-plagioclase with or without muscovite, with or without biotite and (4) perthite-quartz. In the Mica Mine area these zones form the wall zone and core respectively. The preceding zones (plagioclase-quartz-muscovite and plagio-clase-quartz) and the succeeding lithium-bearing zones of the ideal sequence are not present in the Mica Mine area.

Fracture Fillings.—Fracture fillings of quartz and perthite; quartz, perthite, and tourmaline; quartz and tourmaline; and quartz cut the wall zone.

Replacement Unit.—In the Mica Mine No. 1 (Fig. 14) a plagioclase-quartz replacement unit was mapped.

Comparison of Zoned and Unzoned Pegmatites.—In the Mica Mine area zoned and non-zoned pegmatites of identical mineralogy are closely associated. In some places only the wall zone is exposed; in others the full thickness of the pegmatites is exposed. Rectilinear dike-like bodies with sharp contacts and no schist partitions show the best zoning. Pegmatite bodies containing many schist partitions show no discernible zoning, although local areas of coarser quartz and perthite occur throughout the pegmatite. In dike-like bodies these "shoots" of coarse quartz and perthite are parallel to the walls of the body. An idealized section made from a sketch (Fig. 13) shows the effect of a schist partition on the development of a core. The obvious conclusion is that the schist partitions interfered with the crystallization of the pegmatite body as a unit, separating it into a number of poorly connected cells.

Mineralogy and Mineral Relations.

The pegmatites of the Mica Mine area are simple feldspar-quartz-mica pegmatites containing microcline perthite, plagioclase, quartz, muscovite, tourmaline, biotite, spessartite, and magnetite. No rare-earth minerals, lithium minerals, or phosphates were found.

Microcline Perthite.—Blocky crystals of microcline perthite make up, on the average, 30 to 40 percent of Mica Mine area pegmatites. The microcline perthite is usually pink but may be white, flesh-colored, or salmon. The pink color may reflect the iron content of the mineral. Salmon-colored microcline perthite occurs in those pegmatites within the amphibolite-biotite schist sequence. The microcline perthite in the wall zone and core is in subhedral crystals that are resistant to weathering and form rough blocky outcrops. These large perthite crystals are distributed in the pegmatite like phenocrysts in a giant porphyry.

The microcline perthite varies from a clean almost glassy feldspar to an opaque feldspar containing inclusions of quartz and muscovite. The latter type is the most common. A rude graphic intergrowth of quartz and microcline is common; good graphic granite is rare and is restricted to the inner part of the wall zone.

Perthitic structure can be seen in the hand specimen as a network of fine anastomosing bands approximately 1 mm wide. A photomicrograph of this perthitic structure is shown in Fig. 12. This perthite is similar to what Andersen (1) described as "vein perthite." The regular parallel plagioclase lamellae show, on a small scale, an irregular contact with the microcline. This may indicate replacement of microcline by plagioclase along the contact. The anorthite content of the plagioclase from six microcline perthites (from both wall zone and core) was determined and compared with the wall-zone plagioclase from the same pegmatite. In each pegmatite the anorthite content of the plagioclase from the microcline perthite is 1 or 2 percent less than the anorthite content of wall-zone plagioclase. There is no plagioclase in the core other than that perthitically intergrown. These points seem to favor the hypothesis of origin of perthite by exsolution rather than by replacement.

Plagioclase.—Plagioclase occurs only in the fine-grained pegmatite of the wall zone where it is associated with potassium feldspar. The color ranges from white to flesh, and the latter is almost impossible to distinguish from flesh-colored microcline perthite in the fresh sample. On weathered surfaces the plagioclase, being more susceptible to alteration than microcline perthite, is more easily recognized. Plagioclase is generally more intimately intergrown with quartz than is the microcline perthite (which tends to be subhedral), and this aids in identification. An accurate determination of the percentage of plagioclase in the fine-grained pegmatite is almost impossible. The writer estimates 30 to 50 percent plagioclase in the fine-grained pegmatite of the wall zone and 20 to 40 percent in the pegmatite as a whole. Plagioclase is not found in the core.

The anorthite content of the plagioclase was determined by the immersion technique for each pegmatite shown on Figure 2. The total range for the district was An_1 to An_{24}. The values may be grouped as follows :

(1) Abnormally high values of An_{20} and An_{24} were found in the two pegmatites in contact with amphibolite. Plagioclase from these pegmatites was varied in composition but showed consistently high anorthite content. These values in the oligoclase range appear to be the result of contamination by digestion of amphibolite country rock by the pegmatite. The variation of anorthite content of the plagioclase within the pegmatite suggests that the more anorthitic varieties occur in areas of greater contamination and that equilibrium between the contaminated pegmatite and the normal pegmatite material was not reached.

(2) The plagioclase of pegmatites near the mill (Fig. 2), including the Mica Mine No. 1, shows low anorthite values ranging from An_1 to An_7.
(3) The plagioclase in the pegmatites south of the canyon running east of the mill shows a decrease in anorthite content from An_9 in the north to An_3 at the southern limit of the area.
(4) North of the canyon east of the mill the anorthite content of plagioclase increases from An_9 to An_{14} at the northern limit of the area.

Except for the small area just east of the mill there is a general increase in the anorthite content of the plagioclase from relatively pure albite in the south to oligoclase in the north. Unfortunately there is not enough area exposed to reveal any systematic pattern.

Thin sections of the fine-grained pegmatite show plagioclase embaying quartz and microcline and being embayed by quartz and veined by quartz or quartz and muscovite.

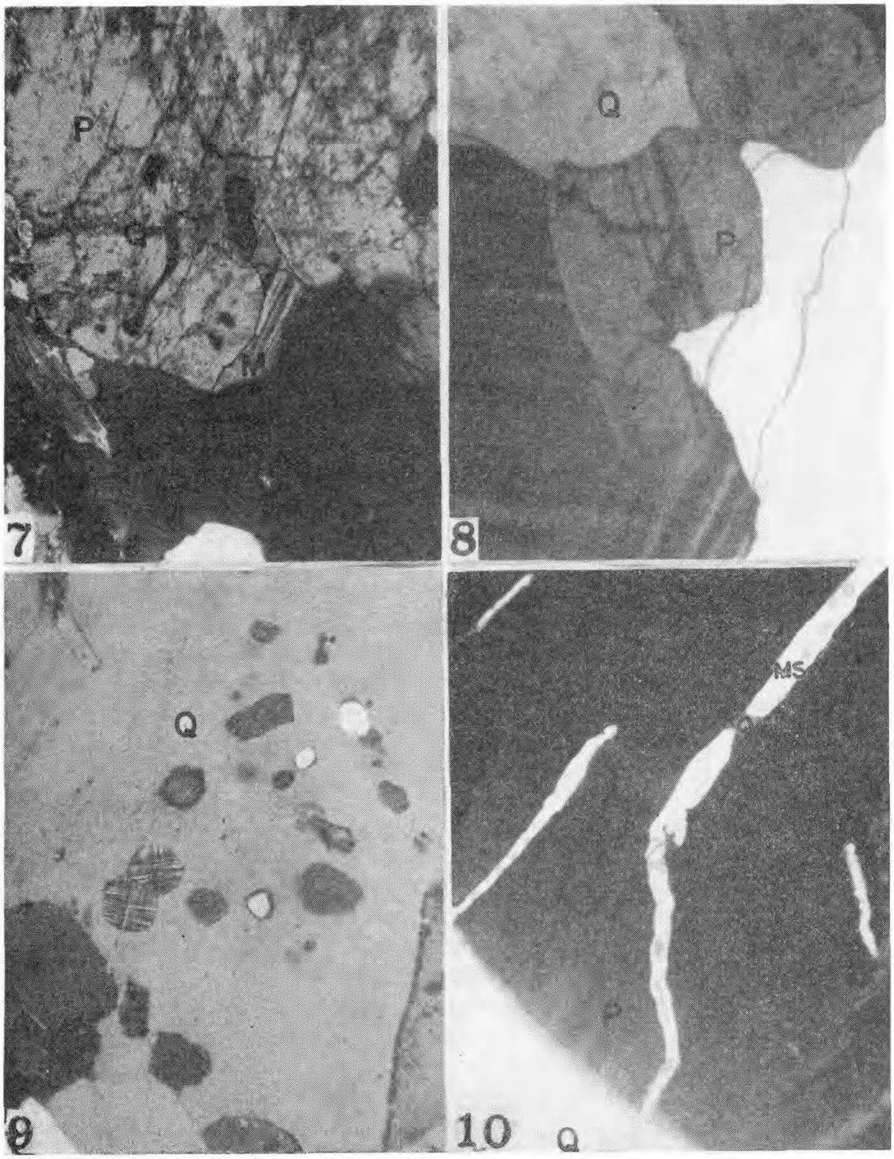
Quartz.—Quartz occurs in the fine-grained pegmatite of the wall zone, in the core, and in fracture fillings. In the wall zone the quartz is intergrown with feldspar and muscovite, making up about 30 percent of the zone. In the core massive white quartz occurs with the perthite and makes up about 30 percent of the zone. In non-zoned pegmatites, masses of white quartz commonly occur throughout the body. Black tourmaline is commonly intergrown with this massive quartz. In facture fillings, quartz may be accompanied by perthite and tourmaline or by tourmaline alone.

Microscopic study of thin sections shows that the quartz within the pegmatite is badly strained and that small quartz veinlets cut previously crystallized pegmatite minerals (Figs. 10, 11). Quartz embays plagioclase and microcline and is frequently replaced by plagioclase.

Muscovite.—The muscovite of the Mica Mine area is a silver-gray to gray-green variety. It occurs in small plates and books within the fine-grained pegmatite, of a size with the fine-grained pegmatite, and as larger books within the core, along the margin of the core, and in local coarse-grained segregations. Muscovite also occurs in intergrowths with quartz (mica aggregate) and in thin sheets in cracks and along crystal boundaries in the wall zone. One pegmatite, the Mica Mine No. 1 (Fig. 14), contains large books of muscovite in a zone of partly kaolinized feldspar cut by numerous quartz-tourmaline stringers.

The muscovite can be divided, on the basis of field observations, into primary muscovite (contemporaneous with the associated minerals) and secondary muscovite (later than the associated minerals). Primary muscovite occurs in the wall zone and core.

The muscovite in the fine-grained pegmatite is in more or less equilateral books that make up on the average of 2 to 4 percent of the fine-grained pegmatite. This muscovite is evenly distributed and is an integral part of the mineral aggregate. An occasional mica book may be somewhat larger than the accompanying minerals. In the Mica Mine No. 1 (Fig. 14) muscovite books up to 8 inches in diameter are found. Although stained and spotted. these books split well. In this zone of abnormally large (for the district) mica books, the surrounding feldspar is partly kaolinized, and the pegmatite is cut



FIGS. 7–10. M, microcline; MS, muscovite; P, plagioclase; Q, quartz. × 75.

FIG. 7. Muscovite schist inclusion almost completely pegmatized. Note remnants of quartz (dark) and embayed microcline remnant (outlined) in the plagioclase.

FIG. 8. Muscovite schist inclusion with pegmatite seams parallel to the foliation. Note quartz embaying plagioclase.

FIG. 9. Muscovite schist inclusion with "sieve" fabric.

FIG. 10. Fine-grained pegmatite. Note quartz-muscovite veinlet extending from quartz grain across plagioclase grain.

by numerous quartz-tourmaline stringers. These large books may be the result of prolonged growth or regrowth of mica under the influence of late solutions.

Roughly elliptical or circular masses of intergrown quartz and muscovite with minor feldspar, known as "mica aggregate" and "bull mica" in the trade, are present in a great many pegmatites. The intergrowths are 2 to 5 inches in diameter and are made up of individual grains ¼ to ½ inch in size. They seem to be restricted to the inner part of the wall zone. They are composed of approximately 60 percent muscovite and 40 percent quartz with the muscovite books oriented in a fan. The lack of muscovite in the surrounding pegmatite indicates that these segregations are primary. The mechanics by which this segregation of quartz and muscovite was affected are not readily explainable. The regularity of size and distribution of the intergrowths in the areas where they occur precludes the possibility that they are reconstituted schist fragments.

Books of muscovite 1 to 3 inches in diameter occur within the core, along the core margin, and in local coarse segregations. These larger books are everywhere associated with coarse perthite and quartz phases. Nearly all these books are "wedged" and "ruled." Just east of the mill (Fig. 2), however, a number of pegmatites contain muscovite books that split very well. This mica is heavily stained and spotted and may be classed as "electrical mica."

Secondary muscovite occurs in cracks and along crystal boundaries as thin sheets and films in the wall zones of most pegmatites in the Mica Mine area. Commonly these thin sheets assume a "bird-foot" arrangement, occupying short radial cooling (?) cracks. Muscovite sheets and films also occur along the boundaries of perthite crystals. This muscovite is later than the accompanying minerals and is the result of penetration of the crystallized pegmatite, along planes of weakness, by the unconsolidated pegmatite fluids. Sericite rims around muscovite, concentrations of sericite along grain boundaries, and veinlets of sericite are seen in thin sections and show there has been transfer of sericite material through the crystallized pegmatite.

Tourmaline.—Black tourmaline, variety schorlite (E, pale pink-brown; O, deep blue-black), is present in quantities of 2 percent or less in nearly all the pegmatites. Tourmaline is intergrown with quartz in the cores, in local coarse segregations, and in fracture fillings. It also occurs as needles coating joints, perthite boundaries, and in quartz stringers. Quartz-tourmaline stringers, in part containing plagioclase, cut the wall zone and the contact of schist and pegmatite. At one place a quartzite near the contact of the pegmatite has been tourmalinized to form a quartz-tourmaline gneiss. There is no tourmaline associated with the quartz veins of the Mica Mine area.

Although tourmaline was very late in the sequence of crystallization, some quartz was deposited still later in minute veinlets that cut the tourmaline crystals.

Biotite.—Biotite occurs only in those pegmatites in contact with biotite schist or amphibolite. The biotite is in books intergrown with the quartz and feldspar and in thin sheets along crystal boundaries. In one pegmatite where the footwall is in contact with amphibolite, biotite is restricted to the footwall wall zone of the pegmatite. It is certain, then, that the elements necessary to the formation of biotite were derived from the host rock. As a corollary, the biotite in individual pegmatites is variable in composition, ranging from a green-brown to a red-brown variety according to the composition of the contaminating rock. A range in γ from 1.650 to 1.680 was found.

Spessartite.—Spessartite is present only in pegmatites in contact with biotite schist or amphibolite and occurs as idiomorphic cinnamon-brown garnets in separated bunches. The specific gravity of the garnet was measured as 3.39. Winchell gives the specific gravity of Spessartite as 3.80 to 4.25. The low specific gravity of the garnet of the Mica Mine pegmatites is caused by small quartz inclusions within the crystals. The garnet has a sporadic and uneven distribution and frequently occurs as inclusions within the large blocky perthite crystals. This suggests an uneven distribution of the contaminated material.

Magnetite.—Occasional small crystals of magnetite occur in those pegmatites that are in contact with the amphibolites and biotite schist.

ORIGIN OF THE PEGMATITES.

During the past decade a detailed and comprehensive study of pegmatites has been made by the U. S. Geological Survey. Part of the results of these pegmatite studies have been published (5). This work and other recent work on pegmatites have presented a great deal of information on the nature of pegmatite bodies but have not solved the problems of (a) the relative importance of primary versus secondary processes in the formation of complex pegmatites, (b) the nature of the pegmatite fluid, and (c) the mode of emplacement of pegmatites.

There are a number of definitions of the term *pegmatite,* many of which are undesirable because of connotations of mode of origin. The writer favors the definition given by Andersen (2, p. 3) : "Pegmatites are mineral associations crystallized in situ, decidedly more coarse grained than similar mineral assemblages in the form of ordinary rocks and differing from those in having a more irregular fabric of the mineral aggregate." Although somewhat unwieldy, the definition has the merit of being free from all references to genetic processes.

Many geologists use the term *pegmatite* in conjunction with the term *dike,* as *pegmatite dike.* The difference between pegmatite bodies and normal igneous dikes is certainly great. Andersen (2, p. 5) has remarked that: "It is true that many of these bodies [referring to pegmatites] apparently have some of the essential characteristics of dikes, such as parallel walls, but a large number of them have forms of such indefinable irregularity that by no stretch of the definition of the term is it possible to classify them as dikes. When other features are considered no pegmatite body to my knowledge answers the description of a typical igneous dike." A normal igneous dike may be defined as a solidified mass of magma injected during a single pulse and occupying a rectilinear fissure.[6] A straight course and a closed system are embodied in this definition. A pegmatite is certainly vastly different from a rhyolite dike, although the chemical composition of the two may be similar.

An excellent summation of the history of the term *pegmatite* and earlier theories of origin of pegmatites is given by Johannsen (14).

Theories of Origin.

Any comprehensive theory of origin of pegmatites must account for certain features characteristic of pegmatites as a whole as well as features peculiar to the district studied. A satisfactory theory must explain the wide variations in pegmatite geology and mineralogy. The following are, in the writer's opinion, the major features of pegmatite occurrence that a theory of origin must explain:

(1) Pegmatites have a common areal association with bodies of rock generally considered igneous in origin. In some places there is an obvious co-magmatic relation between pegmatite and intrusive, for example, syenite-pegmatite and syenite intrusive, but this relation does not always hold; for example, the differentiation of a gabbroic magma may produce syenite-pegmatite.

(2) In some districts pegmatites contain rare and unusual minerals. Some of these minerals are virtually restricted to pegmatites, some are common in igneous rocks, and some are found in hydrothermal veins. In general, however, only a very small percentage of pegmatites contain rare minerals ; most are simple quartz-feldspar bodies.

(3) Pegmatites have distinctive textures, the most prominent of which is coarse and irregular grain size.

(4) Some pegmatites show a regular and systematic internal structure which is reflected in units of varied composition and texture.

(5) Pegmatites commonly assume extremely diverse and irregular forms and penetrate the host in a very intimate fashion.

(6) The composition of some pegmatites is influenced by the composition of the wall rock. Other pegmatites cut across wall rocks of widely differing characters and show no evidence of having been affected by the wall rocks in any way.

(7) Wall-rock alteration is associated with some pegmatites. The alteration takes the form of tourmalinization, biotization, feldspathization, silicification, or introduction of such pegmatite minerals as muscovite and beryl. This alteration is not comparable to the sericitization and kaolinization accompanying normal hydrothermal veins.

(8) Pegmatites commonly distort the foliation of the host rock or impress a secondary foliation on the host.

(9) Pegmatites are commonly associated with aplites.

There are a number of theories of origin of pegmatites which place different interpretations on the physical evidence or which emphasize some features to the neglect of others.

The Granitization Theory.—There are two different ideas on pegmatite formation within the granitization school. One concept holds that pegmatites represent preferred directions of granitization (or pegmatization) and that the volumes now occupied by pegmatite were formerly occupied by country rock

[6] Knopf, Adolph, Lecture, 1949.

(10, 15, 19). This is essentially a theory of selective metasomatism. The second concept holds that a low-temperature liquid rich in expelled elements forms in advance of a theater of granitization and is injected into fissures under hydrostatic pressure (3).

The hypothesis of pegmatization by metasomatism in preferred directions fails to explain a number of the major features of pegmatite occurrence. They are summed up as follows: (1) The presence of textural and mineralogical zones reflecting the shape of the pegmatite body and often containing systematic concentrations of rare elements. Core zones are frequently isolated pods; (2) Evidence of injection (dilation, rolls, distortion of foliation) ; (3) Wall-rock alteration; (4) Fracture fillings extending from the core and cutting wall zone and host rock; and (5) Pegmatite textures. The process of granitization is one in which a mass of crustal rocks of variable composition is converted into an essentially homogeneous granite—it is an homogenizing process. It is difficult to see how a zoned pegmatite could be the result of an homogenizing process. The writer has examined a pegmatite near Gunnison, Colorado,[7] containing a relatively thin core-margin zone averaging 10 to 13 percent beryl in crystals up to 28 inches in diameter. Such a concentration of a relatively rare element by a process of granitization is not probable.

The second concept is less extreme. The liquid that forms in advance of the wave of granitization is rich in volatiles and elements that will not fit into the lattice of the normal granite minerals. This liquid is, then, similar to that formed by differentiation of a granite magma, a granitic rest-magma, and it is emplaced by injection. Backlund (3, p. 115) states that this liquid is at low temperature. Granted, for the moment, that this liquid can form in such a way, the injection of a granitic liquid is again being considered, the same pegmatite fluid derived in a different way by the magmatic theory.

There are some points that might be mentioned concerning the formation of this liquid by a granitization process. In addition to the volatiles expelled in advance of granitization, basic elements (Fe, Mg, Ca) must also be eliminated from the granitized rock. These elements are certainly not constituents of pegmatites in any great degree. What is the relation of the expelled basic elements to the granitic liquid? There may also be a problem in the transfer, by solid diffusion, of elements with large ionic radii.

The Palingenesis Theory.—The theory of palingenesis holds that under deep-seated conditions of high temperature and pressure a partial melting of crustal rocks may give rise to a magma. (If a partial remelting takes place the term *anatexis* is applied.) This idea has been called on to explain the origin of intimately penetrating simple quartz-feldspar pegmatites in migmatite zones. The theory falls down when applied to complex pegmatites because it cannot explain the concentration of rare elements found in these pegmatites. In order for a concentration of rare elements to take place, a large quantity of crustal material would have to be melted *and differentiated.*

The theory of palingenesis might be applied in the Mica Mine area. No intrusive body is exposed; the pegmatites are essentially simple quartz-feldspar-

[7] The Field prospect, Quartz Creek area, Gunnison County, Colorado.

mica rocks; pegmatites intimately penetrate the host; *lit-par-lit* zones are present; and augen and stringers of pegmatite occur throughout the host. The bulk of the country rock is of a composition to yield a granite magma on melting (Table 2). One objection to this theory in the Mica Mine area is the tourmaline content of some of the pegmatites. In some pegmatites the tourmaline content may exceed 1 percent. Many crustal rocks contain boron in small amounts, but in order for tourmaline to be concentrated in the amounts found in the Mica Mine pegmatites, a differentiation of the palingenic or anatectic magma must have taken place. If differentiation is allowed, the palingenic theory and the magmatic theory are one and the same.

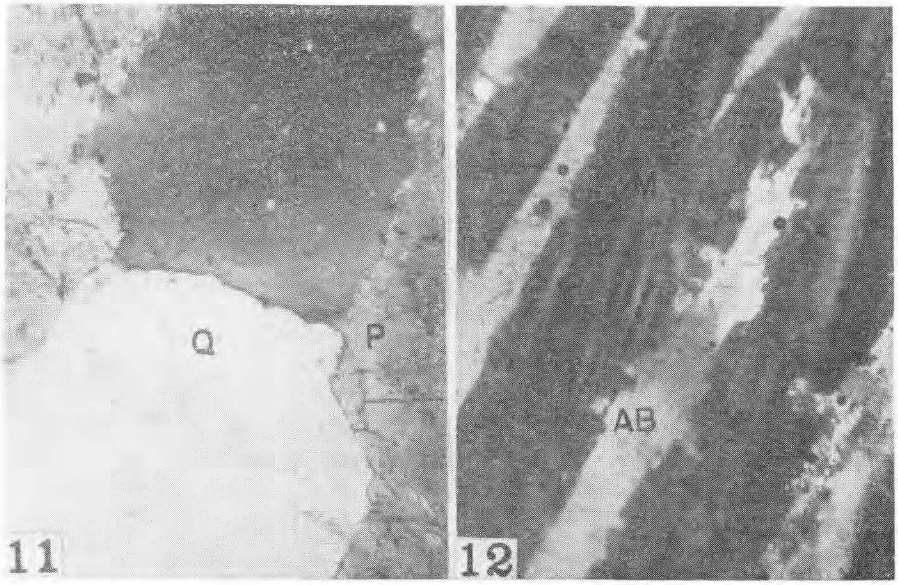


FIG. 11. Quartz veinlet in plagioclase in fine-grained pegmatite. P, plagioclase; Q, quartz. × 75.
FIG. 12. Microcline perthite from the Mica Mine area. M, microcline; AB, albite. × 75.

The Open-System Theory.—The modern open-system theory holds that pegmatites form by crystallization of solutions moving through an open system. Pegmatite units may be formed by progressive filling by solutions changing in composition and/or by replacement (6, 20). There is no general agreement on whether the fluids are attenuated aqueous solutions or magmatic solutions. Andersen (2, p. 32) has suggested that quartz may crystallize from a dilute hydrothermal solution at the relatively cold far end of an opening while quartz and feldspar are crystallizing from a more magmatic solution at the relatively hot end of the same opening.

The general features of pegmatites listed on page 180 can for the most part be explained by the open-system theory. One of the strongest arguments for the theory is that pegmatites have been reportedly traced into quartz veins. See Tolman (23) for a summary of such reports. Against the theory is the fact some pegmatites show evidence of injection, and some pegmatites contain pod-like units completely surrounded by other units. To the writer, however, the picture of "magmatic mother liquors" or "magmatic solutions" moving through channels under pressure and forcing aside the walls is not dissimilar to that of a fluid rest-magma being "injected" in a similar environment. It has been suggested by proponents of the open-system theory that the alleged isolated pods are connected by fine capillary-like channels (2, p. 14).

In the Mica Mine area internal features such as discontinuous cores, interference of schist partitions with zoning, fracture fillings extending from core through wall zone, *localization of contamination by host,* and lack of plagioclase in any of the cores are, in the writer's opinion, more satisfactorily explained by crystallization in a closed rather than open system.

Magmatic Theory.—The thesis of the magmatic theory is that pegmatites result from injection of a granitic rest-magma which, through crystallization in successive stages, produces (if physical conditions during crystallization are favorable) a sequence of mineralogical and textural units. There may be a modification of any of these primary units by still unconsolidated pegmatite fluids within the system or by external hydrothermal solutions in an open system. There is some dissension within the ranks of the magmatists on the importance of this hydrothermal phase. One of the main tenets of the magmatic theory is that pegmatites are emplaced in a closed or restricted system.

In the review of the preceding theories it is seen that the pegmatite source is probably an injectable medium which contains, in some instances, a concentration of rare elements. It must be a solution rich in alkalis and volatiles. Most geologists agree that such a solution is the end-product of a crystallizing, and therefore differentiating, granite magma. It is necessary to have some process of concentration to explain the amount of rare elements in pegmatites no matter how the original solution was derived. The general features of pegmatites listed on page 180 and the features of Mica Mine pegmatites can be satisfactorily explained by the magmatic theory.

Many geologists studying complex pegmatites believe that one or more hydrothermal replacement phases follow the magmatic phase. See Landes (16) for a detailed treatment of this branch of the magmatic theory. In the Mica Mine area only one pegmatite, the Mica Mine No. 1 (Fig. 14), contains a unit that may owe its origin to a later hydrothermal phase. This pegmatite contains a small plagioclase-quartz replacement body that cuts the plagioclase-quartz-perthite-muscovite zone. The Mica Mine area pegmatites are essentially simple quartz-feldspar-muscovite pegmatites, and it is the writer's opinion that they formed in one magmatic phase.

In addition to the concentration of rare elements, pegmatites have many features of texture, form, and relation to host that are not found in the normal intrusive rock. The explanation of these features must come from a study of the nature of the pegmatite fluid during crystallization and the mode and horizon of emplacement of the pegmatite body.

Nature of the Pegmatite Liquid.

Experimental Evidence.—Goransen (8) has shown that under conditions of high pressure a granitic magma can hold as much as 10 percent water. He calculated that at pressure of 5,000 bars (equal to approximately 18 km in depth), the amount of water soluble in the magma is between 9 and 10 percent and that the 10 percent value is approached asymptotically.

Smith (22, p. 545), after a series of experiments, concludes that near the end of magmatic crystallization a water solution is generated which is immiscible with the residual silicate solution. Soluble components are partitioned between the two immiscible liquids. Crystallization of the silicate solution in channels of escape from the magma forms pegmatites, and the crystallization of the water solution in similar channels forms veins containing metallic sulphides. Smith calculated the composition of a residual liquid after 96 percent crystallization of a granitic magma. With 2 percent water in the original magma, the rest-magma contains 20 percent water after 50 percent crystallization, 50 percent water after 96 percent crystallization, and 67 percent water after 97 percent crystallization of the original magma. A sealed bomb was charged with the calculated solution and heated to temperatures as high as 500° C. The temperature was maintained for a specified length of time and the bomb was then chilled. Three phases—crystals, a viscous green silicate liquid, and a water solution—were observed in some instances upon opening the bomb. The temperature range of the three-phase "pegmatitic stage" of Smith (22, p. 543) is 290° to 550°. It should be noted, however, that three phases were observed after cooling the bomb and not at the high temperature. Chilling of the bomb may or may not have preserved the high-temperature relations. Morey (18), in a discussion of Smith's work, says that he can see no experimental evidence that makes probable the formation of two immiscible liquids in water-silicate systems. However, Tuttle and Friedman (25) found two immiscible liquids in the system H_2O-Na_2O-SiO_2. The so-called "heavy phase" found in these experiments was a viscous siliceous liquid immiscible with a second essentially hydrous phase. Equilibrium relations were determined at 250–300–350 degrees C.

Tuttle and Bowen (24) reported that a high and a low temperature form of albite exists and, in the presence of fluxes, the transition between the two forms may take place as low as 700° C. Pegmatite albite is the low-temperature form.

Pegmatite quartz is low quartz with a temperature of formation less than 573° C plus pressure correction, or about 600° C as a round number. Ingerson (12, p. 387), applying the liquid-inclusion method, states that measurements on pegmatite quartz indicate temperatures of formation of less than 250° C.

These various experiments have shown that (1) a substantial amount of water is soluble in a granite magma under pressure, and (2) the temperature of formation of pegmatites is a good deal lower than the 600° C formerly considered a satisfactory figure. The possibility of formation of two immiscible liquids, a water solution and a silicate liquid, in a rest-magma must be considered.

Composition.—Pegmatites are exceedingly variable in composition but nearly all pegmatites are high in potassium, aluminum, sodium, and silicon, With these fundamental pegmatite elements occur variable amounts of calcium, iron, manganese, lithium, beryllium, phosphorus, halogens, boron, uranium, thorium, caesium, cerium, tin, columbium, tantalum, and minor metallic sulphides. Other rare elements are less commonly present. These rarer elements characterize pegmatites of certain districts, but only a very small percentage of pegmatites contain minerals other than quartz, feldspar, and mica. The concentration of these rarer components in the granitic rest-magma depends on their concentration in the original magma. A volatile-rich and alkali-rich rest-magma still appears to be the most likely source of pegmatite fluids. An analysis of a representative sample of pegmatite from the Mica Mine area is shown in Table 2.

Emplacement of the Pegmatites.

Andersen (2, p. 5), in discussing the relation between pegmatites and normal igneous dikes, says: "It is obvious that the igneous dikes have been formed in the upper parts of the Earth's crust, the zone of fracture. At the moment of intrusion the temperature of the surrounding rocks must have been relatively low." This is not a new idea and few geologists will question it. There are a number of points which indicate a different environment for pegmatite emplacement. The intimate penetration of the host rock, irregular forms, coarse uneven texture, and zonal development serve to distinguish pegmatites from igneous dikes. The hypothesis of a relatively deep-seated horizon of emplacement, in some instances concomitant with orogenic stresses, seems to answer many problems.

In a deep-seated environment where pegmatite fluid and host rock are at approximately the same temperature, no chilling and resulting precipitate crystallization would be expected. With evenly-maintained temperature and injection pressures and an almost unlimited time factor, the low viscosity of the pegmatite fluid would facilitate an intimate penetration of the host. Injection pressures would not be suddenly released through open fractures. The injection, although considered a one-pulse mechanism, would be a slow process involving a variable amount of digestion of the host and dilation. Andersen (2, p. 13) suggests that lens-shaped openings may have been created by orogenic forces as well as by pressure of the pegmatite fluid. This is in harmony with the theory that intimately penetrating pegmatites are a feature of larger synkinematic intrusions. The irregular form of some pegmatites is not difficult to envisage under the deep-seated conditions just pictured. Graton (9, p. 36) explains the irregular form of pegmatites in the metamorphic rocks of the southern Appalachians by reference to the nature of failure of the host rock under stress. He says : "It thus appears that the directions or the loci of greatest weakness—those places which would determine the position and form of the intrusion—are not simple planes, but are instead comprised of series of parallel planes of irregular extent, arranged more or less step-wise, in some places branching, in others overlapping, and in still others almost separated by the intervention of localities where the rock is stronger; i.e., of greater cohesion between the two walls of the plane of movement."

In discussing "miniature pegmatites," Andersen (2, p. 12) says that siliceous solutions rich in the constituents of potassium feldspar penetrate the foliated rocks wherever they find suitable openings, forming in some places little lenses, eyes, and streaks, and in other places larger bodies. These solutions, says Andersen, acted in part by replacement and in part by pushing the containing rocks aside. If digestion (replacement in a closed system) is substituted for replacement, this statement applies to the Mica Mine area.

In the Mica Mine area the emplacement of the pegmatites was accomplished in part by forcing aside the host rock, dilation, and in part by digestion of the host rock. Both processes were facilitated by the ease of penetration along foliation in the more schistose rocks.

Crystallization.

In a deep-seated environment the emplacement of pegmatites would cause the collection of diffused elements in large crystals as the result of: (a) a very slow and prolonged period of crystallization and/or (b) low viscosity of the crystallizing fluid. The occurrence of a gigantic single crystal of beryl, for example, is known. This amounts to a single center of crystallization in a system maintained in that precarious balance until diffusion of large quantities of beryllium to that center could take place. This, of course, is an extreme example. However, the solubility relations of the various pegmatite constituents must be maintained in delicate balance to explain zoning and coarse textures. A high concentration of a given substance also tends to increase crystal size. The number of centers of crystallization in the system must have been limited in contrast to normal igneous rocks.

Order of Crystallization.—The sequence of crystallization in the Mica Mine area results from a crystallizing liquid containing a large excess of potash. The solubility product for potassium feldspar was exceeded early in the cooling history, giving rise to large crystals of microcline perthite around a relatively few centers. The fine-grained matrix represents a later period of crystallization. Small microcline perthite crystals, plagioclase, quartz, and muscovite characterize this assemblage. If any of the perthite formed by replacement by albite along fracture planes within microcline, rather than by exsolution, it probably formed during this period of crystallization. Microcline in the wall zone and in schist inclusions undergoing digestion was corroded and embayed by plagioclase and by quartz. The potash released probably migrated into the uncrystallized part of the pegmatite and was used later in the growth of the larger microcline perthite crystals in the core.

Crystallization of the wall zone exhausted the soda and lime content of the pegmatite liquid and left a highly siliceous residue rich in potash and containing the boron and iron necessary for the formation of tourmaline. This liquid, or parts of this liquid, filled fractures in and sought out planes of entry to the crystallized wall zone. Quartz-tourmaline stringers and quartz-perthite-tourmaline-muscovite fracture fillings formed during this period. The secondary muscovite found along crystal boundaries and in cracks also probably formed at this time. Final consolidation produced a coarse quartz-microcline perthite core containing minor muscovite. If partitions of country rock interfered with crystallization of the pegmatite as a unit, a number of coarse, perthite-quartz segregations formed instead of a single core.

Source of the Plagioclase in the Mica Mine Area.—A number of points lead the writer to consider the plagioclase of the wall zone as material crystallized from the original injection of liquid and not added by hydrothermal solutions. They are as follows:

(1) The anorthite content of plagioclase from pegmatites in contact with amphibolite is definitely influenced by the amphibolites and reflects digestion of the amphibolite.
(2) The anorthite content of the plagioclase in the pegmatites changes progressively from north to south showing a definite, though undetermined, pattern. The plagioclase of the northern part of the area is oligoclase, not a common hydrothermal mineral.
(3) The plagioclase-bearing wall zone is symmetrical about a core that does not contain plagioclase. Why a later hydrothermal plagioclase should respect earlier primary boundaries and reflect the shape of the pegmatite body is difficult to understand.
(4) The plagioclase of the wall zone is cut by later quartz-tourmaline stringers emanating from the core.
(5) The microcline in the wall rocks does not show evidence of albitization.

Problem of the Quartz Core.—The presence of a pure quartz core in a pegmatite has sometimes been considered as a point against the magmatic theory. Progressive crystallization should leave a quartz magma or pure quartz melt which, because of the extreme temperature necessary to maintain such a melt, appears impossible. Jahns (13) discusses this problem and concludes that this quartz represents a late-magmatic stage where temperatures did not exceed 300° C. Jahns says that this *magma-like* (writer's italics) solution rich in SiO_2 could exist at such temperatures, provided that substantial amounts of alkalis were present. This is in accord with the evidence of the quartz-perthite cores of the Mica Mine area. The quartz-tourmaline stringers and the fracture fillings extending from the core indicate that this residuum was a very mobile fluid and certainly not a highly viscous melt.

One can only speculate on the nature of the solution giving rise to the quartz core. Apparently it is not a magma and not a dilute hydrothermal solution but a relatively low temperature siliceous liquid somewhere in between. Present experimental evidence does not indicate the existence of such a liquid unless it is represented by Smith's (22) silicate solution or the heavy immiscible phase of Tuttle and Friedman (25).

CONCLUSIONS ON ORIGIN OF PEGMATITES OF THE MICA MINE AREA.

(1) The formation of pegmatites by crystallization of a siliceous, alkali-rich, volatile-rich rest-magma in an essentially closed or restricted system is the most satisfactory explanation of the major features of pegmatites.

(2) Local palingenesis or anatexis cannot explain the concentration of rare elements found in some pegmatites. In order to account for the amount of rare elements in some pegmatites some process of concentration is necessary. The rest-magma may have been formed by : (a) Crystallization (and resulting differentiation) of an original granitic magma; (b) crystallization (and resulting differentiation) of a granitic magma formed by wholesale palingenesis or anatexis of a large mass of crustal rocks; (c) production of a fluid rich in volatiles and expelled elements in advance of a wave of granitization. The product of these three processes would be similar and it is not possible to determine the process from the crystallized product.

(3) The hypothesis of formation of pegmatites by metasomatic replacement of host rocks is not satisfactory in the light of information on the internal features of pegmatites.

(4) Pegmatites are emplaced in a deep-seated environment, perhaps under orogenic stresses, by a combination of dilation and digestion. The relative importance of the two processes varies widely in different districts. The process of entry of the pegmatite fluid is one of injection under conditions of sustained heat and pressure. There was little thermal contrast between pegmatite-

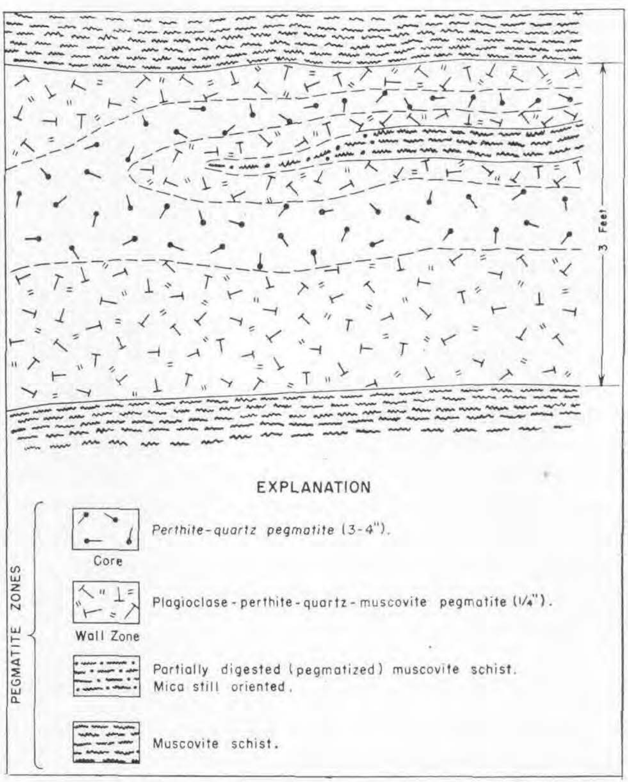


FIG. 13. Idealized section showing perthite-quartz core split by schist partition. Schist partition grades into pegmatite.

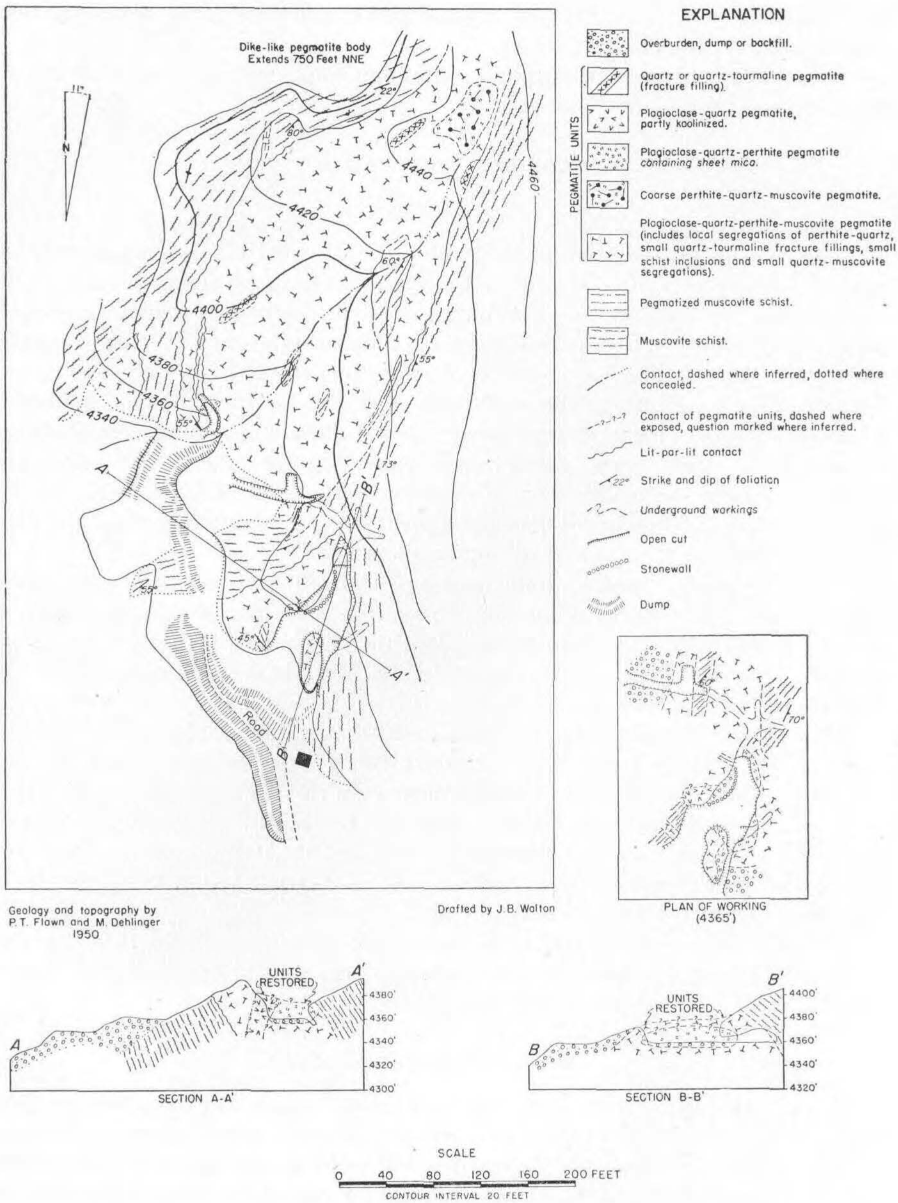


FIG. 14. Geologic map of Mica Mine No. 1.

forming solution and host. The low viscosity of the pegmatite fluid under such conditions and with an almost unlimited time factor would facilitate intimate penetration of the host rock.

(5) Physical conditions maintained in a deep-seated environment during crystallization are such as to produce a delicate balance of solubility factors,

limiting the number of centers of crystallization and producing pegmatite textures and zonal features.

(6) A later hydrothermal phase, although important in some districts, is not present in the Mica Mine area.

ECONOMIC POSSIBILITIES.

General Remarks.

The first organized attempt to develop the Mica Mine area began in 1920 with the formation of the Micolithic Company of Texas, a stock company with a very large capitalization. The purpose of this company was to develop a product for facing cutstone. The installations established by this company were impressive. They consisted of a large steel-framed mill and warehouse, 5 miles of railroad linking the mica mine with the Southern Pacific Railroad, a Fairbanks Morse diesel electric power plant (240 volt), a number of dwelling houses, and a pipe line and pump house connecting the mine with a well in the bolsom. At this time the Mica Mine rivaled the town of Van Horn in size. The only traces of the actual quarrying operations conducted by this company, strangely enough, are a few small pits in the schist.

The Micolithic Company went bankrupt in 1930, and its assets were taken over by the Rio Grande Quarries Company. The property and assets of this company were in turn sold, in 1940, to the present owners, a syndicate composed of twelve members, represented by Mr. M. A. Baldwin and Dr. W. H. Scherer of Houston, Texas.

During the war the property was leased to the Texas Mica and Feldspar Company which operated it for a short time. The lessees hoped to take advantage of the Government subsidy on sheet mica. It was during this period of operation that the U. S. Bureau of Mines conducted exploration and testing (11). The writer is informed by Mr. H. O. DeBeck of the Research Laboratory in Ceramics, The University of Texas, that about $5,000 worth of mica was sold as “strategic mica” during this period.

The present workings consist of two short adits in the pegmatite opposite the mill (Figs. 2, 14) and a number of small cuts in other pegmatites. Small stock piles of feldspar are found near some of the cuts.

Possibilities for Development.

Mica.—In spite of the name, the area has no future in production of sheet mica or of scrap and sheet mica as a *primary* product unless there is a marked price increase. Some of the pegmatites will yield an average of 5 to 8 percent scrap mica recovery from a process separating run-of-the-mine pegmatite for feldspar. This scrap mica would be an important by-product. A good grade of “electrical” mica occurs in the pegmatites in the immediate vicinity of the mill. The existence of any sizable reserve of this “electrical” mica remains to be proved. A very small amount, too small for economic production, was classed as “strategic” during the war. The results of power factor and flotation tests run by the Bureau of Mines are given by Holt and Bowsher (11).

Feldspar.—There is a considerable tonnage of feldspar in the Mica Mine area. The average pegmatite consists of 30 to 40 percent easily-cobbed potash spar, and a number of pegmatites are large enough for quarrying operations. Should it prove feasible to mill and float run-of-the-mine pegmatite, a scrap mica and perhaps a clean quartz tailing would be salable in addition to the spar. Black tourmaline is the only deleterious constituent of the pegmatite and should be easily separated.

The important point for investigation is the iron content of the feldspar. The Bureau of Mines (11, p. 7) found 0.28 percent Fe_2O_3 in a minus 20-mesh flotation concentrate, of which feldspar made up 51.8 percent of the product (7.4 percent mica, 32.2 percent quartz, 8.5 percent slime). It should be noted that these tests were run on mill tailings, and it was not specified from which pegmatite these tailings were derived. If the iron content of the feldspar has any relation to the color of the feldspar it must be extremely variable throughout the area. It will be necessary to determine the iron content of the feldspar from individual pegmatites and this will entail systematic sampling. The University of Texas Bureau of Economic Geology plans to carry out additional metallurgical testing on the feldspar of the Mica Mine area.

Advantages and Disadvantages of the Area.—The advantages of the Mica Mine area are proximity to a railroad, abundant Latin-American labor, and installations already at hand.

An adequate water supply may constitute a problem. Water may be produced from the basin fill and pumped to the mine area. The fault zone along the west front of the range should be explored for water.

The specifications of the feldspar product may be different from that now in use in Texas industry. The feldspar industry is a "closed industry" in the sense that a consumer may be forced to change his plant in order to change his source of feldspar and thus must be assured of supply before making such a change.

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Oct. 30, 1950.

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