# THE PETROLOGY OF THE JUDITH MOUNTAINS

# FERGUS COUNTY, MONTANA

by
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Frontispiece

Panorama of the Judith Mountains. Looking east from the South Moccasin Mountains.

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# ABSTRACT


The Judith Mountains are a group of Tertiary (?) porphyry stocks and related intrusives that have cut and domed a thick series of sedimentary rocks ranging in age from Cambrian to Upper Cretaceous. Quartz monzonite intrusions mark the beginning of irruptive activity and form the major stocks in all parts of the mountains. Later igneous rocks represent two lines of descent: (1) more siliceous types best exemplified by rhyolite, and (2) rocks relatively poor in silica and high in the alkalies represented by syenite, alkali syenite and tinguaite. The alkali granite porphyry of Judith Peak occurs late in the igneous sequence. It is rich in both silica and the alkalies and is believed to represent a union of the two separate lineages.

A strong but irregular east-west fault divides the mountains into two structural units, each with a distinct assemblage of igneous rocks. The southern unit is characterized by calc-alkaline rocks, the monzonites and the rhyolites. The northern unit is characterized both by alkaline rocks, the syenites, alkali syenites, tinguaites and the alkali granite porphyry, and by calc-alkaline rocks, the monzonites. The northern unit contains only a few small bodies of rhyolite. The general sequence of irruption is monzonitic rocks, rhyolite, syenite, alkali syenite, tinguaite and alkali granite.

At the time of intrusion the Madison limestone was more deeply buried beneath the surface in the northern part of the mountains than in the area to the south. The position of the Madison within the crust was important in that it affected the mode of intrusion. Detailed mapping shows large-scale magmatic stoping of the Madison limestone north of the strong east-west fault but not south of it. This suggests that limestone syntexis has desilicated the magma at depth to yield the silica-poor and silica-deficient alkaline rocks which are restricted to the northern part of the mountains. In the southern part of the mountains where the Madison limestone was not thus stoped, the rocks that follow the early monzonitic intrusions are highly siliceous rocks, the rhyolites. The alkali granite is believed to represent a late siliceous differentiate of the calc-alkaline series, contaminated by alkaline fluids expelled from the cupola area of a tinguaite magma chamber.

# INTRODUCTION

The petrology of the Judith Mountains is of special interest for several reasons: (1) The igneous assemblage of the mountains contains calc-alkaline, silica-deficient alkaline, and silici-alkalic rocks. Thus the area provides an opportunity to study the association and genetic relations of three distinct general rock types. (2) The Judith Mountains are one of a group of isolated mountain ranges containing alkaline igneous rocks that collectively make up the petrographic province of central Montana (Pirsson, 1905) and (Larsen, 1940). The peculiar concentration of alkaline rocks in this province has long been a controversial subject and an explanation of the genesis of the Judith Mountain rocks may contribute to the understanding of the more general problem of the origin of the alkaline rocks that occur in the platform areas of the Rocky Mountain region.

## LOCATION, CULTURE, AND ACCESSIBILITY

The Judith Mountains are in central Montana (fig. 1), 5 to 25 miles northeast of Lewistown, the county seat of Fergus County. They cover approximately 140 square miles in the northeastern part of the Lewistown quadrangle and the northern part of the Judith Peak quadrangle. These two quadrangles lie between parallels 47°00' and 47°15' and meridians 109°00' and 109°30'. The mountain area also includes a narrow strip of land just north of parallel 47°15' and several square miles adjoining the northeast corner of the Judith Peak quadrangle.

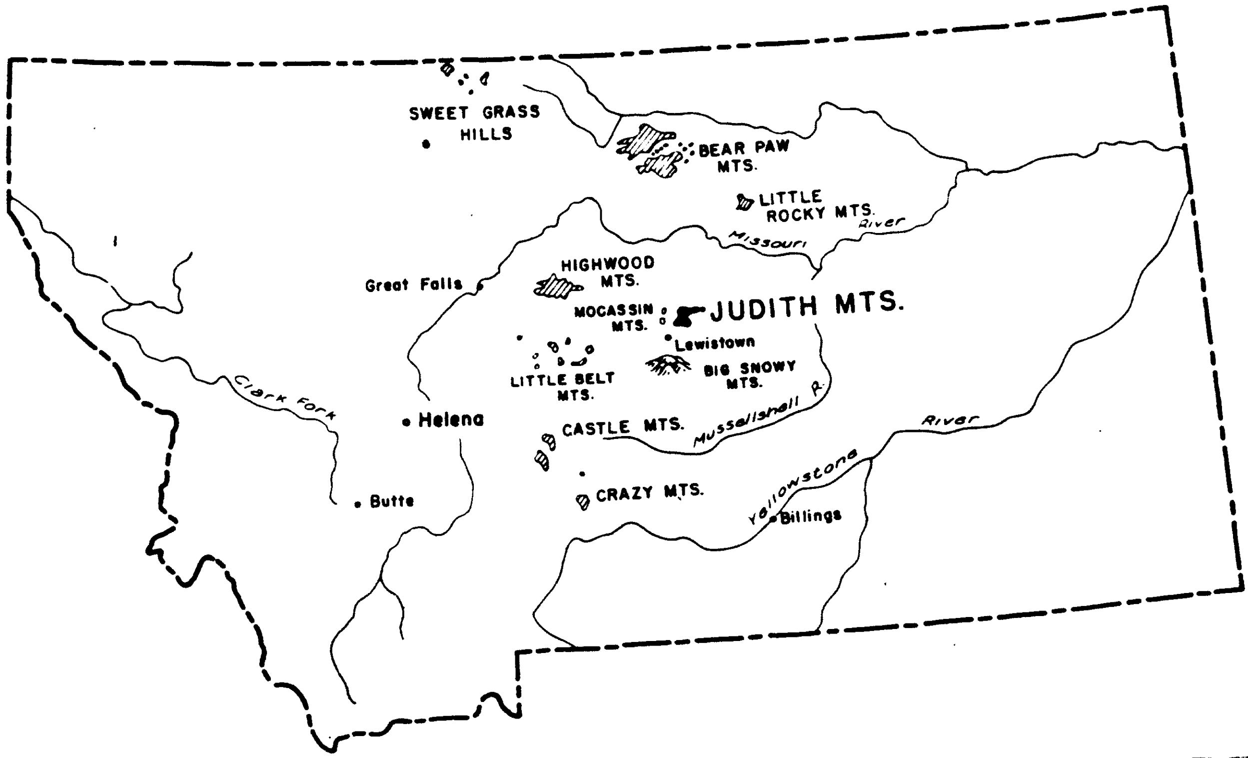



Figure 1.--Index map of Montana showing location of the Judith Mountains. The oblique ruled pattern indicates areas containing alkaline igneous rocks similar to those exposed in the Judith Mountains.

Maiden, near the head of Warm Spring Creek, and Giltedge, on the southeast flank of the mountains, were important mining camps in the eighties, but today are inhabited by only a few families. The area surrounding the mountains and the lower reaches of Warm Spring Creek valley are largely devoted to the dry farming of wheat and to cattle and sheep ranching.

Lewistown is on highway, U. S. No. 87, the main route between Billings and Great Falls. From Lewistown, the mountain area is easily accessible on a peripheral and radial network of gravel and dirt roads that are in fair condition most of the year. A spur line of the Chicago, Milwaukee, St. Paul and Pacific Railroad connects Lewistown with the main line at Harlowtown, 45 miles to the south.

## PHYSICAL FEATURES

The Judith Mountains form an isolated range 18 miles long and 3 to 8 miles wide that rises abruptly 2,000 to 2,500 feet above the surrounding plains of central Montana. Judith Peak, the highest point, is at an altitude of 6,428 feet, 400 to 900 feet higher than most of the peaks in the range. The main range extends northeastward from a point about 5 miles northeast of Lewistown to Lookout Peak, 23 miles northeast of Lewistown. Black Butte is an isolated peak about two miles east of the northeastern end of the main mountain mass.

The surface in the mountain area is one of distinct peaks separated by deeply cut stream valleys and is a surface of early maturity. Maximum relief from peak to adjacent valley bottom is generally less than 1,000 feet. Most of the area can be readily covered on foot. Steep slopes of porphyry talus are common, but sheer cliffs occur at only a few places: notably in Maiden Canyon, at Cone Butte, at Black Butte, and on the south side of Maginnis Mountain.

The major valley in the mountains is that of Warm Spring Creek. This valley heads about 1 mile east of Maiden, widens rapidly to the west, and forms a large east-west embayment that almost completely divides the mountains into northern and southern parts. Immediately surrounding the mountains are three levels of dissected pediments.

## CLIMATE AND VEGETATION

The records (U. S. Dept. of Agriculture, 1941, p. 956) of the weather station at Lewistown over a 38-year period show an average temperature for July of 65.4°F. and a maximum range of 151°F. The annual precipitation averages 17.87 inches of which 8.5 inches, or more than 47 percent, falls during the months of May, June, and July. The mountain area receives considerably more rain and snow, but by late July the streams are low, and only the major ones carry water throughout the summer.

Alder, willow, aspen, and in places birch, grow along the stream valleys, and various types of conifers are common on the slopes. These include juniper, ponderosa pine, white pine, western balsam fir, and a few Englemann spruce and Douglas fir. Most of the large timber has been used for the mining industry or burned off. The burned areas, especially those underlain by porphyry, are covered with small lodgepole pine, locally called "jack pine." Parts of Red Mountain and Judith Peak are almost impassable because of the dense second growth of these trees. The eastern part of the mountains receives less precipitation, and sage brush and small cacti are common.

## PREVIOUS WORK

The only previous systematic study of the Judith Mountains was made by W. H. Weed and L. V. Pirsson (1898). The map accompanying their report is at a scale of 1/125,000. During the early nineteen hundreds a number of short articles appeared in the various mining periodicals, but these were concerned chiefly with mining development and production. An excellent resume of the history of the mines and prospects with production figures and brief descriptions of the occurrences was compiled by Robertson (1950).

## FIELD AND LABORATORY WORK

The Judith Mountains were mapped as a project of the U. S. Geological Survey. Dr. E. N. Goddard, now of the University of Michigan, was in charge of the project and spent four field seasons in the area. The writer served as his assistant during the summers of 1948 and 1949, and was assigned the study of the igneous rocks for the Judith Mountain report.

The geologic mapping was done on aerial photographs at a scale of 1/20,000. Plate 1, of this report was compiled on the 1/62,500 topographic sheets of the Lewistown and Judith Peak quadrangles.

Microscopic studies of the igneous rocks were carried out in the laboratories of the U. S. Geological Survey in Washington, D. C. during the winter of 1948-49 and in the Mineralogical Laboratories of the University of Michigan during the academic years of 1949-50, 1950-51, and 1951-52. The specimens were examined in thin section and by immersion techniques. X-ray studies and chemical analyses were made available by the U. S. Geological Survey.

## ACKNOWLEDGMENTS

Part of the work on the report was done under a grant from the University of Michigan, Horace H. Rackham, School of Graduate Studies. Dr. W. T. Pecora of the U. S. Geological Survey, and Dr. E. Wm. Heinrich and Dr. Walter F. Hunt of the Department of Mineralogy examined many of the thin sections. Dr. O. F. Tuttle of the Geophysical Laboratory of the Carnegie Institution of Washington made x-ray studies of some of the feldspars. Alfred Levinson, research assistant of the University of Michigan measured some of the feldspar crystals with the reflection goniometer. John Lemish, graduate student of the University of Michigan gave valuable assistance in the determination of clay minerals. Thanks are extended to Professors F. S. Turneaure, L. B. Kellum and E. N. Goddard of the Department of Geology and to Professor E. Wm. Heinrich of the Department of Mineralogy, who read the manuscript and made many helpful criticisms and suggestions. Most of the geologic information presented to support the petrologic part of this paper is the result of Dr. Goddard's work.

# GEOLOGY

## GENERAL FEATURES

The Judith Mountains are a group of coalescing domes formed in early Tertiary (?) time by the intrusion of quartz monzonite and rhyolite magma. Available evidence indicates that the main intrusive bodies are stocks rather than laccoliths as pictured by Weed and Pirsson (1898) although some of the stocks do have sill-like or small laccolithic appendages.

The major domes are well shown on the geologic map (pl. 1) as areas of igneous rock surrounded by concentric belts of sedimentary formations ranging in age from Cambrian to Upper Cretaceous. The sediments dip away from the intrusive centers at angles of 20 to 50 degrees and are locally vertical or overturned. Some of the smaller domes have been modified by roughly hexagonal or circular faults (trap-door structures and bysmaliths) which developed after the initial doming occurred.

In the northern part of the mountains, magma from several centers has coalesced to form a large irregular pluton, and the outlines of the individual domes are nearly obliterated. Igneous cores are not exposed in all domes, but several lines of evidence clearly indicate their existence (See p.120).

The igneous rocks of the Judith Mountains are of the "porphyry" type and include a variety of rocks belonging to both the alkaline and calc-alkaline clans. Monzonitic rocks predominate and form the cores of most of the domes. Subordinate types include rhyolite, syenite, alkali syenite, tinguaite, alkali granite, and intrusion breccia. These occur as small stocks, dikes, sills, and irregular bodies.

Deuteric and hydrothermal alteration are common features in all rock types. Large mineralized areas with abundant disseminated pyrite are found in the Alpine Gulch stock, the Linster Peak stock, and surrounding the alkali granite of Judith Peak. Silicified sandstone and shale and mineralized limestone are found in some places where hydrothermal alteration extends beyond the porphyry contacts. Elsewhere exomorphic effects are slight. Bleached and partially marbleized limestone is common, but recrystallized carbonate rock is generally fine grained and abundant lime silicate minerals are developed in only a few places. Shale beds are commonly soft and unaltered only a few inches from contacts, but in a few places the shale is baked.

The most significant structural feature of the mountains is the Warm Spring Creek fault. It is a strong but irregular normal fault which trends approximately N. 75° W. and dips at varying angles to the north. East of Maiden this fault is connected to a trap-door type fault which swings north around the Crystal Peak dome. Displacement varies, but in some places the north side has dropped at least 1,000 feet.

## SEDIMENTARY ROCKS

The sedimentary rocks exposed in the mountains form a stratigraphic column about 6,000 feet thick. The lithologic features and approximate thicknesses of the various formations are given in table 1.[1/]

TABLE 1.--Sedimentary formations of the Judith Mountains, Montana.

| Period | Formation | Thickness in Feet | Description |
|---|---|---|---|
| Cretaceous | Eagle sandstone | 140+ | Light-gray to yellowish-gray massive, medium-grained sandstone with some layers of yellowish-gray sandy shale. |
| | Telegraph Creek formation | 285 | Light olive-gray sandy shale, finely laminated. Sand content increases upward. |
| | Colorado shale | 1525 | Dark-gray to black fissil shale with a few thin sand-stone layers. Cat Creek sandstone 75 feet thick at base and Mowry beds 140 feet thick, 550 feet above base. Mowry, fine-grained sandstone and limy shales that weather light-gray and contain abundant fish scales in some layers. |
| | Kootenai formation | 320 - 500 | Red, yellow, and gray shales alternating with medium- to fine-grained sandstone beds. At base is 60-90 feet of thin-bedded to massive arkosic sandstone; cliff forming (Lakota(?)sandstone) |

1/ On the map accompanying this report, Cambrian and Devonian sediments, the three formations of the Big Snowy group, and the beds of Jurassic age are shown as single units in order to simplify the geologic picture and bring out the essential structural features.

| Period | Formation | | Thickness in Feet | Description |
|---|---|---|---|---|
| Jurassic | Morrison formation | | 220 | Alternating gray shales and brown sandstones with 15-foot bed of dense, light-gray limestone 25 feet above base and 2-3 feet of coal or carbonaceous shale at top. |
| | Ellis group | Swift formation | 55 | Thin-bedded brownish-gray arkosic sandstone: some layers contain abundant glauconite grains. |
| | Ellis group | Rierdon formation | 90 | Light- to dark-gray sandy, limy shale with a few thin layers of limy sandstone. |
| | Ellis group | Piper formation | 120 - 230 | Interbedded dark-gray limestone and shale, locally some red shale. On south flank of Flat Mountain, contains three beds of gypsum, 10-12 feet thick. |
| Carboniferous | Big Snowy group | Heath formation | 0 - 500 | Gray to black shale with thin beds of gray limestone and brownish-gray sandstone. Mostly absent in southern part of mountains due to pre-Jurassic erosion. |
| | Big Snowy group | Otter formation | 0 - 145 | Green, gray and red shale with thin beds of light-gray limestone absent in places due to pre-Jurassic erosion. |
| | Big Snowy group | Kibbey sandstone | 0 - 110 | Light-brown to yellowish-gray sandstone with thin beds of red shale absent in places due to pre-Jurassic erosion. |

| Period | Formation | Thickness in Feet | Description |
|---|---|---|---|
| **Carboniferous** | Madison limestone | 1350 | Massive gray limestone; contains gray to black chert in some layers and some thick layers of brecciated limestone. |
| Devonian (?) | Jefferson (?) limestone | 150 | Gray- to dark-gray dolomite and limestone. |
| Cambrian | Shale, and limestone undivided | 0 - 1280 | Brown and green shales with numerous thin beds of limestone, edgewise conglomerate and gray limestone. |
| | Flathead quartzite | 0 - 160+ | Pale-yellow to brown quartzite overlain conformably by fissile black shale. Exposed only on Black Butte. |

## Cambrian system

### Flathead Quartzite

The Flathead quartzite is exposed at only one place in the Judith Mountains - on Black Butte. On the south side of Black Butte white to light-tan, brown-weathering, medium- to coarse-grained quartzite is found beneath typical Cambrian beds. Approximately 160 feet of quartzite are exposed, but the beds are in igneous contact with the porphyry core of Black Butte, and the total thickness is unknown.

Strata Overlying the Flathead Quartzite

Conformably overlying the quartzite at Black Butte are approximately 150 feet of black fissileshale. This is probably the Wolsey shale, although lithologically it is quite different from the section in the Big Snowy Mountains 45 miles to the southwest, measured by Deiss (1936, pp. 1292-1293).

In addition to the occurrence at Black Butte, Cambrian beds are found partially surrounding the igneous cores of the Alpine Gulch, Pyramid Peak, and Burnette Peak domes. Nowhere is the Cambrian section either well exposed or complete, and with the exception of the Flathead quartzite, and possibly the Wolsey shale, a division of the Cambrian strata into separate formations is not warranted.

A section on the southeast slope of Burnette Peak consists largely of dark-green, gray, and brown shales with interbedded limestones. Thin intraformational conglomerate beds of elongate limestone fragments cemented by shale and limestone are found throughout the section. Some units consist of thin alternating lenticular laminae of gray limestone and dark-green, hard, siliceous shale. The limestone and shale weather differentially and form conspicuous banded outcrops. This banded limestone and the intraformational conglomerate are the most diagnostic lithologic units of the Cambrian. Total thickness of the composite section is approximately 1,300 feet.

## Devonian System

### Jefferson Limestone

The Jefferson limestone is exposed at the same localities as those given above for the Cambrian strata. It comprises about 150 feet of gray dolomite and limestone with a few shale partings. The most noticeable lithologic unit is a very dark-gray crystalline limestone, speckled with numerous unoriented elongate light-colored streaks as much as 2 centimeters in length. The origin of these markings is unknown.

## Carboniferous System

### Madison Limestone

The Madison limestone is approximately 1350 feet thick, structurally competent, and resistant to erosion. In the southern part of the mountains it forms the steep mountain slopes, and in many places the summits of peaks. It outcrops in a broad belt surrounding the porphyry stocks. In the northern part of the mountains it is almost entirely absent and is exposed at only four widely separated localities - Elk Peak, the West Fork of Armell Creek, on the south side of Black Butte, and 1 1/2 miles north of Porphyry Peak.

It consists of alternating units of massive and thin-bedded, fine- to medium-grained, blue-gray limestone which weather light gray. Many of the thin-bedded units are sandy or shaly. Some layers contain abundant nodules of black chert.

Big Snowy Group

The Big Snowy group comprises three formations: the Kibbey sandstone, the Otter shale, and the Heath formation, listed in ascending order. Except where cut out by faults or erosion, beds of the Big Snowy group are exposed in a narrow band surrounding the Madison outcrop areas. They are also exposed in the Warm Spring Creek dome, the Deer Creek dome, and in the Linster Peak dome.

During much of the post-Mississippian -- pre-Jurassic interval, the area was emergent, and in many places all or part of the Heath and Otter formations were removed by erosion prior to the deposition of the basal Jurassic beds. On the southeast flank of the Crystal Peak dome, the entire Big Snowy group is missing, and the Ellis group rests disconformably on the Madison limestone.

The Kibbey sandstone is 110 feet thick and consists of light-gray to yellowish-brown, medium-grained friable sandstone intercalated with thin beds of red shale. Many of the sandstone outcrops are faintly mottled a dark reddish brown.

The Otter shale contains some thin beds of light-colored limestone interbedded with gray, green, and red shales. Exposures are generally poor, but some of the shale beds are a bright "apple" green and these are easily identified. The formation is 145 feet thick.

At most exposures of the Heath formation gray to black shales predominate. At some places these are interbedded with gray to very dark-gray limestone. Brownish-gray sandstone beds are exposed near the base of the formation in the Deer Creek dome. Maximum thickness is approximately 500 feet.

## Jurassic System

Jurassic beds are exposed in the foothill belt surrounding the southern part of the mountains and appear in isolated outcrop areas in the several domes in the northern part of the mountains.

### Ellis group

The Ellis Group, comprising three formations: the Piper, the Rierdon, and the Swift, with an aggregate thickness of about 300 feet, was mapped as a single unit.

Interbedded gray limestone and shale predominate in the lower 250 feet and thin bedded brown arkosic sandstone with scattered grains of glauconite constitutes the upper 50 feet. Locally red shale and gypsum are present in the lower part of the section. Some of the limestone beds are oolitic, and this plus the presence of Gryphea sp. and the glauconite sands distinguish the Ellis from underlying Carboniferous beds and the Morrison formation above.

### Morrison Formation

Gray shales constitute most of the Morrison formation, which averages about 220 feet in thickness. Brown arkosic sandstones interbedded with shales are similar in appearance to those of the Ellis group, but lack the glauconite. The best marker bed is a 15-foot layer of dense dove-gray limestone which forms ledges in the soft shale about 25 feet above the base of the formation. The upper contact is marked by a 2- to 3-foot bed of coal or carbonaceous shale which underlies the basal (Lakota ?) sandstone of the Kootenai formation.

## Cretaceous System

### Kootenai Formation

Red and gray shale and mudstone interbedded with fine-grained buff-colored sandstone predominate in most of the 320- to 500-foot section. At the base are 60 to 90 feet of thin-bedded, cross-bedded and massive-bedded, cliff-forming, salt and pepper arkosic sandstone. This member has been correlated with the Lakota sandstone.

### Colorado Shale

In the Judith Mountains the Colorado shale comprises about 1550 feet of soft, easily eroded, dark-gray to black shale with some sandstone layers. These beds are poorly exposed and therefore were mapped as a single formation. However, in areas where the various lithologic units are easily recognized they are given formation rank, and the term Colorado group is applied to this same series of beds.

In the Judith Mountains, the base of the Colorado shale is marked by the Cat Creek sandstone which consists of 75 feet of fine-grained, thin- to medium-bedded buff-colored sandstone with abundant worm-trail markings. This sandstone and approximately 475 feet of overlying dark-gray to black shale with a few thin sandstone beds are equivalent to the Thermopolis shale. The Mowry shale, next above, comprises 140 feet of thin-bedded and fissile, silvery-gray weathering arenaceous shale with some bentonite beds near the top. Fish scales are diagnostic. Overlying these beds are 240 feet of dark-gray Belle Fourche shale. These shales include a 5-foot bed of fine-grained dirty tan-colored sandstone, the Mosby, which in places carries abundant gastropods (Exogyra collumbella and others). The upper 600 feet of the Colorado shale is equivalent to the Greenhorn limestone, the Carlisle shale, and the Niobrara shale, but consists almost entirely of dark-gray and black fissile shale, with light-gray to buff elongate limestone concretions as much as 20 feet in length. Smaller ferruginous concretions occur near the base of the Carlisle equivalent. The upper part of the Niobrara beds contains Baculites codyensis and numerous fragments of Inoceramus grandus.

## Telegraph Creek Formation

The Colorado shale grades upward into the so-called "transition beds" of the Telegraph Creek formation which consists of about 285 feet of fine alternating laminae of sandstone and shale. The sand content increases toward the top. Hill slopes covered with fine sandy soil derived from these beds are marked with crescentic slump scars. The upper contact is gradational with the overlying Eagle sandstone.

## Eagle Sandstone

The Eagle sandstone outcrops in an irregular belt along the northern edge of the mountains and appears in the mapped area at only a few places. The lower part of the formation consists of gray- and buff-colored sandstone interbedded with gray shale, carbonaceous shale and thin seams of lignite. Above these beds is a 60-foot layer of light-gray to tan, massive and cross-bedded cliff-forming sandstone. Glauconite and chert granules, small clay pellets and plant remains are found at some places. The sandstone is medium grained, well sorted and friable, and weathers to rounded cavernous outcrops. The upper part of the formation lies outside the area mapped and the 140-foot section measured does not include these beds.

## Deposits of Tertiary and Quaternary Age

### Gravels

Gravels are found on three levels of dissected pediments which surround the Judith Mountains. These pediment surfaces slope away from the mountains on all sides and intersect similar surfaces sloping away from the North and South Moccasin Mountains on the west and the Big Snowy Mountains to the south. All are covered with a thin veneer of locally derived rock material, which thickens toward the plains and apparently represents large coalescing alluvial fans. The surfaces steepen toward the source areas where the slopes exceed 100 feet per mile.

The highest surface, 4,200 to 4,500 feet in altitude is capped with approximately 20 feet of very coarse gravel which Alden (1932, p. 22) has correlated with the Flaxville gravels of probable Miocene and early Pliocene age (Collier and Thom, 1917, p. 183) Alden

(1932, p. 50, p. 62) assigns the two lower surfaces to the Pleistocene.

## Travertine

Flat Mountain, in the southeastern part of the area, is covered by a layer of travertine 65 to 85 feet thick. Similar deposits are found 3 to 5 miles south of Flat Mountain and 10 to 12 miles north of Lewistown, in the Moccasin Mountains (Calvert, 1909, pp. 35-40). The largest single deposit in the Moccasin Mountains covers approximately 6 square miles and lies on the Flaxville surface (Alden, 1932, p. 22). Flat Mountain and the deposits to the south cover about 2 square miles each and lie on a still higher surface (5,000 to 5,300 feet) which slopes south and east from Flat Mountain. Gravel is exposed at one place beneath the travertine on the east side of Flat Mountain and this may be equivalent to the Cypress Hills surface of Oligocene age.

The source of the travertine is unknown, but a series of faults with collapse structural features just north of Flat Mountain suggests that calcium-carbonate-bearing waters may have issued in the vicinity. The Flat Mountain deposit dips gently to the southeast and may once have been continuous with the travertine south of Flat Mountain.

The travertine is thought to represent hot-spring deposits which derived their carbonate material from the Madison and other limestones during the subsiding stages of igneous activity. Physiographic evidence suggests that these deposits are not older than latest Oligocene and not younger than mid-Pliocene.

# IGNEOUS ROCKS

## General Statement

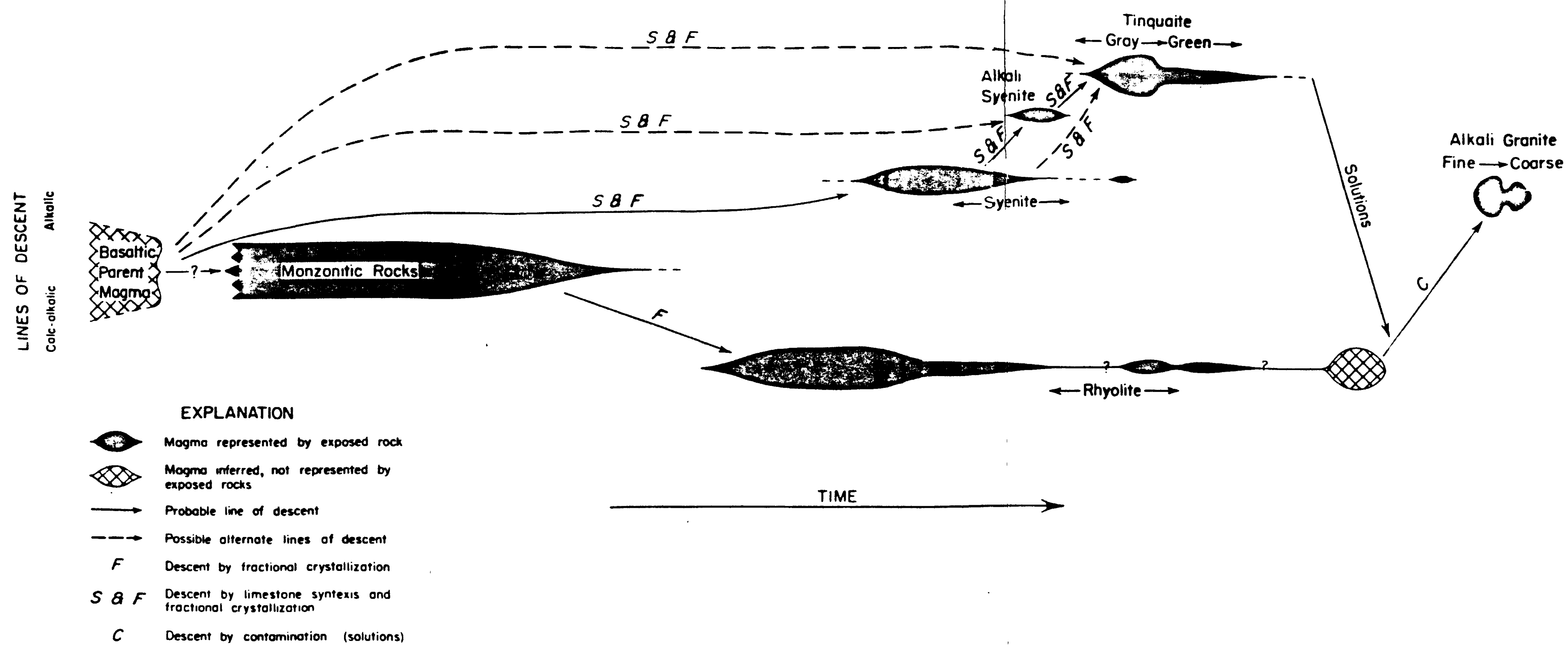
The igneous rocks exposed in the Judith Mountains represent a variety of types of intermediate to acid composition belonging to both the alkaline and calc-alkaline clans. Rocks of the calc-alkaline clan include quartz monzonite and rhyolite, form the major intrusive bodies, and constitute the bulk of the igneous rock in the mountains. Syenite, alkali syenite, tinguaite, and alkali granite compose the alkaline suite and occur as dikes, sills, and small stocks. Basic representativesof both clans are absent except for a few cognate inclusions of sodic pyroxene, apatite, and magnetite in the tinguaites. Various bodies of intrusion breccia include fragments of all other igneous rock types.

With very few exceptions all rocks are porphyritic, and variations in texture depend upon the kind, size, habit, abundance, and orientation of the phenocrysts, which are invariably set in fine-grained to almost glassy groundmass material.

The general order of intrusion of these rocks is as follows: monzonitic rocks, rhyolite, syenite, alkali syenite, tinguaite, and alkali granite; but there are exceptions to this sequence. A specimen of monzonite from the Alpine Gulch stock contains an inclusion of rhyolite, and a large dike of syenite cuts one of the tinguaite sills on the east flank of the Linster Peak dome. In addition to these specific reversals of sequence, the relative ages of some of the rocks are unknown. The alkaline rocks are restricted to the northern part of the mountains whereas almost all of the rhyolite is found in the southern part of the mountains. Because of this geographic separation of types, there is no field evidence to establish the age relations of the syenite and the alkali syenite to the rhyolite. Tinguaite and rhyolite occur together at only one locality - the southeast flank of Judith Peak. Here rhyolite is the older rock, but there are reasons for believing that some rhyolite magma was present beneath the northern part of the mountains following the injection of most of the tinguaites (p.177). It is quite possible that much of the rhyolite is younger than the syenite, the alkali syenite, and perhaps even the tinguaite. Plate 2 illustrates the age relations of the various rocks. Intrusion breccias are genetically associated with rhyolite, with alkali syenite-tinguaite, and with the alkali granite porphyry of Judith Peak, and their ages vary accordingly. The distribution of the different rock types is shown on plate 1.

Ten specimens, believed to provide a representative sampling of the major rock types of the Judith Mountains, were selected for chemical analysis. The chemical and normative compositions of these specimens are shown in tables 2 and 3.

PLATE 2




GENETIC SEQUENCE OF JUDITH MOUNTAIN IGNEOUS ROCKS

TABLE 2. Analyses of specimens of Judith Mountain rocks. *

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 65.37 | 65.96 | 69.42 | 73.35 | 60.64 | 57.63 | 60.01 | 58.05 | 58.11 | 73.88 |
| $Al_2O_3$ | 16.30 | 15.74 | 14.58 | 13.88 | 16.60 | 14.54 | 17.14 | 15.63 | 16.74 | 13.44 |
| $Fe_2O_3$ | 1.95 | 1.12 | 1.02 | 0.90 | 1.91 | 4.02 | 2.40 | 2.56 | 3.03 | 1.16 |
| FeO | 1.66 | 1.52 | 1.23 | 0.58 | 3.94 | 1.84 | 2.07 | 3.24 | 1.38 | 0.47 |
| MgO | 1.02 | 0.68 | 0.66 | 0.24 | 1.33 | 1.96 | 0.60 | 1.37 | 0.58 | 0.11 |
| CaO | 3.23 | 2.74 | 2.94 | 1.42 | 4.17 | 3.14 | 3.16 | 4.66 | 1.94 | 0.05 |
| $Na_2O$ | 5.01 | 4.68 | 4.86 | 4.07 | 4.85 | 3.18 | 5.08 | 4.12 | 6.73 | 5.41 |
| $K_2O$ | 3.92 | 4.04 | 3.12 | 4.45 | 5.33 | 8.72 | 7.50 | 5.04 | 7.68 | 5.08 |
| $H_2O$ - | 0.05 | 0.12 | 0.03 | 0.13 | 0.06 | 1.14 | 0.12 | 0.55 | 0.05 | 0.04 |
| $H_2O$ + | 0.31 | 1.13 | 0.45 | 0.67 | 0.42 | 1.36 | 1.12 | 1.68 | 2.78 | 0.32 |
| $TiO_2$ | 0.42 | 0.14 | 0.67 | 0.10 | 0.23 | 0.66 | 0.52 | 0.65 | 0.52 | 0.11 |
| $P_2O_5$ | 0.18 | 0.08 | 0.10 | 0.03 | 0.23 | 0.20 | 0.06 | 0.26 | 0.06 | 0.01 |
| MnO | 0.07 | 0.08 | 0.10 | 0.05 | 0.14 | 0.10 | 0.12 | 0.14 | 0.10 | 0.01 |
| $CO_2$ | tr. | 1.59 | 0.10 | 0.16 | 0.21 | 0.53 | none | 1.39 | none | none |
| BaO | 0.10 | 0.16 | 0.15 | 0.09 | 0.27 | 0.48 | 0.15 | 0.14 | 0.19 | 0.11 |
| S | 0.04 | 0.04 | tr. | 0.02 | 0.03 | 0.06 | 0.03 | 0.03 | 0.07 | 0.03 |
| $ZrO_2$ | 0.05 | 0.03 | 0.09 | 0.02 | 0.02 | tr. | 0.02 | tr. | 0.03 | none |
| $F_2$ | 0.02 | 0.01 | 0.03 | 0.03 | 0.03 | 0.02 | 0.07 | 0.07 | none | 0.01 |
| $Cl_2$ | --- | tr. | --- | --- | --- | 0.05 | tr. | tr. | 0.08 | --- |
| | 99.70 | 100.04 | 99.55 | 100.19 | 100.41 | 99.23 | 100.26 | 99.57 | 100.07 | 100.24 |

* Specimens 1, 3, 4, 5, and 10 analysed by A. C. Vlisidis
Specimens 2, 6, 7, 8, and 9 analysed by Charlotte M. Warshaw
$Na_2O$ and $K_2O$ determinations by S. M. Berthold, flame photometer method.

1. Coarse-grained quartz monzonite porphyry from east slope of Porphyry Peak.
2. Coarse-grained quartz monzonite porphyry from Alpine Gulch, 1 1/2 miles southwest of Maiden.
3. Medium-grained quartz monzonite porphyry from near top of Black Butte.
4. Rhyolite porphyry from near top of Pyramid Peak.
5. Fine-grained syenite porphyry from northeast base of Maginnis Mountain along East Fork of Ford Creek.
6. Coarse-grained gray tinguaite porphyry from sill on northeast side of Armell Creek 2 1/2 miles northwest of Judith Peak.
7. Gray tinguaite (crowded) porphyry from north side of Lookout Peak
8. Fine-grained syenite porphyry (Lewis Peak type) from dike that cuts gray tinguaite sill 1 1/4 miles southwest of Lookout Peak.
9. Green tinguaite porphyry from dike 1 mile northwest of Maiden.
10. Coarse-grained facies of the alkali granite porphyry from the east spur of Judith Peak.

TABLE 3. Norms of specimens of Judith Mountain rocks.*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Quartz | 13.86 | 20.04 | 23.10 | 29.40 | 2.04 | 1.26 | - | 7.80 | - | 23.52 |
| Orthoclase | 22.80 | 23.91 | 18.35 | 26.69 | 31.14 | 51.71 | 44.48 | 29.47 | 45.59 | 30.02 |
| Albite | 42.44 | 39.82 | 41.39 | 34.58 | 41.39 | 25.15 | 35.63 | 34.58 | 22.53 | 40.35 |
| Anorthite | 10.56 | 5.56 | 8.62 | 5.84 | 7.78 | 0.28 | 1.67 | 6.67 | - | - |
| Nepheline | - | - | - | - | - | - | 3.98 | - | 11.08 | - |
| Zircon | 0.18 | - | 0.18 | - | - | - | - | - | - | - |
| Corundum | - | 2.55 | - | 0.10 | - | - | - | - | - | - |
| Acmite | - | - | - | - | - | - | - | - | 8.78 | 3.70 |
| Sodium metasilicate | - | - | - | - | - | - | - | - | 0.37 | 0.24 |
| Wollastonite | - | - | - | - | - | - | 2.67 | - | 0.35 | 0.12 |
| Halite | - | - | - | - | - | 0.12 | - | - | 0.12 | - |
| Thenardite | - | - | - | - | - | 0.43 | - | - | 0.43 | - |
| Diopside | 3.80 | - | 3.75 | - | 9.60 | 9.29 | 5.47 | 4.66 | 7.71 | 2.13 |
| Hypersthene | 1.70 | 3.55 | 0.31 | 0.73 | 3.34 | 0.60 | - | 3.82 | - | - |
| Apatite | 0.34 | 0.34 | 0.34 | - | 0.34 | 0.34 | 0.34 | 0.67 | 0.34 | - |
| Ilmenite | 0.76 | 0.15 | 1.37 | 0.15 | 0.46 | 1.37 | 0.91 | 1.37 | 0.91 | 0.15 |
| Magnetite | 3.02 | 1.62 | 1.39 | 1.39 | 2.78 | 3.48 | 3.48 | 3.71 | - | - |
| Hematite | - | - | - | - | - | 1.60 | - | - | - | - |
| Fluorite | - | - | - | - | - | - | 0.23 | 0.18 | - | - |
| Calcite | - | 3.60 | 0.20 | 0.50 | 0.05 | 1.10 | - | 3.20 | - | - |

* Numbers refer to the specimens of table 2.

Except for the tinguaites, which are extremely durable, the igneous rocks are slightly less resistant to weathering than is the Madison limestone. The Madison crops out over large areas in the southern part of the mountains and the summit of every major peak except Pyramid Peak is composed of the Madison or older Paleozoic rocks (pl. 3, A). In contrast, most of the major peaks in the northern part of the mountains are composed of igneous rock. The sedimentary rocks that crop out in the northern part of the mountains are largely Jurassic and Cretaceous in age. Compared with these, the igneous

A. VIEW OF ALPINE GULCH LOOKING NORTHEAST FROM SOUTHWEST MARGIN OF ALPINE GULCH STOCK

Low area in center foreground and middle ground is underlain by porphyry of the Alpine Gulch stock. Most of the peripheral ridges and peaks are composed of Madison limestone or older Paleozoic sediments. The peaks in the background are in the northern part of the mountains and are porphyry.

B. AIR VIEW OF BLACK BUTTE FROM THE WEST

Notch at base of long straight slope near south end of butte marks contact between upturned Paleozoic sediments on right and porphyry. Plains surrounding the butte are underlain by Upper Cretaceous sediments.

rock is relatively resistant, and porphyry-sediment contacts are commonly marked by a sharp break in slope (pl. 3, B).

Hydrothermal alteration is a common feature of the igneous rocks, and prospect pits and other small workings in altered material mark the surface of much of the Judith Mountains. Clay minerals, sericite, silica, and pyrite are the most common alteration products, but their relative abundance varies greatly from one place to another.

Most of the major igneous bodies in the Judith Mountains are composite intrusives consisting of different textural facies of one or more rock types. The intrusive pattern within these bodies is intricate, and the various facies and types are difficult to distinguish in the field. With one or two exceptions no attempt has been made to map in detail the complex relations between different textural and compositional facies. The size, shape, and distribution of the different igneous units and their petrologic significance are discussed in more detail on following pages.

## Depth Environment of Intrusions

Structural and stratigraphic evidence indicates that these rocks were emplaced beneath a sedimentary cover 2,000 to 4,500 feet thick (pl. 44, sects. 6 and 7), and they are classed as hypabyssal. This theoretical depth environment, based on a reconstruction of the geologic conditions at the time of intrusion, is supported by certain textural and mineralogical features of the invading rocks. The presence of aphanitic groundmass suggests a relatively thin cover, with consequent rapid loss of heat during the final stages of consolidation. Vesicles in some of the dikes and sills and the occurrence of intrusion breccia, some of which contain gas cavities, require a sudden release of pressure and connote a near-surface environment. In the igneous assemblage, primary muscovite is unknown and biotite is extremely rare. Hornblende crystals are commonly surrounded by fine-grained aggregates of magnetite and pyroxene indicating oxidation of Fe++ and loss of OH-. These facts suggest that the magma was relatively dry - a condition that may have originated in the ready loss of volatiles to the surface. Furthermore, the "sanidine" phenocrysts of the tinguaites are x-ray perthites.[1/] This implies only a minor amount of unmixing and, according to Tuttle (1952, p. 114), "would be expected only in explosive volcanics and associated tuffs", i.e., chilled, surface or near surface rocks.

## Quartz Monzonite

### Distribution

Rocks of quartz monzonitic composition are widely distributed in the Judith Mountains. They comprise essentially all of the igneous rocks exposed on Bald Butte, Porphyry Peak, and Black Butte, and

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1/ Tuttle, O. F., 1951, written communication.

are the dominant rock type in the Linster Peak stock, the Elk Peak stock, the igneous body 1 1/2 miles northwest of Maiden, the large irregular mass in the north-central part of the mountains, and many of the dikes, sills and smaller plugs. In the southern part of the mountains they make up at least 50 percent of the Burnette Peak stock, the Alpine Gulch stock, and the Gold Hill stock. Thus, rocks of the quartz monzonite family are by far the most common rock type and probably constitute 60 to 70 percent of the igneous assemblage.

As previously indicated, the complex nature of the intrusive pattern and the similarity in appearance of many of the different rock types preclude their detailed separation in the field. Distinct types such as rhyolite and syenite were separated from the quartz monzonite where possible, but no attempt was made to map different compositonal varieties of rocks considered to be essentially quartz monzonite. Study of the collected specimens clearly indicates that the great preponderance of these rocks is quartz monzonite; but there is a considerable range in composition, and types transitional to monzonite, diorite, and quartz diorite are recognized. Rocks approaching diorite in composition are found as border facies along the western edge of the Burnette Peak stock, along the western and northwestern margin of the large irregular intrusive in the north-central part of the mountains, and near the southeastern border of the small stock southwest of Ross Pass. Similar rocks are also recorded from several localities in the central part of the Linster Peak stock; like occurrences have probably gone unnoticed in other stocks.

## Age Relationships

The intrusion of the quartz monzonites marks the beginning of major irruptive activity in the Judith Mountains. Nowhere has quartz monzonite been observed cutting other igneous rocks, although one hand specimen does contain rhyolite inclusions, indicating that some of the quartz monzonites postdate some of the rhyolities. It is probable that detailed mapping of the igneous complexes would reveal rhyolite cut by quartz monzonite in a few places, but all of the rhyolite-quartz monzonite contacts recognized and the structural relationships, show that most of the rhyolite postdates the monzonitic rocks.

## Petrography of the Fresh Rock

Four textural varieties of monzonitic rocks were recognized in the field: fine, medium, coarse and very coarse-grained. This fourfold division, based on the size of the feldspar phenocrysts, is inadequate for the intermediate or gradational types, but it does make possible the separation of distinct and contrasting types in the field. Specimens of the fine-grained, medium-grained, and very coarse-grained monzonite porphyries are shown on plates 4 and 5.

The groundmass material generally varies from very-light, almost chalky-gray, to dark-gray, with medium-gray the most common color. In some specimens the groundmass has a distinct brownish cast.

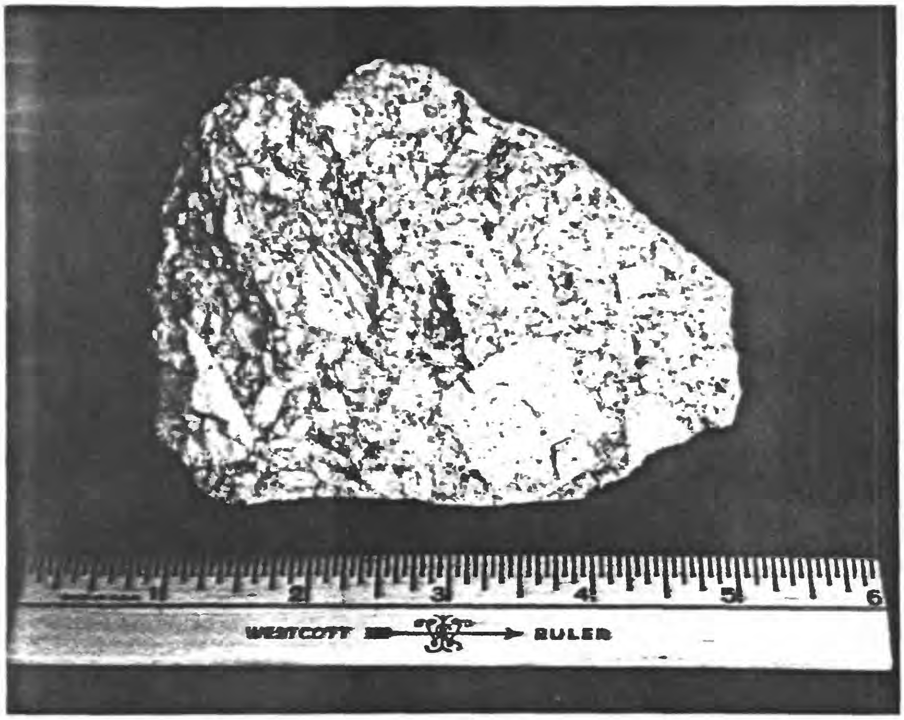
Plate 4

A. VERY COARSE-GRAINED QUARTZ MONZONITE PORPHYRY FROM ALPINE GULCH

The large phenocrysts are sanidine. Specimen from 7,600 feet S. 50° W. of Maiden road junction.

B. FINE-GRAINED QUARTZ MONZONITE PORPHYRY FROM BURNETTE PEAK

Dark material at right end of specimen is inclusion of baked shale. Specimen from Ruby Gulch - southeast part of Burnette Peak stock.



1 2 3 4 5 6
WESTCOTT RULER


2 3 4 5
WESTCOTT RULER

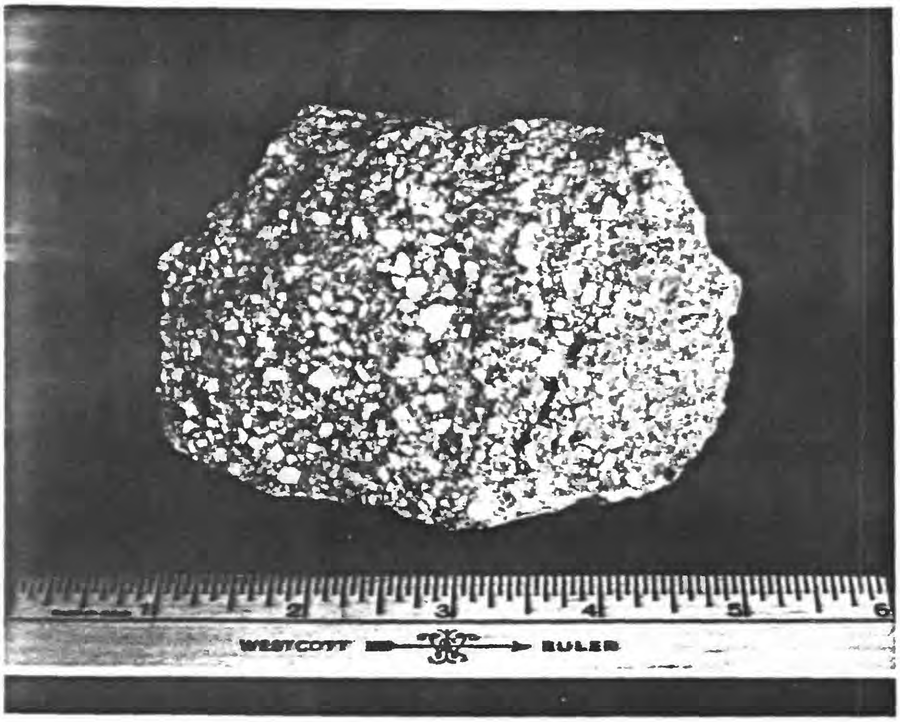
Plate 5

A. MEDIUM-GRAINED QUARTZ MONZONITE PORPHYRY FROM THE GOLD HILL STOCK

Specimen from 7,800 feet N. 77° E. of Maiden road junction.

B. MEDIUM-GRAINED QUARTZ MONZONITE PORPHYRY FROM BLACK BUTTE

Dark mineral is hornblende. Difference in appearance of specimens A and B is due to difference in color of groundmass.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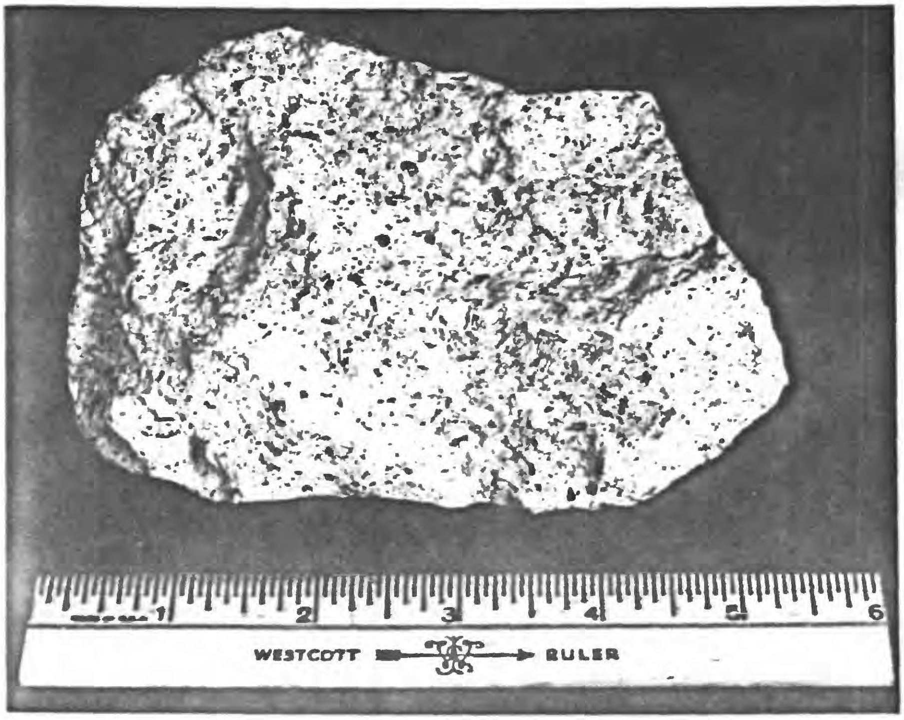
RULER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RULER

Plagioclase and potash feldspar are the dominant phenocrysts and the porphyritic appearance of the rocks varies as the color of these crystals contrasts with that of the groundmass (pl. 5). Other minerals recognized in hand specimen are dark needles of hornblende and diopside, as much as 4 millimeters long, and quartz, either as small bi-pyramids, corroded crystals, or as sugary aggregates.

Basic oligoclase is the predominant mineral of the monzonites and commonly constitutes 40 to 50 percent of the normative composition. Phenocrysts range from 2 millimeters or less in the fine-grained varieties, to 8 millimeters in the coarser-grained facies, and generally compose an estimated 20 to 35 percent of the mode. In some sections all of the feldspar phenocrysts are plagioclase, and the corresponding hand specimens show only one or two megascopic crystals of potash feldspar. In these rocks the potash feldspar to plagioclase ratio is markedly less than in the average quartz monzonite, and with varying amounts of quartz, they approach quartz diorite and diorite in composition. The plagioclase is more calcic and in several specimens is $Ab_{61}$.

Potash feldspar phenocrysts range from 2 millimeters to more than 3 centimeters in length and are usually larger than the associated plagioclase crystals.

The grain size of the groundmass is independent of the size of the phenocrysts. Even in the coarse-grained porphyries, the groundmass is aphanitic (pl. 6, A), and in some rocks it is so fine grained that it appears almost isotropic. Under high power, this material is seen as a fine granular matrix of potash feldspar intimately mixed with varying amounts of quartz, the whole containing small grains of magnetite and numerous microlites of ferromagnesian minerals. Plagioclase, as anhedral grains, is present in some specimens, but in most sections, it is not to be recognized in the groundmass. However, the high percentage of normative plagioclase as compared with the modal percentage indicates that the potash feldspar contains significant amounts of soda.

As phenocrysts, quartz attains a maxiumum size of approximately 4 millimeters. The crystals are generally much corroded and embayed with groundmass material (pl. 6, A), and a few are surrounded by thin selvages of granophyre (pl. 6, B).

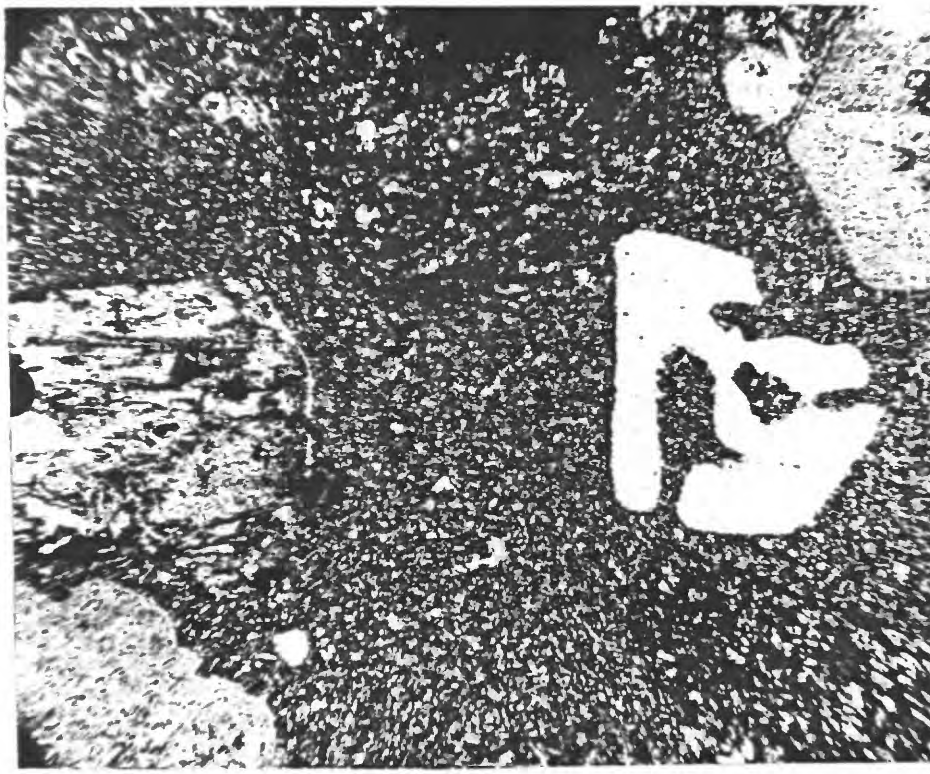
The common accessory minerals in order of their general abundance are sphene, apatite, and magnetite and ilmenite. A few sections show allanite and zircon. Biotite, commonly with reaction rims of granular pyroxene and magnetite, is exceedingly rare. A single exception is a specimen from a small sill on the east flank of the Elk Peak dome. The rock contains hornblende and diopside in about equal amounts, with biotite totaling approximately 50 percent of the mafic constituents.

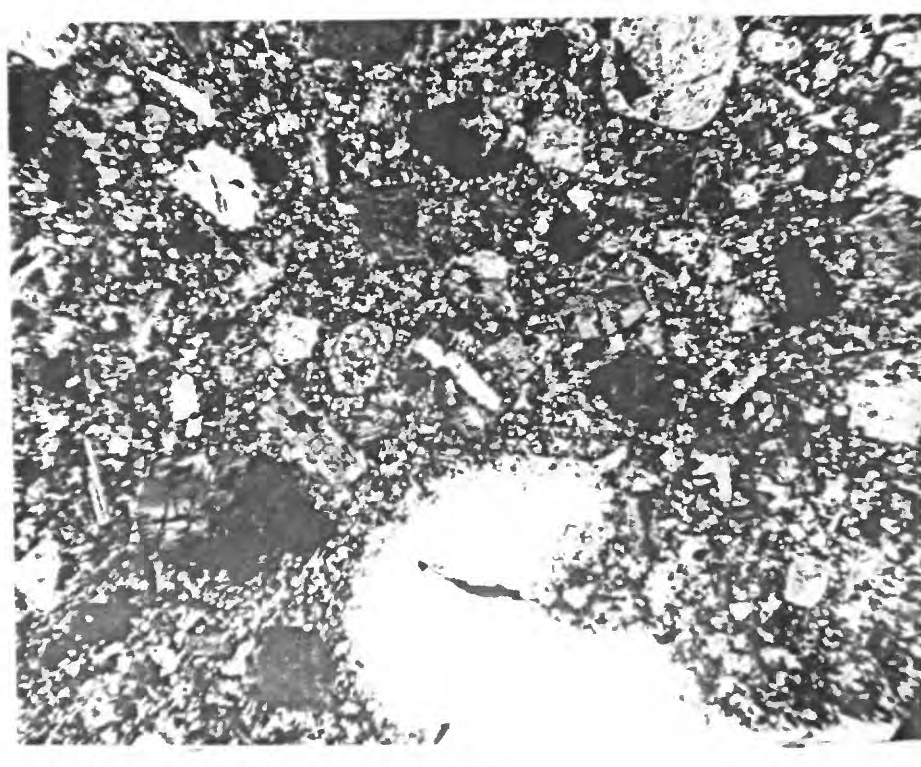
A. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM ALPINE GULCH STOCK

White is corroded quartz. Light gray crystal in upper right is plagioclase. Crystals in lower right and top center are sanidine. Sericite replaces both feldspars. At left center is pseudomorphic aggregate (after pyroxene or amphibole) of calcite, chlorite, and magnetite. Groundmass is aggregate of quartz and alkali feldspar with fine secondary sericite. Specimen from Alpine Gulch stock 8,400 feet S. 46° W. of Maiden road junction. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM PORPHYRY PEAK

Corroded quartz (bottom center) with thin selvage of granophyre. Basal section of diopside shows above and slightly to left of quartz. Black corroded diamond shaped crystal near top center is apatite. Large light gray crystal at top right is hornblende. Other microphenocrysts are plagioclase and sanidine. Small black grains are magnetite. Groundmass is quartz and alkali feldspar. Specimen from east slope of Porphyry Peak. Crossed nicols. X104.





Plagioclase, --Under the microscope, the plagioclase is seen as euhedral to subhedral crystals which range from $Ab_{61}$ to $Ab_{76}$. The composition is remarkably uniform; of 40 specimens taken in the order in which they were collected, 29, or nearly 75 percent, fall between $Ab_{70}$ and $Ab_{74}$.

Zoned plagioclase is common in the Judith Mountain rocks, but in most specimens the zoning is very faint. It is almost invariably oscillatory, and even in those sections that show moderately zoned plagioclase (pls. 7, A and 9, A), the difference within a single crystal rarely exceeds 6 or 8 percent Ab. Several specimens contain crystals in which the oscillatory zoning is highly irregular. Individual zones are discontinuous, and truncation of zones, and "unconformities" result in a pattern which resembles a crude cross bedding (pl. 7, B). In regularly zoned crystals the pattern is seldom perfect. But in the "cross-bedded" crystals, it is so irregular that it must be ascribed to some independent factor, rather than simply to imperfections in the delicate mechanism responsible for oscillatory zoning (Bowen, 1913), (Phemister, 1934), and (Hills, 1936). It may reflect slight relative movement of the liquid and the growing crystal, with a consequent disturbance of the liquid zones surrounding the loci of crystallization and corrosion.

In some specimens plagioclase phenocrysts are armored with potash feldspar. This feature and other major discontinuities of the plagioclase crystals are discussed on pages 150 and 151.

Potash feldspar.--Potash feldspar phenocrysts are generally less abundant than those of plagioclase, but because of their size, they are the most conspicuous mineral constituent of many of the monzonites. The crystals are commonly stubby and nearly equidimensional in shape, although a few are flattened parallel with (010) and elongated parallel with a. These latter are usually twinned according to the Carlsbad law. A very few crystals show Manebach twins.

The dominant forms are {110} , {001} , {010} , and {201} . In a few crystals this simple habit is modified by poorly developed second order prisms, {130} , and pyramids, {111} .

The microscope shows euhedral to subhedral sanidine phenocrysts which in some sections exhibit a faint zoning (pl. 8, A). This may be due to barium or possibly sodium. Certainly, the crystals contain appreciable amounts of the albite molecule, but the writer hesitates to use the term soda-sanidine. The 2V varies from less than 20° to about 45°, with the optic plane perpendicular to (010). With this orientation the optic angle increases with declining temperature of formation and increasing soda content (Spencer, 1935-1937). Based on the soda content of the potash-soda feldspars in the tinguaites (p. 72), the amount of $NaAlSi_3O_8$ in the sanidine of the quartz monzonite is estimated as less than 15 percent, and the dominant factor producing the "intermediate" values of 2V is believed to be temperature.

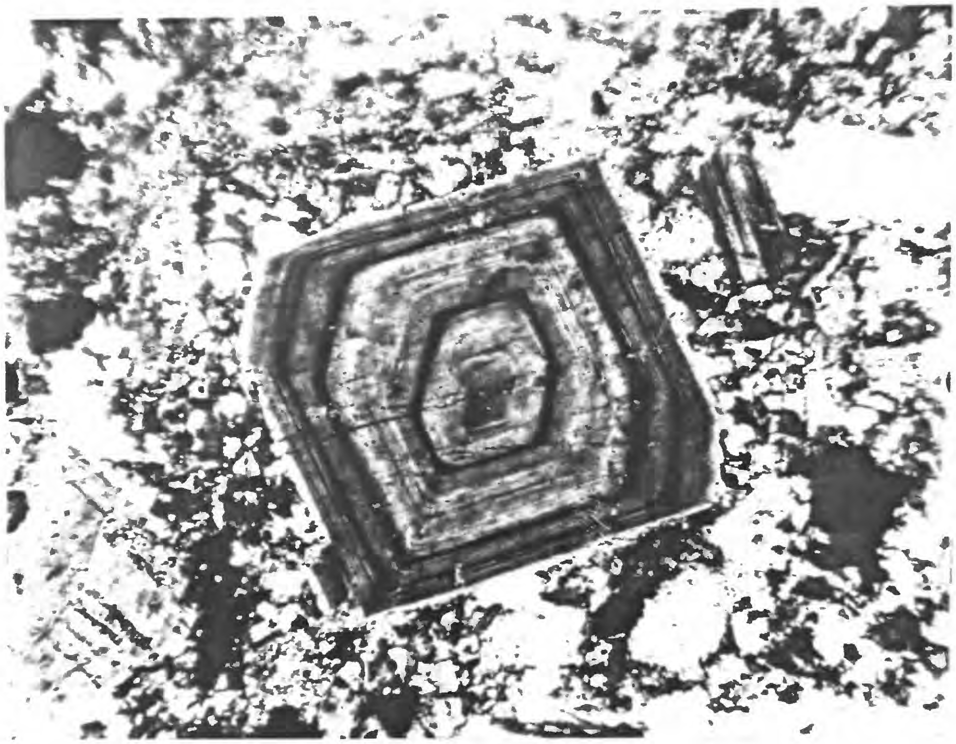
The total potash feldspar, as phenocrysts and in the groundmass, was estimated as between 20 and 30 percent, but the norms show these

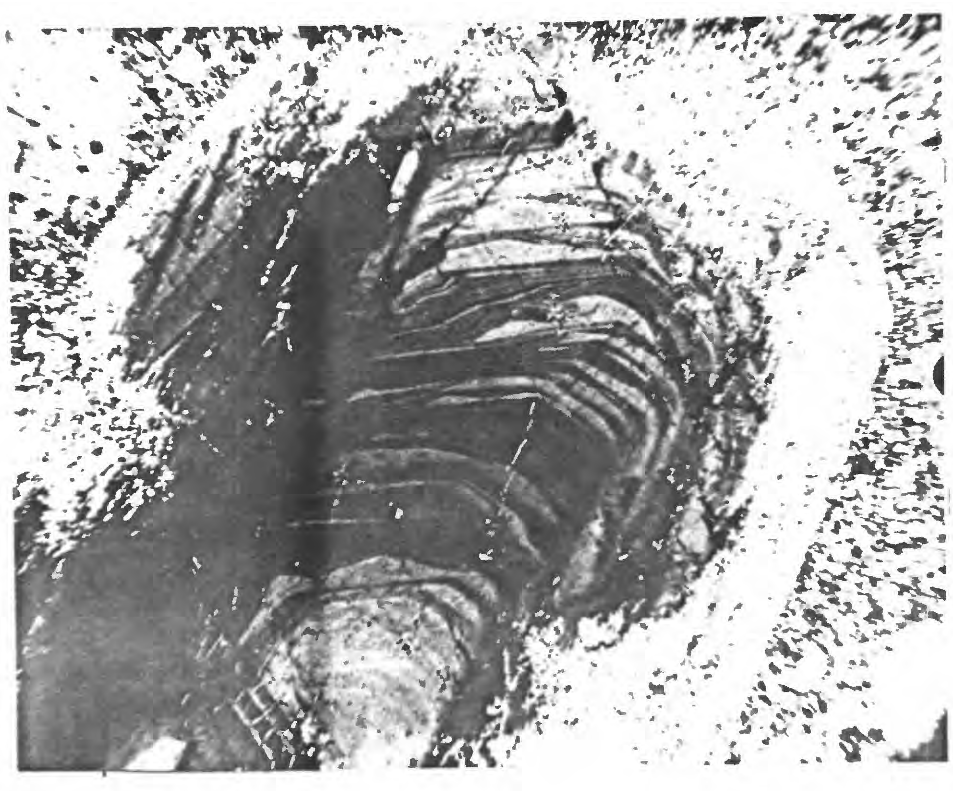
A. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM ELK PEAK

Plagioclase (acid andesine) with "uniform" oscillatory zoning. Specimen from 4,600 feet N. 33° E. of summit of Elk Peak. Crossed nicols. X 104

B. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM LARGE DIKE ON NORTHWEST SIDE OF ELK PEAK

Plagioclase (basic oligoclase) showing irregular oscillatory zoning which in some parts of crystal resembles cross-bedding. Margin of crystal attacked by sericite. Specimen from tunnel 6,000 feet N. 68° W. of summit of Elk Peak. Crossed nicols. X 50



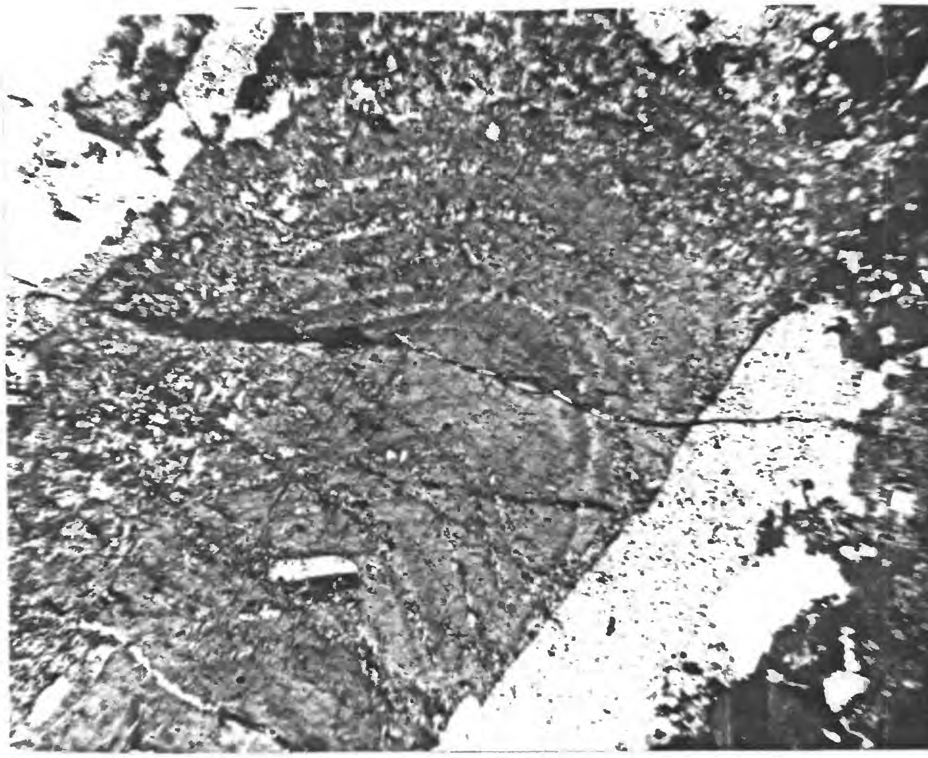


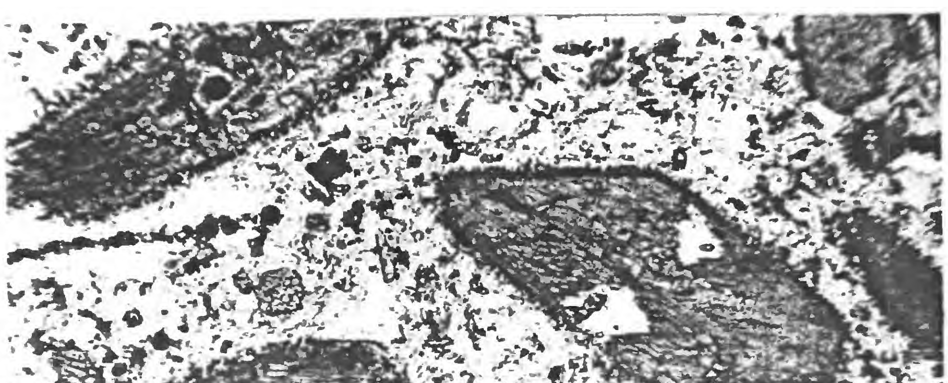
A. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM WEST SIDE OF JUDITH PEAK

Zoned sanidine phenocryst, with certain zones selectively replaced by sericite. Specimen from 3,700 feet N. 70° W of summit of Judith Peak. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF MONZONITE PORPHYRY FROM CONE BUTTE

Prominent crystals are hornblende surrounded by reaction rims of magnetite and pyroxene. Smaller and lighter gray crystals are diopside. Light clear area at bottom is sanidine with two concentric bands of allophane alteration. Specimen from fine-grained facies of porphyry at top of Cone Butte. Plane-polarized light. X 50.





figures to be slightly high - probably as a result of isomorphous substitution of soda for potash.

Ferromagnesian Minerals, --Hornblende is the most common mafic mineral and occurs as elongate prisms as much as 4 millimeters in length. The crystals are generally well formed, but some of the larger ones show skeletal growth with irregular crystal outlines, are much embayed, and contain numerous inclusions of the groundmass. In many sections, the hornblende shows corrosion, with reaction rims of magnetite and fine granules of pyroxene (pl. 8, B). In extreme cases, the smaller crystals have been completely destroyed, and their former presence is shown only by pseudomorphic aggregates of their alteration products.

The optical properties conform with those of normal hornblende: $Z \wedge c$, approximately 23° with absorption, $X < Y < Z$, pale yellow brown to greenish brown, to dark olive green.

Hornblende and diopside generally constitute 5 to 10 percent of the quartz monzonites. Of this amount hornblende commonly accounts for 60 to 80 percent, and in some specimens it is the only mafic constituent. Diopside has been observed as the sole ferrogmagnesian mineral in only one section.

Megascopically, diopside is difficult to distinguish from hornblende, although it tends toward crystals of a more stubby habit In thin section it is seen as euhedral crystals which vary from an almost colorless, very faint green, to a distinct "sea" green. The more deeply colored crystals are faintly pleochroic. Uralite is rare, but a few of the larger crystals show partial replacement by hornblende.

## Alteration

In addition to the late orthomagmatic reactions already mentioned, the quartz monzonites show the effects of deuteric reactions, hydrothermal alteration and weathering.

Deuteric replacement of the feldspar phenocrysts by albite is a common feature of the monzonitic rocks and is seen in various stages of development in almost all sections except those which show extreme hydrothermal alteration. Oligoclase is the preferred host; sanidine generally exhibits replacement albite only in those sections in which the oligoclase shows well developed albitization. Commonly the alteration is not intense, and many of the plagioclase crystals show little or no replacement. In some specimens, a few individuals may be 50 percent transformed to albite, but these represent the maximum.

The albite generally replaces the oligoclase as minute anastomosing stringers or as irregular patches and blebs. The contacts between albite and host are commonly gradational, and the finer stringers and centers of replacement show only incipient alteration. Very rarely the replacement albite exhibits twinning (pl. 11, A). In a few specimens albite veins the sanidine, but usually it is in the form of a patch perthite. One or two crystals of sanidine and oligoclase show albite selectively replacing certain zones. Plates 8, A, 9, 10, and 11, A, illustrate various features of albitization.

Some question arises concerning the origin of the albite. In the oligoclase, the habit of the albite and the mixed crystal relations of the plagioclase series clearly point to a deuteric origin. In the sanidine, some of the finer and more regular intergrowths may be due to unmixing. However, the perthite commonly exhibits an irregular development both within single crystals and with respect to all the sanidine phenocrysts in a thin section, and this suggests deuteric alteration rather than exsolution. Some of the sanidine crystals show irregular veining by albite, and in one slide, an area of incipient albitization within a sanidine phenocryst passes into a distinct veinlet which cuts a plagioclase inclusion in the sanidine. Exsolved albite is probably present in the form of an x-ray perthite (p. 74 ) which cannot be observed under the microscope.

Hydrothermal alteration of varying degrees of intensity has affected a large percentage of the igneous rocks of the Judith Mountains. In addition to the major areas of pyritic alteration and numerous local concentrations of pyrite and associated hydrothermal minerals, there are large tracts in which the rocks show the effects of very low grade hydrothermal attack.

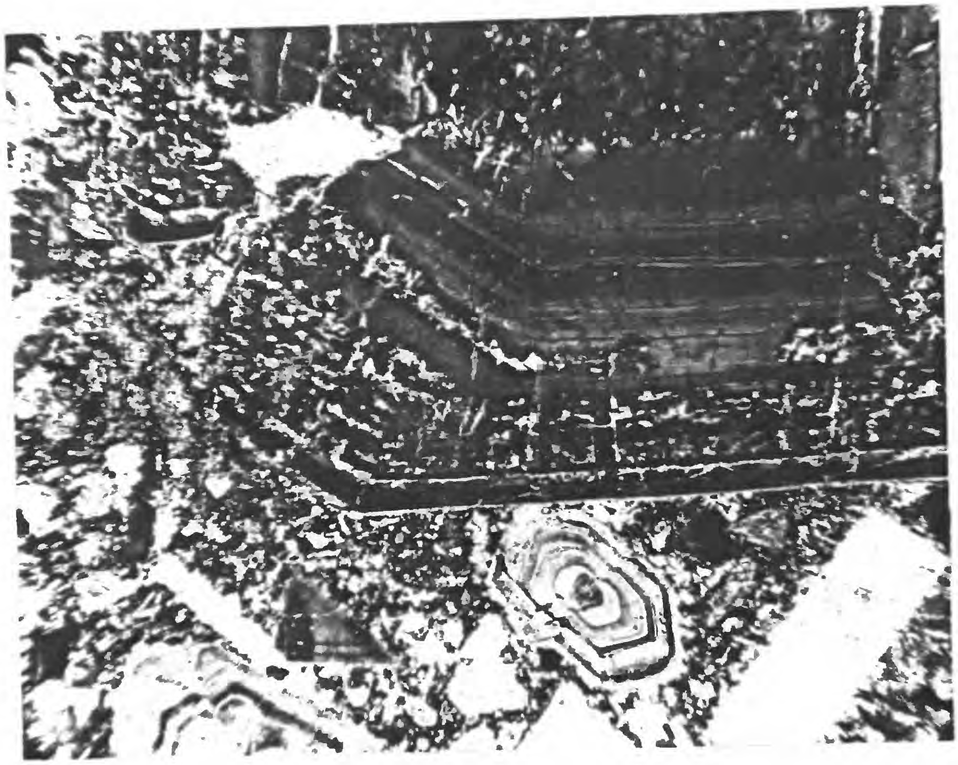
In every specimen of quartz monzonite the writer has examined which was collected from the southern part of the mountains, the primary

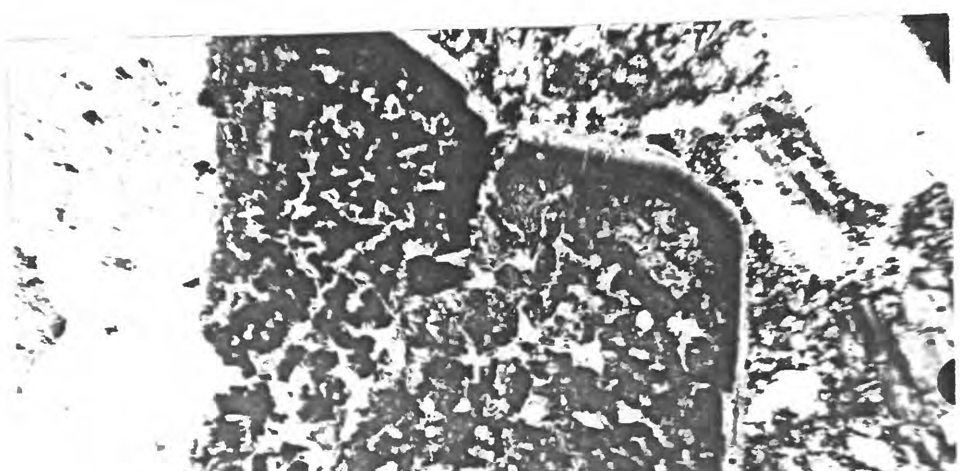
A. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM NORTHEAST FLANK OF ELK PEAK DOME

Albitized plagioclase. Note selective replacement of certain (more calcic) zones. Specimen from 4,600 feet N. 33° E. of summit of Elk Peak. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM LINSTER PEAK STOCK

Albitized plagioclase. Right half of crystal at extinction. Light-colored material is albite. Note that in both A and B the larger crystals are more strongly attacked. Specimen from 2,400 feet S. 10° E. of Linster Peak. Crossed nicols. X 50.



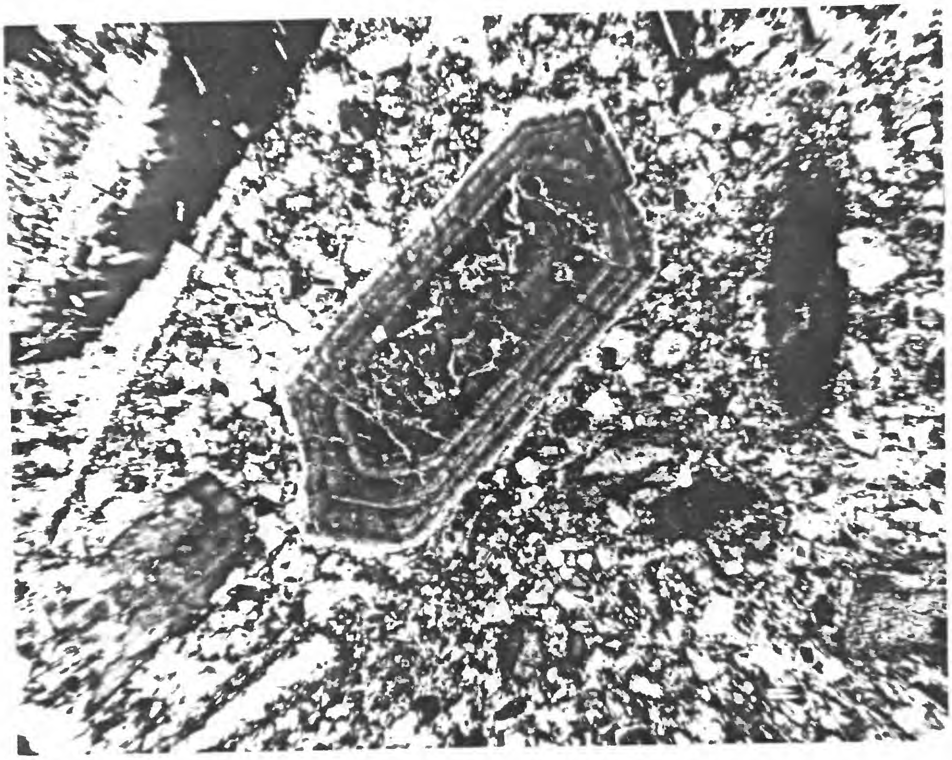


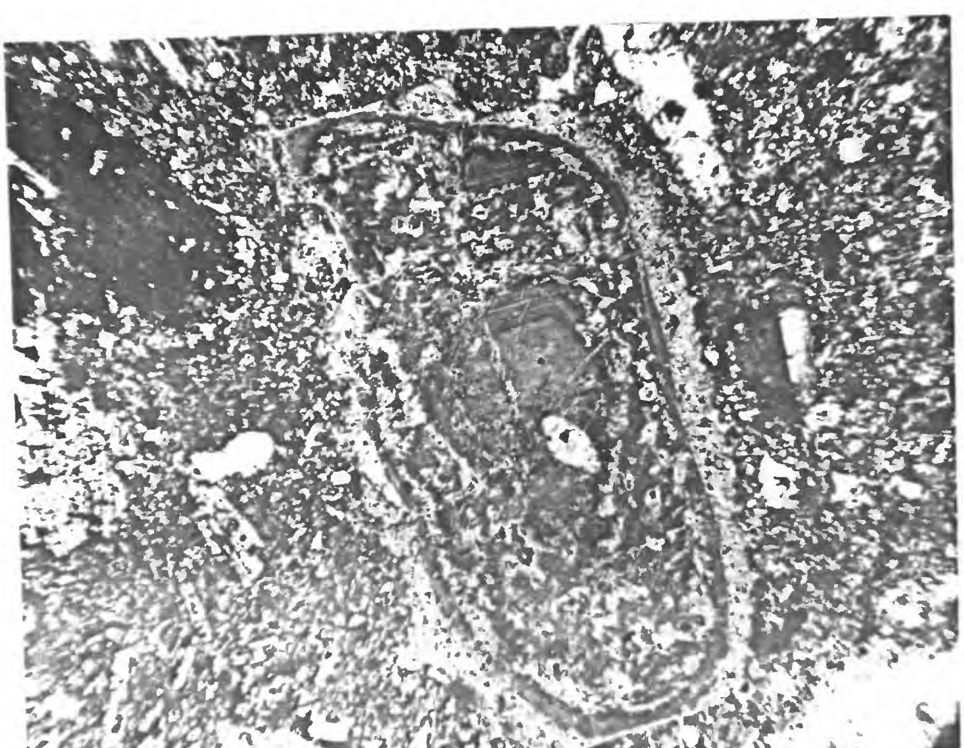
A. PHOTOMICROGRAPH OF HORNBLENDE SYENITE PORPHYRY FROM LEWIS PEAK

Albite (light) replacing central part of zoned plagioclase. The other phenocrysts are hornblende. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF SYENITE PORPHYRY FROM MAGINNIS MOUNTAIN

Albitized plagioclase phenocryst with potash feldspar rim. Crystal to right of upper right corner of plagioclase and large crystals along left margin of plate are diopside. Small dark grains are magnetite. Crossed nicols. X 50.



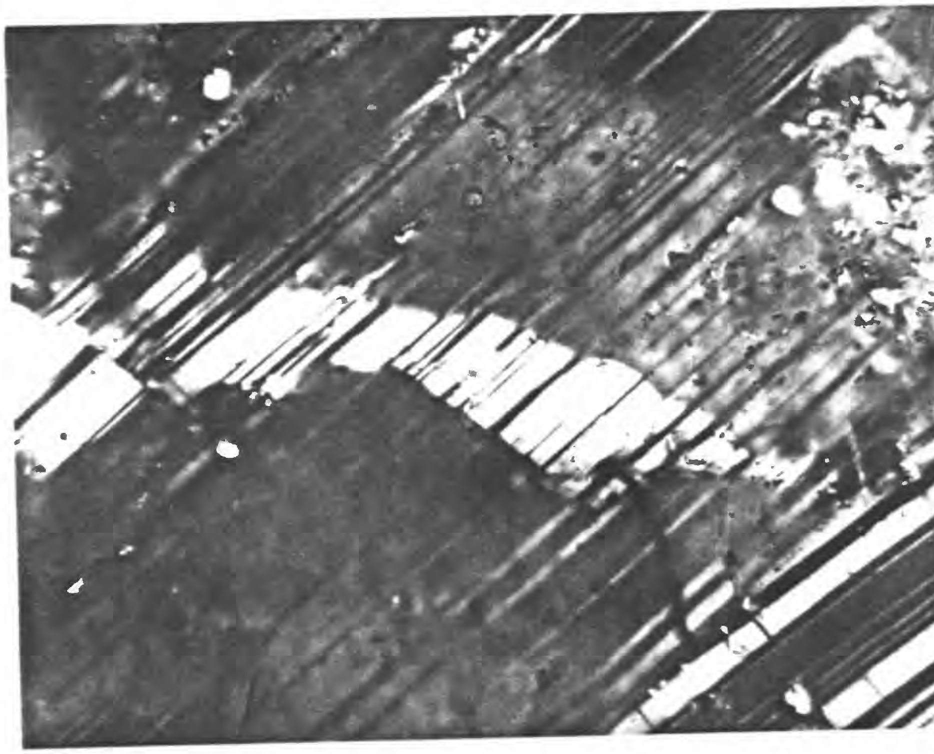


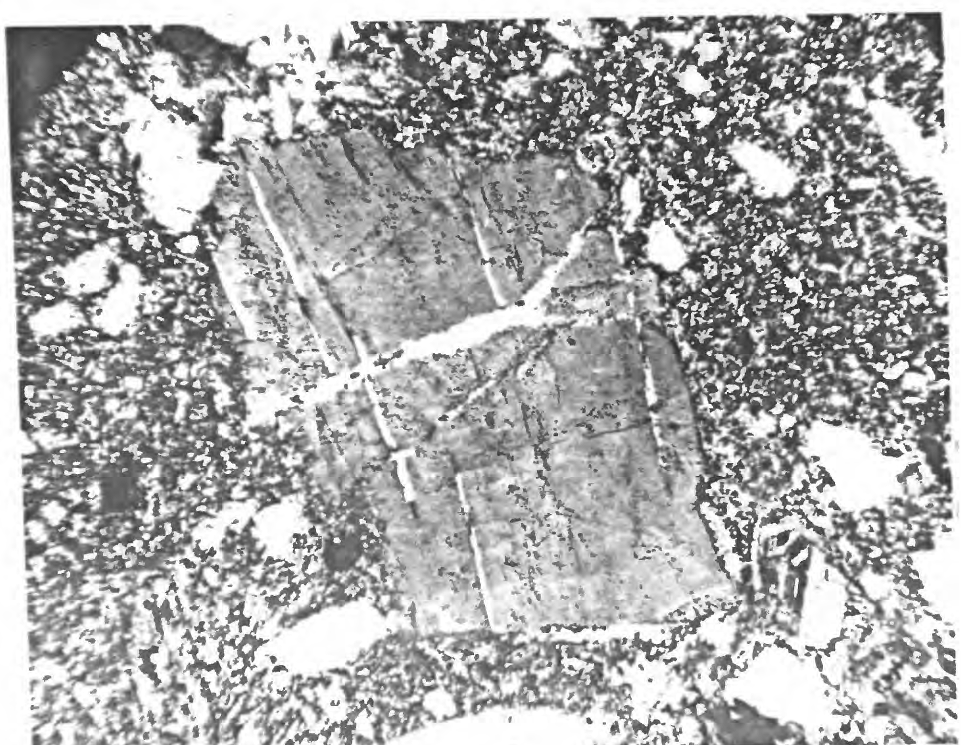
A. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM WEST SLOPE OF JUDITH PEAK

Fine stringer of albite (light) replacing basic oligoclase (dark). Replacement albite is unusual in that it shows twinning. Bright spots are sericite. Specimen from 3,700 feet. N. 70° W. of summit of Judith Peak. Crossed nicols. X 475.

B. PHOTOMICROGRAPH OF DARK GRAY TINGUAITE FROM LINSTER PEAK STOCK

Hydromica (light colored vertical streaks) replacing faintly zoned sanidine crystal. East - west streak through sanidine is calcite veinlet which is later than the hydromica. Specimen from 4,000 feet S. 24° E. of Linster Peak. Crossed nicols. X 50.





mafic minerals have been completely destroyed. The most common alteration products are chlorite, calcite, and magnetite or hematite (pl. 6, A). In some sections a little antigorite, hydromica, and sericite are present, and very rarely epidote and clinozoisite are observed.

Allophane is a common alteration product of the feldspar. With increasing intensity of alteration, hydromica, sericite, halloysite, kaolinite, beidellite, and possibly other members of the montmorillonite group appear in greater abundance (pls. 11, B and 12). In some places the mafic minerals and the groundmass are similarly altered, yielding a bleached and crumbly rock material. Apatite commonly remains fresh although it may show some cloudy alteration and corrosion. Sphene is usually corroded or altered to an aggregate of calcite and leucoxene.

Near contacts with carbonate rock calcite is especially abundant - much of it late. Some has doubtless been deposited as open filling by circulating ground water, but most of it is probably due to solution and reprecipitation by hydrothermal waters. Barite is present in a few specimens.

Pervasive silicification is rare, although a number of sections show replacement of some of the groundmass and the feldspar phenocrysts by quartz (pl. 13, A). More commonly, the secondary quartz occurs in thin seams as fracture fillings (pl. 13, B). Pyrite has been introduced

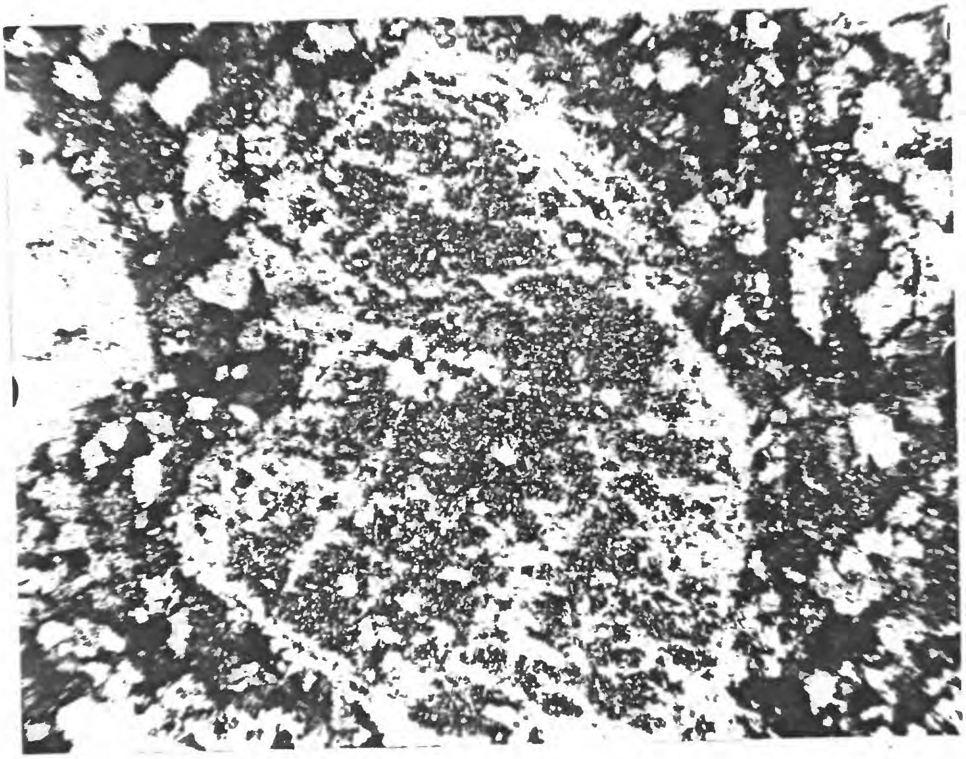
Plate 12

A. PHOTOMICROGRAPH OF QUARTZ MONZONITE OR RHYOLITE PORPHYRY FROM GILTEDGE MINE

Central part of plate is pseudomorphic aggregate of clay minerals (dark, fine-grained mosaic), and calcite and sericite (light) after feldspar. Specimen from altered zone above ore body in large open stope, Giltedge mine. Crossed nicols. X 50.

B. SAME AS A

Fine intergrowth of halloysite and kaolinite (dark) partly replaced by sericite and calcite (light). Crossed nicols. X 475.



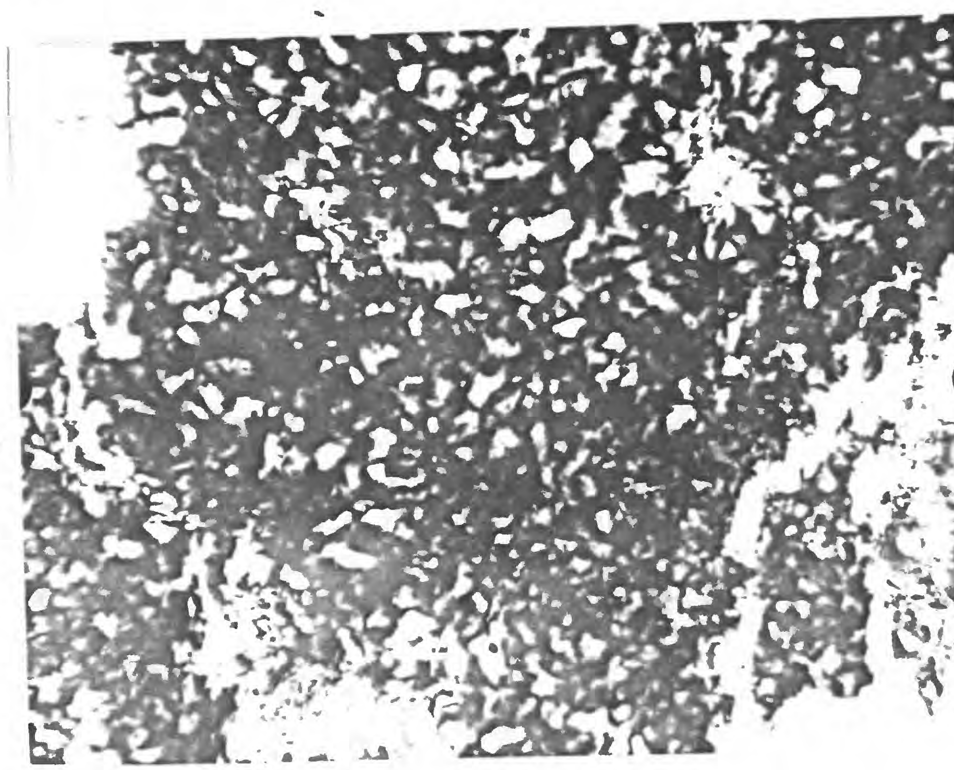


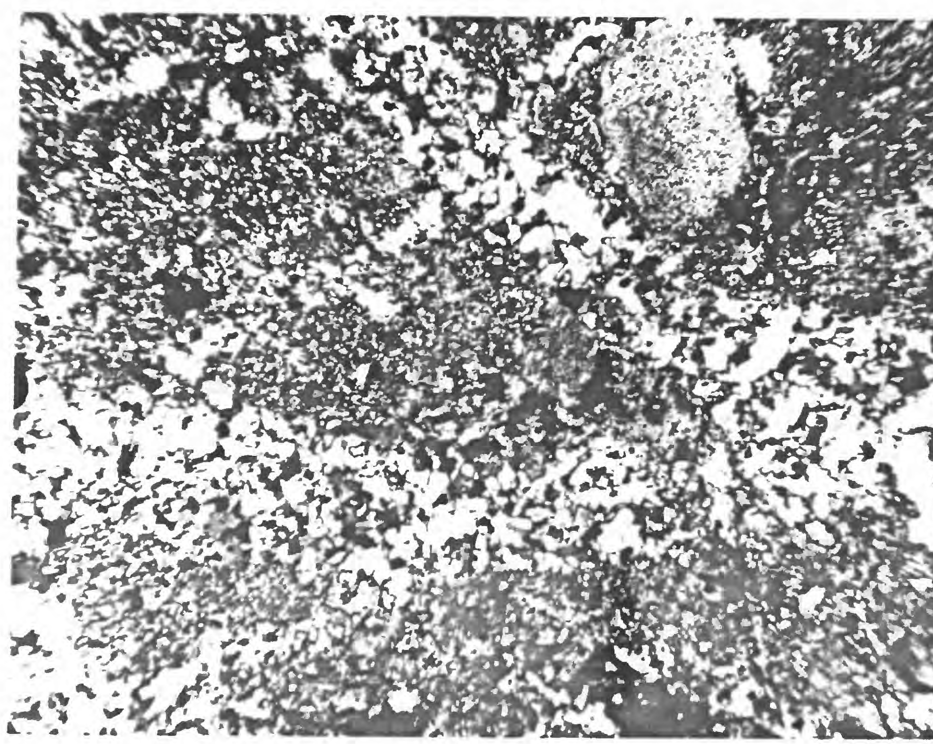
Plate 13

A. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM LINSTER PEAK STOCK

Quartz replacing sanidine phenocryst. Specimen from 4,000 feet S. 24° E. of Linster Peak. Crossed nicols. X 50.

B. SAME AS A

Quartz stringers cutting porphyry. Crossed nicols. X 104.



in varying amounts in different hydrothermal intensity environments, but too little is known to establish any definite relationships. Pyritic rocks weather readily and are stained in various shades of red, yellow, and brown by limonite and hematite. Jarosite, either granular or fibrous, is common in specimens from the weathered pyritic zones.

## Rhyolite

### Distribution

Rhyolitic rocks are abundant in the Judith Mountains, and in the area south of the Warm Spring Creek embayment may equal or exceed the quartz monzonites in volume. Rhyolite comprises all of the small circular stock of Pyramid Peak, the mass just south of Pyramid Peak, and many of the irregular dike- and sill-like bodies that are exposed in the flanking sediments of the Alpine Gulch, Burnette Peak, and Crystal Peak domes. In addition, rhyolite is found intimately mixed with the quartz monzonite in the cores of these domes and here probably constitutes 30 to 40 percent of the igneous rocks exposed (pl. 46).

Rhyolite bodies are also found along or near the Warm Spring Creek fault and its possible sub-surface extension to the east of the mountains: the two small bodies on the east flank of the Crystal Peak dome, the irregular mass just north of Maiden, and the sill-like intrusion exposed in the Warm Spring Creek dome.

The area north of this line is almost entirely devoid of rhyolite. The small irregular mass on the southeast flank of Judith Peak is the only known rhyolite body in the northern part of the mountains that has lithologic features sufficiently distinct to permit separation in the field. Several scattered bodies of undetermined size and shape are known from thin section study.

## Age Relationships

Rhyolite occurs as irregular dikes that cut the quartz monzonite (pl. 46) and as separate bodies that transect the early domal structures formed by the intrusion of the monzonitic rocks. The rhyolite mass of Pyramid Peak is surrounded by outward dipping beds, but the steep bounding faults and the sharp reversal of dips (pl. 1, B-B') indicate that it is a secondary structure imposed on the primary Burnette Peak and Alpine Gulch domes. The small plug east of the Crystal Peak dome breaks through the Colorado shale without disturbing the general eastward dip; this suggests that it postdates the early doming. As noted on page 30, a little rhyolite may be older than some of the monzonite, but most of it is younger.

In the one locality where rhyolite and tinguaite are associated in the field (on the southeast flank of Judith Peak) the rhyolite is the older rock. There is no evidence to establish the relative ages of the rhyolite and the syenite.

## Petrography

In the hand specimen the rhyolites are typically light-gray to tan with sparse phenocrysts of glassy sanidine and corroded quartz from 2 to 5 millimeters in size set in a felsitic base (pl. 14). These grade on one hand into rocks with almost no phenocrysts and on the other into those containing large phenocrysts of sanidine and numerous smaller crystals of plagioclase; these latter resemble many of the monzonitic rocks (pl. 15, A). In general the finer-grained varieties occur as separate bodies, and the coarse-grained types are associated with the quartz monzonites in the composite stocks. Much of the rhyolite from the small plug east of the mountains shows flow banding.

Under the microscope the fine-grained varieties show a crypto-crystalline groundmass of alkali feldspar and quartz in which are set small scattered crystals of sanidine, plagioclase, $Ab_{88}$ to $Ab_{94}$, and small quartz bi-pyramids, usually much corroded (pl. 15, B). In some sections quartz is found only in the groundmass.

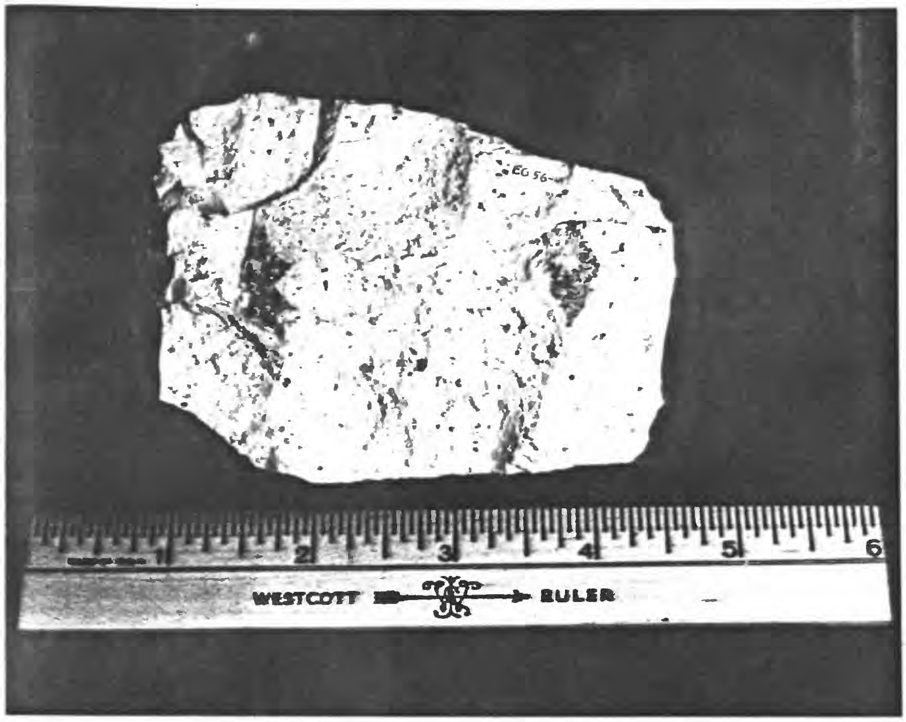
The ferromagnesian minerals are much less abundant than in the quartz monzonites. Hornblende has been identified in crushed material from several specimens, but in every thin section examined, all dark minerals are altered to the same pseudomorphic aggregates found in the quartz monzonites. Sphene, apatite, and magnetite are the most common accessary minerals, but are much less abundant than in the monzonitic rocks; zircon and allanite are rare.

A. RHYOLITE PORPHYRY FROM SMALL BODY 2 MILES SOUTH OF PYRAMID PEAK

Specimen from small rhyolite body 10,400 feet S. 7° E. of Pyramid Peak.

B. RHYOLITE PORPHYRY FROM SOUTHWEST PART OF ALPINE GULCH STOCK

Gray, oval-shaped spots on cut surface of specimen are phenocrysts of corroded quartz. This is typical of the coarse-grained rhyolite porphyry shown on plate 46. Specimen from 10,000 feet N. 67° E. of Pyramid Peak.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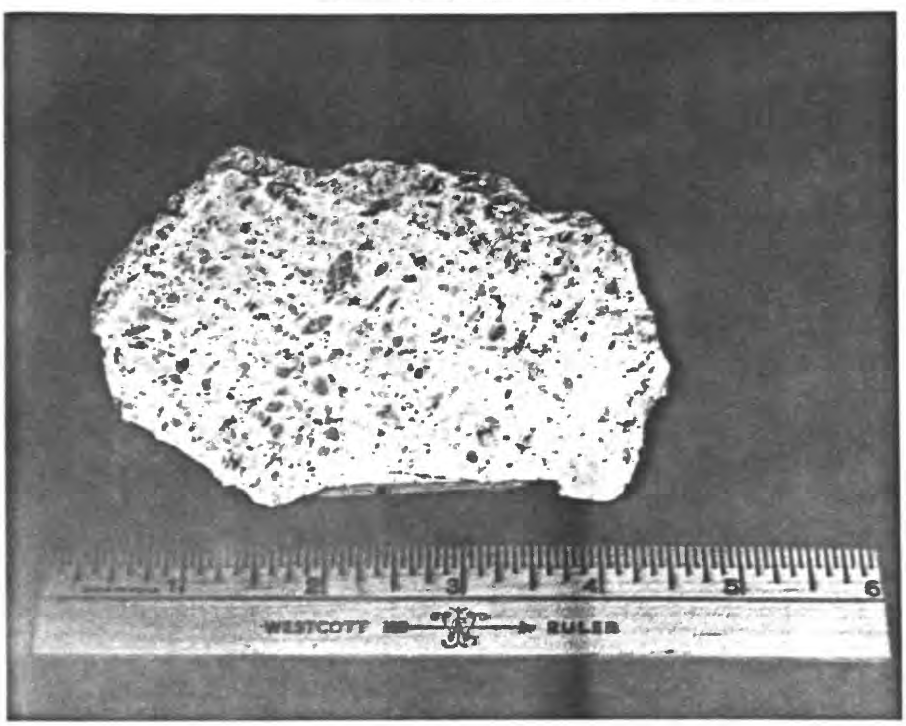
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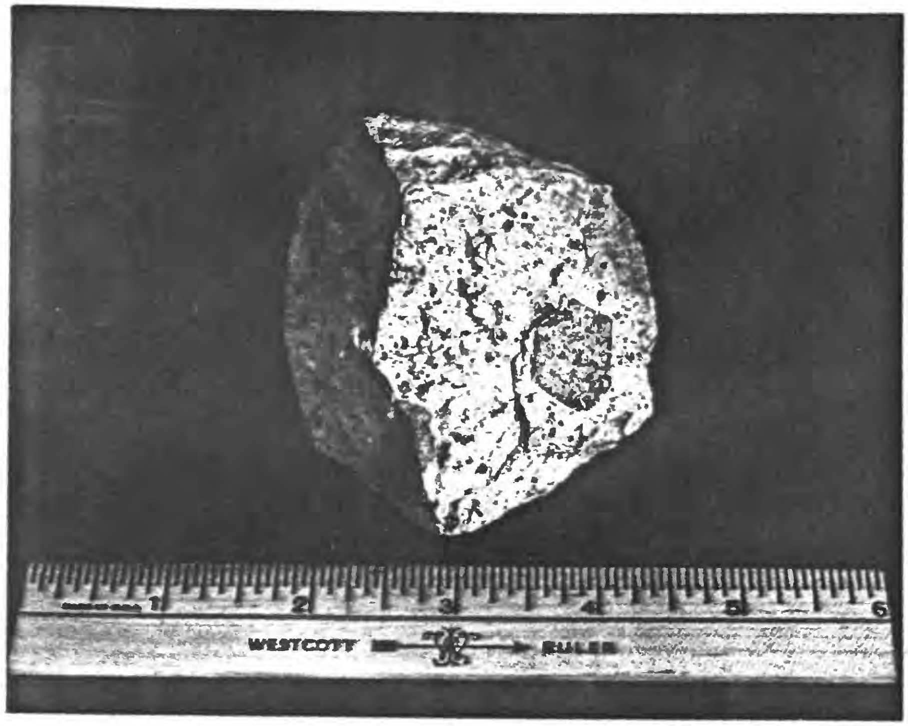
A. RHYOLITE PORPHYRY FROM ELK PEAK DOME

Large phenocrysts are altered sanidine. Specimen taken 4,000 feet S. 45° E. of summit of Elk Peak.

B. PHOTOMICROGRAPH OF SAME SPECIMEN AS A

Corroded quartz, large crystal and two small rounded grains at top center and left center. Large light and dark area just above large corroded quartz is carlsbad twin of sanidine replaced by calcite. Small black crystal at bottom center is pyrite surrounded by sericite and calcite (light). At left center is another mass of sericite and calcite. Groundmass is fine aggregate of quartz and alkali feldspar with fine sericite and calcite alteration. Crossed nicols. X 104.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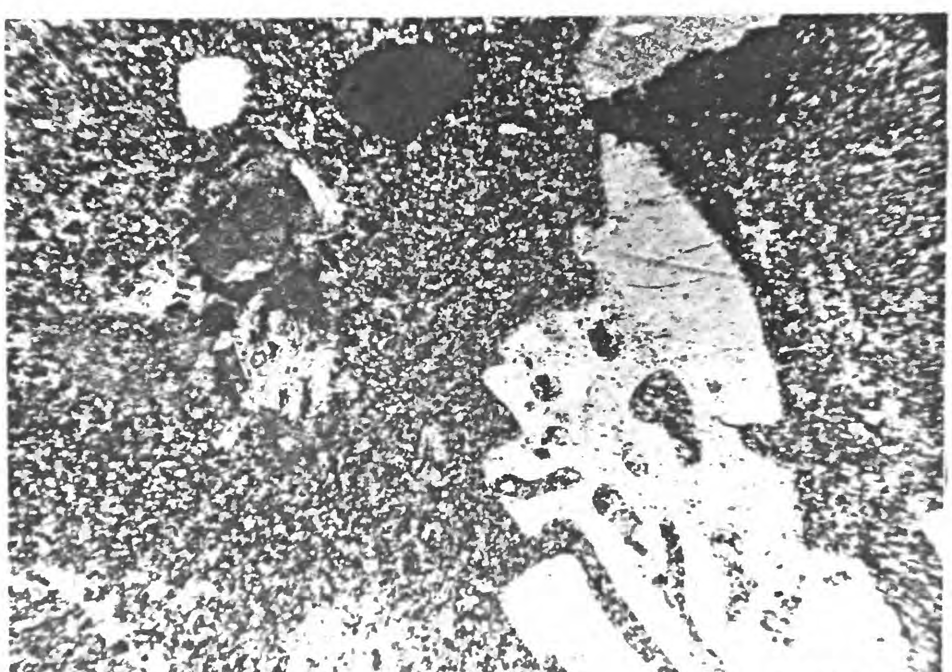


The coarser-grained rhyolites are very similar to the quartz monzonites except that they contain more quartz, fewer mafic minerals, and the plagioclase is more sodic and less abundant.

Albitization is much less common than in the monzonitic rocks, but a few of the plagioclase phenocrysts do show slight replacement by albite. Changes produced by hydrothermal solutions are the same as those described for the quartz monzonites (p. 41).

## Syenite

### Distribution

Syenite is much less abundant than rhyolite and is restricted to the area north of the Warm Spring Creek fault. Large exposures of syenitic rocks are found at only three localities - Maginnis Mountain, Lewis Peak, and south and west of Lookout Peak (pl. 1), and structural evidence indicates that each of these bodies is in large part a floored intrusive (p.122). Syenite is also found as dikes and small irregular bodies associated with the monzonitic rocks in the Linster Peak stock, on Cone Butte, Elk Peak, and in the large mass which surrounds Judith Peak. Most of these were discovered by microscopic examination and are not shown on the map.

### Age Relationships

Syenite is younger than the quartz monzonite and with one exception is older than the tinguaite (p. 63). The relative age of the syenite and the rhyolite is unknown.

## Petrography

The syenites that form Lewis Peak, the mass south and west of Lookout Peak, and the dike on the east side of the Linster Peak dome are almost identical in appearance; these differ markedly from the syenite found on Maginnis Mountain. The Lewis Peak type is a light-gray, fine-grained rock with small equidimensional feldspars, generally about 1 millimeter in size, and conspicuous elongate prisms of black hornblende, as much as 10 millimeters in length, which define well developed foliation and lineation (pl. 16, B). In thin section small sanidine and plagioclase, $Ab_{64}$ to $Ab_{68}$, phenocrysts are seen in about equal amounts. Sphene, apatite, and magnetite are the common accessary minerals. The groundmass is fine-grained, usually trachytic, and contains small scattered nests of quartz.

The Maginnis Mountain syenite is a medium brownish gray with abundant tabular feldspar phenocrysts from 2 to 6 millimeters across. In most specimens, these show a sub-parallel arrangement and give the rock a planar flow structure. The mafic minerals constitute about 12 to 15 percent of the rock, but are stubby in habit compared with the hornblende of the Lewis Peak type, and do not stand out against the darker groundmass (pl. 16, A).

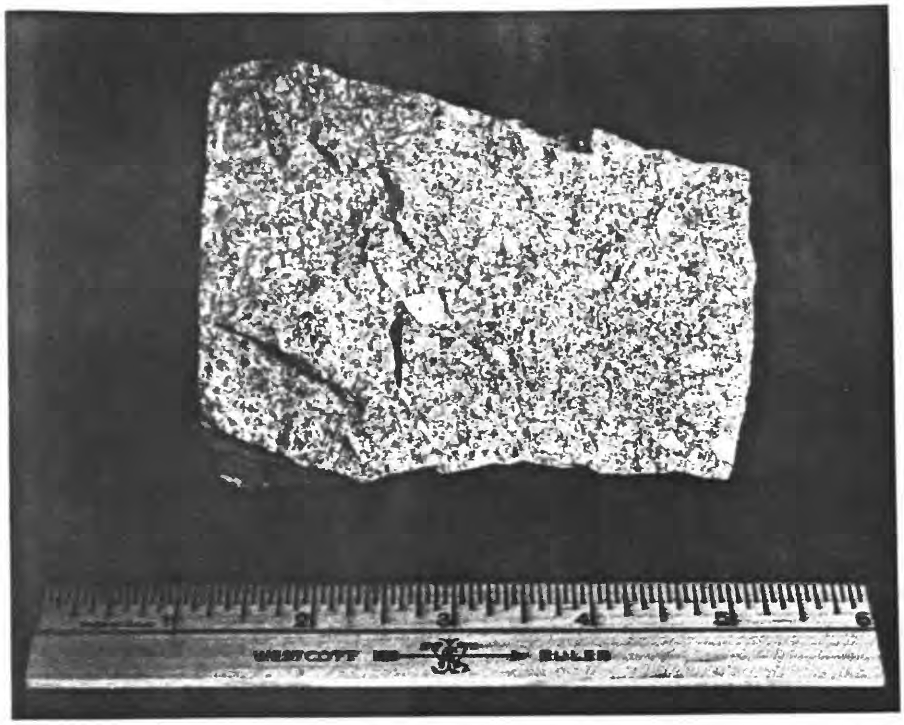
Under the microscope the Maginnis Mountain syenite shows elongate sections of sanidine, as much as 6 millimeters in length, and somewhat smaller laths of sodic andesine. Diopside is the principal mafic mineral

A. SYENITE PORPHYRY FROM MAGINNIS MOUNTAIN

Sanidine phenocrysts delineate flow structure (faint in photograph). Specimen from 3,400 feet S. 85° E. of summit of Maginnis Mountain.

B. SYENITE PORPHYRY FROM DIKE IN LONE TREE GULCH (Lewis Peak Type)

Flow structure shown by hornblende needles. Specimen from dike which cuts gray tinguaite porphyry 7,000 feet S. 12°W. of Lookout Peak.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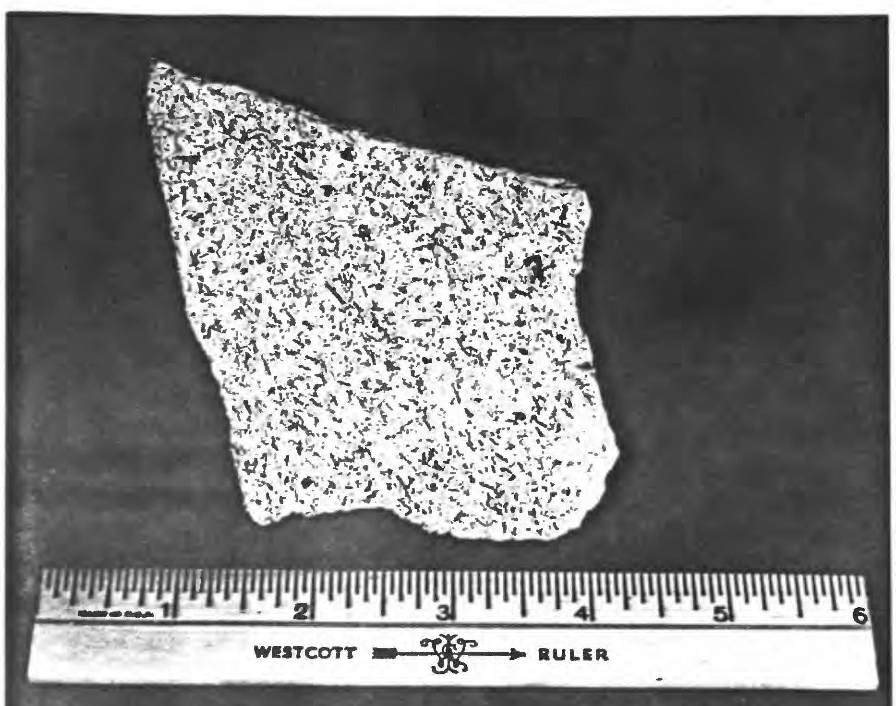
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and occurs as euhedral crystals, generally less than 1 millimeter long. One or two crystals of hornblende and a very few small plates of biotite are noted in almost every section; both minerals show some corrosion and are bordered by thin rims of magnetite grains. Other accessory minerals are sphene, apatite, and magnetite, and minor amounts of interstitial quartz. The groundmass is largely composed of tiny alkali feldspar laths in either sub-parallel or random orientation.

Most of the smaller bodies of syenite that occur within the quartz monzonite complexes are similar to the Maginnis Mountain type. One notable exception is represented by a specimen collected 4,400 feet N. 66° W. of the summit of Judith Peak. The size and the shape of the body it represents are unknown.

In hand specimen, the rock is massive and even grained with a distinctive pale chocolate-brown color. The bulk of the rock is composed of euhedral to subhedral feldspar crystals which are remarkably uniform in size - 1 to 2 millimeters. Under the microscope practically all of these cyrstals are seen to be sanidine. Sodic andesine is a minor constituent and occurs almost entirely as small inclusions within the sanidine. The sanidine crystals are closely packed together, with sea-green diopside and accessory sphene and apatite concentrated along the crystal boundaries and occupying the interstices., Minor amounts of quartz formed last and took up whatever space remained in the crystalline mush. Of particular interest is the complete lack of the usual groundmass material. The feldspars are bounded by crystal faces, the bulk of the crystals are uniform in size, and there are no phenocrysts. The peculiar textural features of the rock suggest that it represents a crystalline residue separated by crystal settling or filter pressing from a highly potassic magma.

Deuteric and hydrothermal alteration of the syenites is similar to that of the quartz monzonites.

## Alkali Syenite

### Distribution

Alkali syenite is relatively rare in the Judith Mountains. It is represented by one or two bodies of undetermined size and shape in the Linster Peak dome, and by a well exposed bifurcating sill on the north side of Collar Gulch, east of Collar Peak. The sill lies in the Colorado shale and is paralleled at different horizons, both above and below, by sills of green tinguaite. Some of the highly altered rocks from the Red Mountain area are probably best classified as alkali syenite. These are discussed separately under the Rocks of the Red Mountain Complex (p. 82).

### Age Relationships

The detailed age relationships are unknown. The bodies in the Linster Peak dome are known only from thin section, but are probably younger than the monzonites with which they are associated.

Petrography

Specimens from the sill in Collar Gulch have a light- to medium-gray fine-grained groundmass, with phenocrysts of plagioclase about 3 millimeters in size, sanidine, commonly a little larger than the plagioclase but exceptionally as much as 10 millimeters long, and dark stubby prisms of a ferromagnesian mineral, which under the microscope are identified as sodic pyroxene. The plagioclase is albite, $Ab_{95}$, and most of the crystals are surrounded by thin rims of potash feldspar. The groundmass is trachytic with minor amounts of analcite, probably in part deuteric. Apatite, sphene, and magnetite are accessories. Near the upper contact of the sill, the rock contains oval shaped vesicles, many of which are filled with amygdaloidalcalcite.

## Tinguaite

The name tinguaite is derived from the Serra de Tingua, in Brazil, and was applied to certain porphyritic dike rocks of phonolitic composition that occur in these mountains. Rosenbusch (1887), who examined specimens sent him from Brazil, believed the rocks occurred only as dikes and introduced the term for the hypabyssal equivalent of the phonolites. Actually, these same rocks occur as extrusives (Derby, 1891, p. 254), and no new name was necessary. However, the term is well established in the literature of the alkaline rocks and is retained here to include the rocks of phonolitic composition that occur in the Judith Mountains.

In the field these rocks were divided into two principal types: green tinguaite porphyry and gray tinguaite porphyry. The two types are closely related both geographically and genetically, and probably represent "end members" in a complete series; intermediate types are common and many of them are difficult to classify. A third type - a very dark-gray - is known from a few dikes in the Linster Peak dome.

Distribution and Topographic Expression

Both the green and the gray tinguaites occur chiefly as dikes and sills, and are concentrated in two areas; the north central and the northeastern parts of the mountains (pl. 1). Small irregular plugs of gray tinguaite, associated with the dikes and sills, are found at Lookout Peak, approximately 1 mile southeast of Linster Peak, and near the head of Lone Tree Gulch. One or more similar bodies probably exist within the Red Mountain complex (p. 62).

The sills are particularly numerous in beds of the Colorado shale that are exposed along the eastern margin of the Red Mountain-Collar Peak intrusive, and along the eastern flank of the Linster Peak dome. The Colorado shale apparently offered little resistance to the injection of tinguaite magma along the bedding, and these local concentrations may possibly be due to the proximity of these favorable beds to the source magma.

The longest sill varies from 3 to 12 feet in thickness and can be traced along the outcrop from the southeast side of Collar Peak to the east flank of Crystal Peak, a distance of more than 3 miles. Most of the larger sills are less than 2 miles long and many of the smaller ones extend for only a few tens of feet.

The dikes are especially abundant in igneous host rocks and range in size from those with an outcrop length of more than a mile and a maximum thickness of over 100 feet, to those a few feet long and an inch or so in width (pl. 17).

Locally, the attitude and distribution of the dikes are controlled by pre-existing joint systems in the host, but the overall dike pattern is radial, with dikes converging about two separate centers. The northeastern dike swarm centers on the plug of gray tinguaite porphyry about 1 mile southeast of Linster Peak; dikes in the north central swarm radiate from Red Mountain.

The Red Mountain area is a complex of various types of igneous rocks which are strongly fractured and variously bleached and stained by hydrothermal and subsequent supergene alteration. Detailed geologic relationships are obscure, but small plugs of tinguaite may be present at two localities. The green hachures on the map (pl. 1) indicate tinguaite dikes too numerous and too highly altered to map. In the two areas thus shown, nearly all the rock fragments picked up appear to be altered tinguaite. Not all fragments have the same texture (pl. 17, B), and in places short discontinuous segments of dikes can be seen cutting the host in various directions. However, these relations

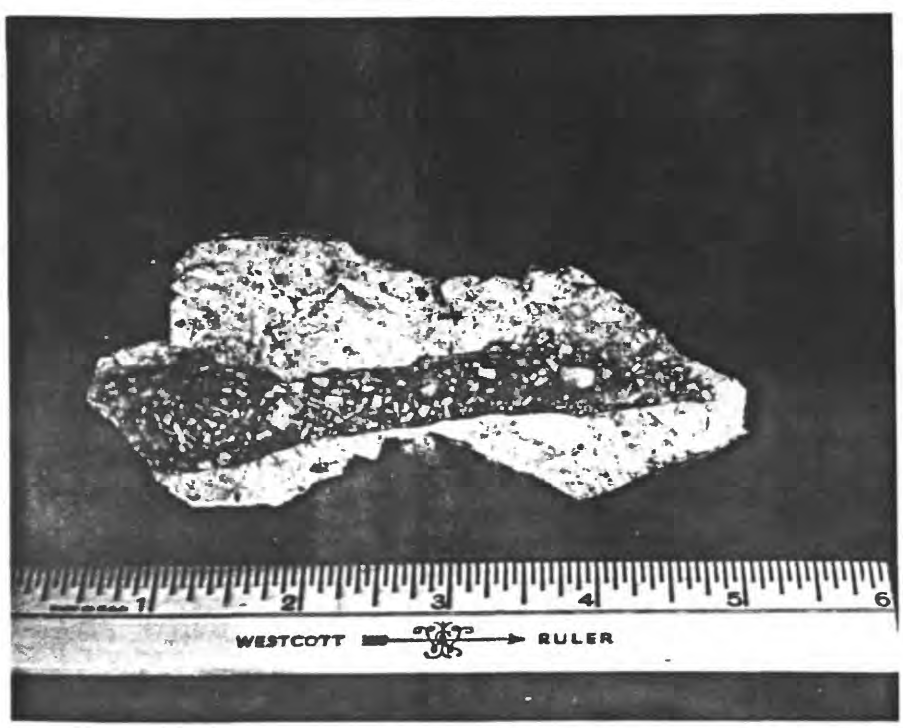
Plate 17

A. AIR VIEW OF TINGUAITE DIKES IN SOUTHEAST PART OF LINSTER PEAK STOCK

View looking northwest. Large dike, notched by stream in middle ground, strikes northeast across Sec. 20, T. 17 N., R. 21 E. Another prominent dike (striking north) shows at left edge of photograph. Country rock is monzonite.

B. ALTERED TINGUAITE FROM RED MOUNTAIN

Small tinguaïte dike (dark) cutting coarser-grained tinguaite. Specimen found loose on surface in Red Mountain alteration zone.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are common in the tinguaite plugs that can be mapped in detail, and it seems probable that the areas of abundant tinguaite float represent bodies that are considerably larger and less regular than the ordinary tinguaite dikes.

The fresh tinguaite is an extremely tough, durable rock and commonly difficult to break with the hammer. Dikes are generally marked by low craggy outcrops, and lines of boulders and resistant debris; in some places long segments of dikes stand out as conspicuous walls (pl. 17, A). Some of the sills form prominent hogback ridges in the Colorado shale. The large linear to arcuate exposures of tinguaite on the east flank of the Linster Peak dome are the dip slopes of sills, and appear on the map as disproportionately large bodies.

## Age Relationships

All tinguaite rocks are younger than the quartz monzonite and older than the alkali granite porphyry of Judith Peak. On the southeast slope of Judith Peak, a dike of green tinguaite cuts rhyolite, but some rhyolite may be younger than some of the tinguaite (p.177). The green tinguaite is younger than the syenite, the gray tinguaite, and the dark gray tinguaite. The relative ages of the gray and the dark-gray tinguaite are unknown.

Numerous dikes of gray tinguaite are found cutting both the Maginnis Mountain and Lewis Peak types of syenite and most of the syenite is older than the gray tinguaite. A single exception is seen on the east flank of the Linster Peak dome where a dike of the Lewis Peak type syenite cuts a large sill of gray tinguaite and, in turn, is cut by a dike of green tinguaite. This syenite is intermediate in age and is probably separated from both of the tinguaites by relatively short time intervals.

## Petrography of the Fresh Rock

The tinguaites are quite variable in aspect depending upon differences in color, texture, and mineral composition; all types are porphyrytic. Various types of tinguaite are shown on plates 17, B, 18, 19, 20, A, and 21, A.

Crystals of potash feldspar 2 millimeters to 8 centimeters in length are the most common phenocrysts and generally impart a conspicuous flow structure to the rocks. Other phenocrysts are dark-green prisms of sodic pyroxene as much as 7 millimeters long, and black glassy melanite, commonly about 1 millimeter across but exceptionally attaining 5 millimeters. One sill of green tinguaite contains numerous "crystals" of pseudoleucite as much as 5 millimeters in diameter.

These minerals are set in a fine-grained, compact groundmass which varies from a dark green through greenish gray, to a medium gray. Under the microscope, the green groundmass material is seen to consist of small alkali feldspar laths, either simple crystals or singly twinned, and countless tiny needles of aegirine (pls. 20, B, 21, B, and 23, B). These are intimately mixed with clear glassy interstitial material with a low index, either weakly birefringent or

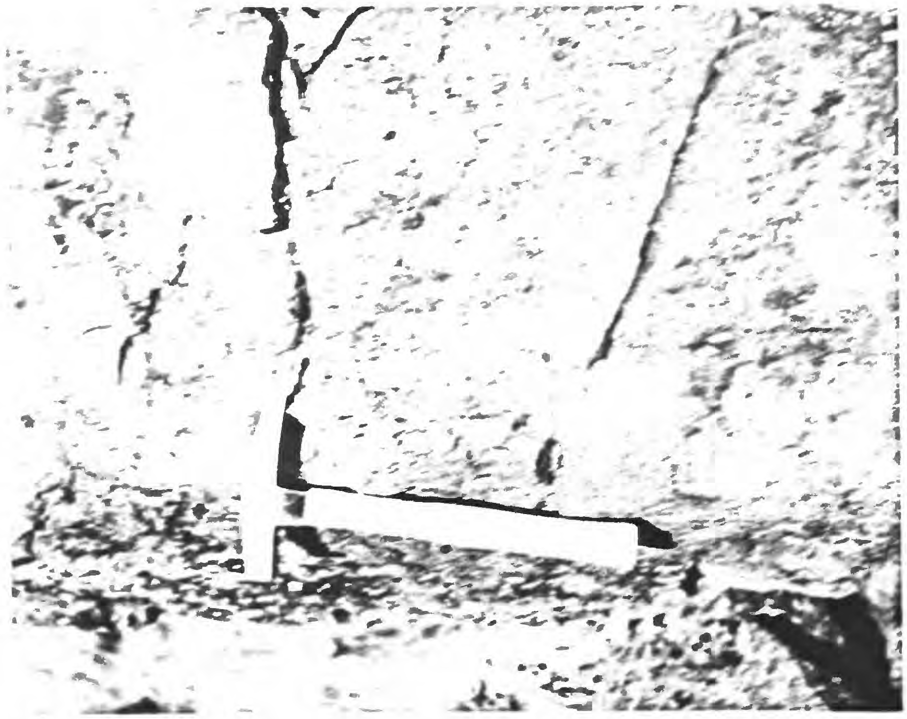
Plate 18

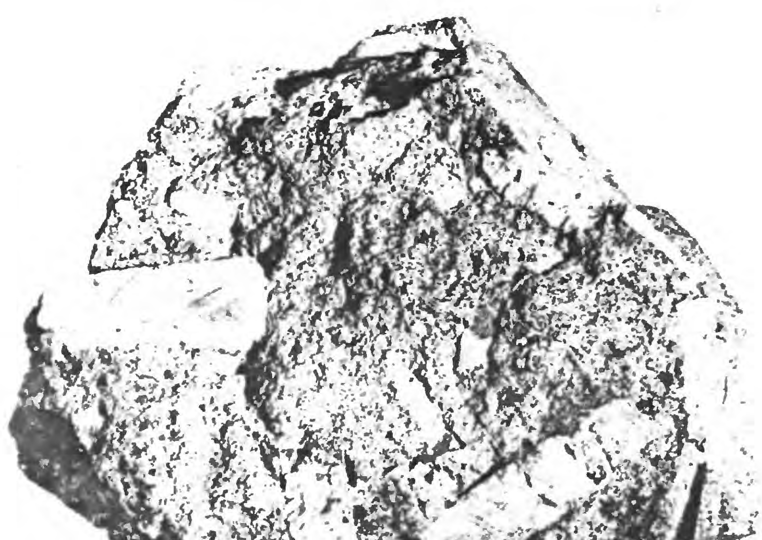
A. VIEW OF GREEN TINGUAITE DIKE 1 MILE NORTHWEST OF MAIDEN

Large tabular sanidine phenocrysts show excellent flow structure. Foliation dips gently to left.

B. COARSE-GRAINED GRAY TINGUAITE FROM SILL ON ARMELL CREEK

Large sanidine phenocrysts from gray tinguaite sill in Colorado shale on north side of West Fork of Armell Creek.





A. GREEN TINGUAITE PORPHYRY FROM LARGE SILL SOUTHEAST OF ROSS PASS

Specimen at left is medium-grained green tinguaite from 1,200 feet S. 29° W. of Linster Peak. Specimen at right contains only a few small phenocrysts. From 2,000 feet S. 29° E. of road junction in Ross Pass.

B. CROWDED (GRAY) TINGUAITE PORPHYRY FROM SILL ON SOUTHEAST FLANK OF LINSTER PEAK DOME

Gray tinguaite with abundant tabular sanidine phenocrysts. Most of the dark spots are lichen, but a few are melanite.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A. PSEUDOLEUCITE TINGUAITE PORPHYRY FROM SILL AT EAST BASE OF LOOKOUT PEAK

Light circular spots are pseudoleucite. Other phenocrysts are sanidine. Specimen from small sill in Colorado shale at east base of Lookout Peak.

B. PHOTOMICROGRAPH OF GREEN TINGUAITE DIKE 1 MILE WEST OF JUDITH PEAK

Large rectangular crystal with light core is diopside with rim of aegirine-augite. Dark spot at upper end of crystal is melanite and fluorite. Dark spot to left of crystal is melanite (on right) and spinel (on left) with lighter-colored reaction rim. Dark-gray crystal at lower left is sphene. At upper right are analcite and natrolite (large light area). Smaller patch of these minerals is seen at lower right center. Light grain with high relief at left end of this patch is apatite. Groundmass is alkali feldspar laths and needles of aegirine. Specimen from 5,300 feet S. 86° W. of Judith Peak. Plane-polarized light. X 31.


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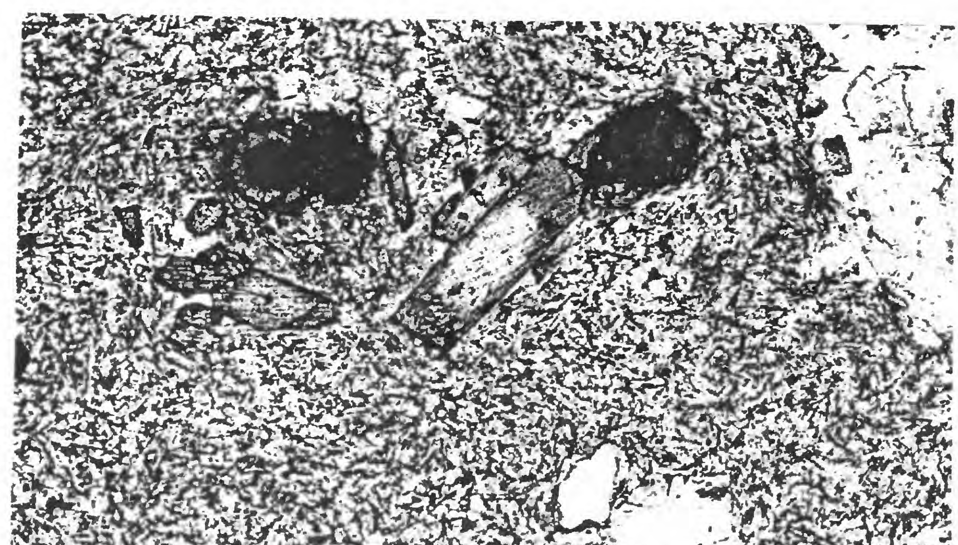


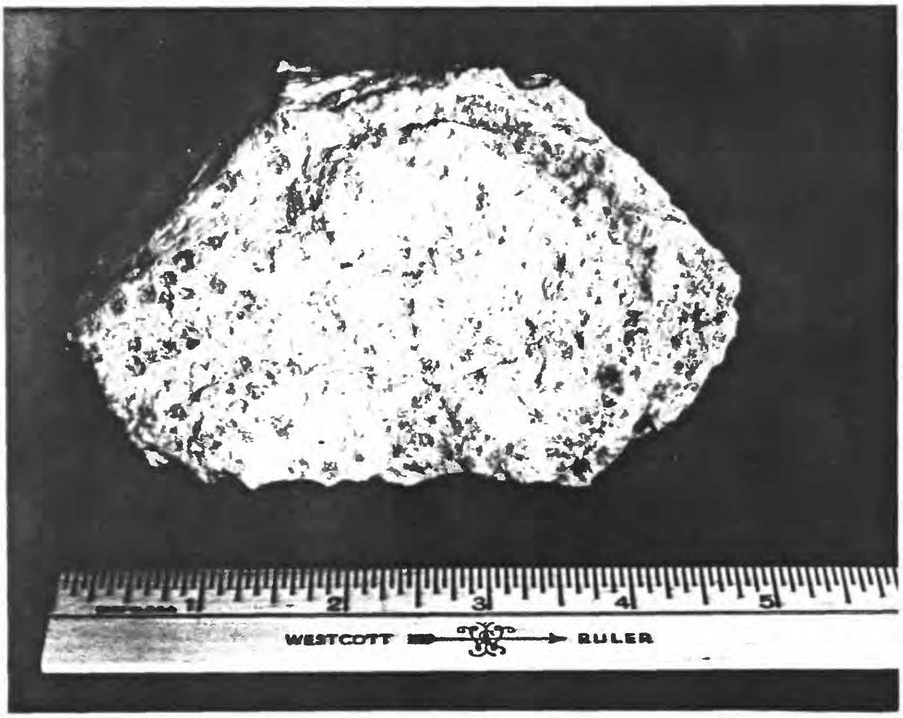
Plate 21

A. GREEN TINGUAITE PORPHYRY FROM SMALL SILL ON SOUTH-EAST SIDE OF LINSTER PEAK DOME

On weathered surface color of green tinguaite fades to grayish green. Small circular spots appear dark green. See B.

B. PHOTOMICROGRAPH OF SAME SPECIMEN AS A

Circular spots on hand specimen, A, are rosettes of natrolite. Note that the tiny aegirine needles are not replaced. Crossed nicols. X 19.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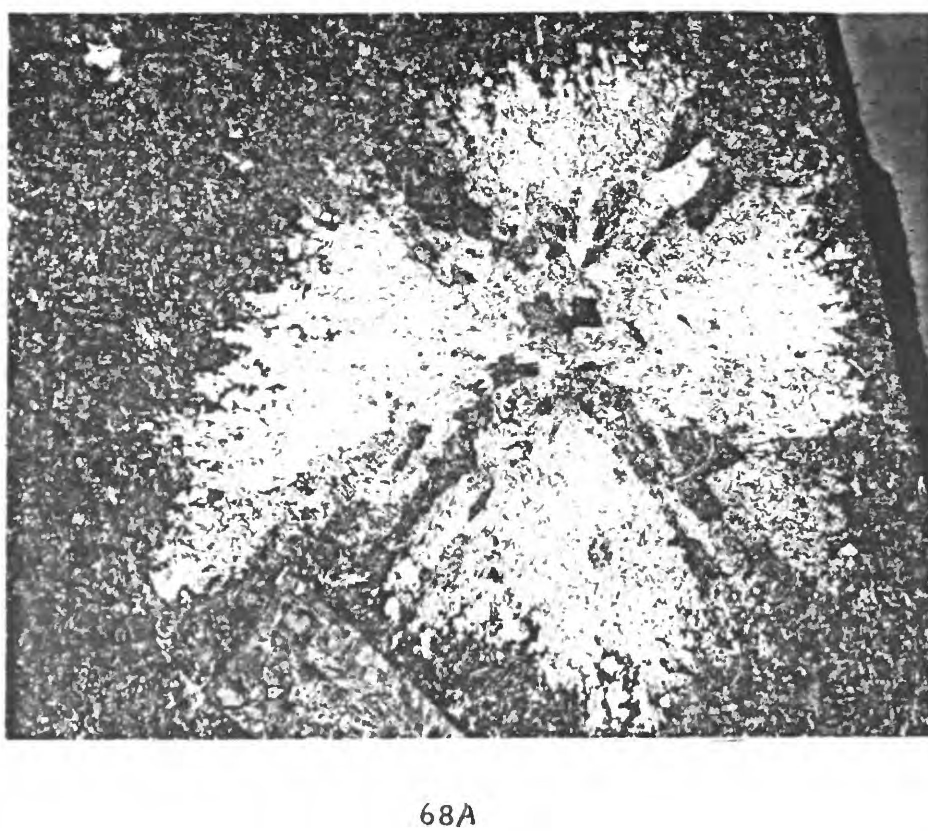


isotropic. Differences in indices and double refraction indicate the presence of at least two distinct substances.

Many of the tinguaites show strong deuteric alteration (p. 78), with the development of minerals whose optical properties are similar to those described above, and it is difficult to separate the late orthogenic minerals from those of secondary origin. Both types gelatinize with acid. The clear interstitial material is probably a mixture of nepheline, sodalite, plus or minus other feldspathoids, and analcite (in part secondary), all partially replaced by natrolite (pls. 21, B, 24, B, and 25, A). A little glass, partially devitrified, is present in a few sections. Accessory minerals include sphene, apatite, magnetite, nepheline, as small euhedra as well as in the groundmass, sodalite, green spinel (?), usually much altered, and rarely biotite, fluorite, and vesuvianite.

In thin section the green and the gray tinguaites show the following differences: (1) The groundmass of the green tinguaite contains a higher concentration of tiny aegirine needles. In the gray tinguaite the aegirine tends to form larger but fewer crystals. (2) The gray tinguaite generally contains less nepheline and related feldspathoids. (3) Deuteric analcite and natrolite are commonly more abundant in the green tinguaite.

The dark-gray tinguaite includes the mineral association, dark greenish-brown amphibole, aegirine-augite, and plagioclase, $Ab_{65}$ to $Ab_{75}$. The presence of plagioclase and amphibole readily separates these rocks from the green and the common gray tinguaites. The significance of the association, amphibole-plagioclase, is unknown.

Pyroxene, --In thin section the sodic pyroxenes are seen as euhedral prisms with faint to strong pleochroism, green to yellow green. The crystals show a considerable range in optical properties, probably corresponding to changes in chemical composition within the series, diopside - aegirine, or possibly augite - aegirine. Aegirine-augite is the most common member. Many of the crystals are zoned, commonly with lighter cores, and darker more sodic rims; some show the reverse relationship, and a few exhibit oscillatory zoning (pl. 22).

Amphibole, --Amphibole is a rare constituent of the tinguaite and has been observed only in those sections, 6 in number, which contain both potash and soda-lime feldspars. In one section it is the only mafic mineral; in the others it is associated with varying amounts of aegirine-augite and aegirine.

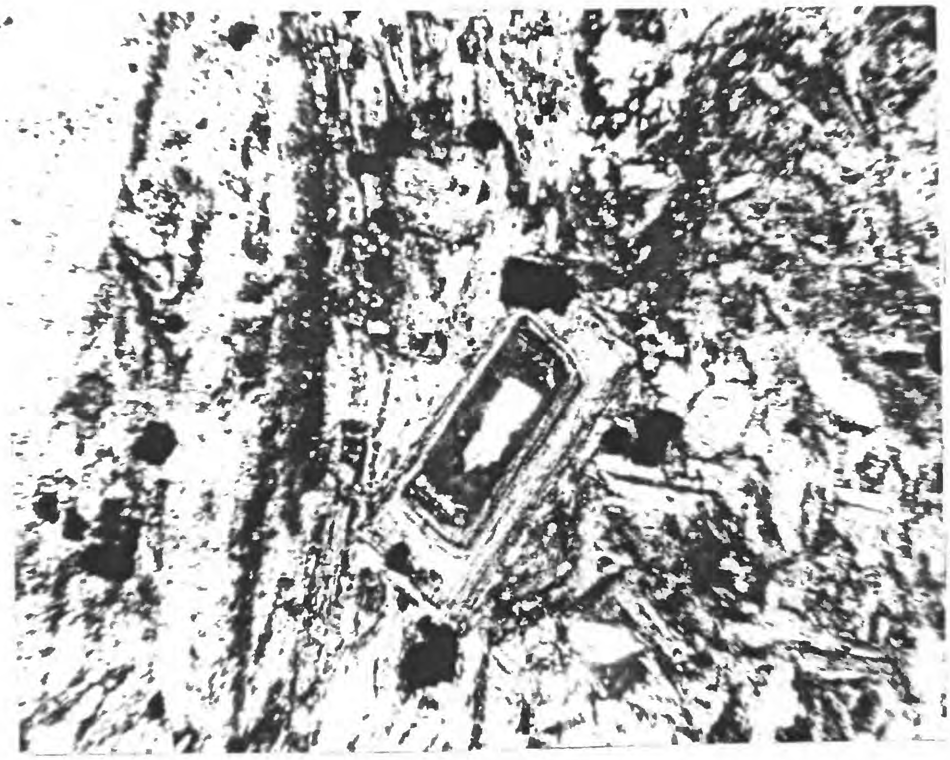
The color of the amphibole is somewhat darker than that seen in the monzonites. Shades of yellow brown, dark green, and dark liver brown, almost black, are common. A few crystals show dark-bluish-green color. The exact cause of color differences in the amphiboles is unknown (Winchell, 1924) (Graham, 1926) and (Deer, 1940) but the dark color of the amphibole in the gray tinguaite and its association with sodic pyroxene strongly suggests that it is more sodic than the hornblende of the quartz monzonites; it is probably closely related to hastingsite or arfvedsonite.

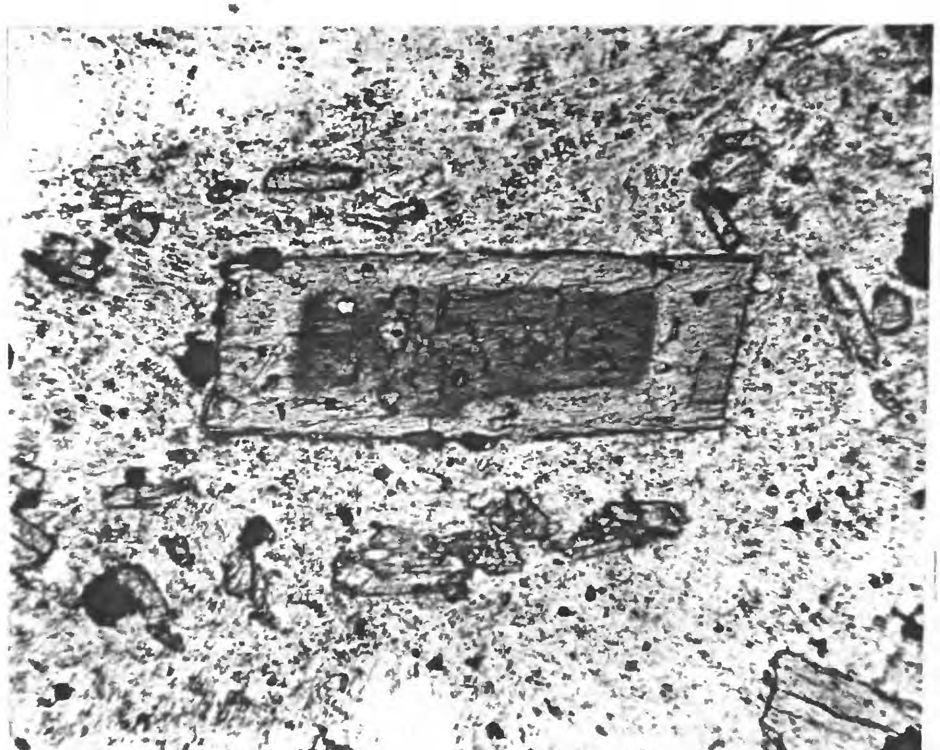
A. PHOTOMICROGRAPH OF GRAY TINGUAITE PORPHYRY FROM LOOKOUT PEAK

Zoned crystal in center is "sodic" pyroxene. Light core is diopside. Next outer zone (dark) is aegirine-augite. Gray zones are intermediate in composition. Black spots are magnetite. Remainder of slide is alkali feldspar laths, small sodic pyroxene, and large sanidine crystal along left edge. Specimen from dike 600 feet N. 45° W. of summit of Lookout Peak. Crossed nicols. X 104.

B. SAME SPECIMEN AS A

Zoned pyroxene with core of aegirine-augite and less sodic next outer zone. Very thin mantle of aegirine-augite on exterior of crystal. Black grains are magnetite. Plane-polarized light. X 50.





Some of the amphibole phenocrysts exhibit zoning similar to that seen in the sodic pyroxenes; in a few crystals the zoning is oscillatory (pl. 23, A).

Potash Feldspar, --The potash feldspars of the tinguaites are quite unusual and illustrate the present state of confusion regarding the alkali feldspars. The crystals are white to glassy, generally tabular, flattened parallel with (010), or "prismatic," elongated parallel with a. One large tabular crystal measured approximately 8 x 4 x 0.7 centimeters. The most common forms are {001}, {010}, {110}, and {201}. Some crystals show {130} and {111}, and a very few have poorly developed {021} and {100}. Many crystals have a marked (100) parting (?).

The microscope reveals variations in 2V from about 20° to 45°, with the optic plane normal to (010). Material from one of the crystals from a sill on the north side of the West Fork of Armell Creek near the mouth of the canyon, was x-rayed by O. F. Tuttle of the Geophysical Laboratory. He reports [1] that the feldspar belongs to the low-sanidine - high-albite series (Tuttle and Bowen, 1951) and that the composition as determined by the x-ray is $Or_{76} - Ab_{24} \pm 4$ percent.

Goniometric measurements, made by Alfred Levinson of the Mineralogy Department of the University of Michigan, indicate that the crystals are triclinic. This suggests that they are anorthoclase, and

---

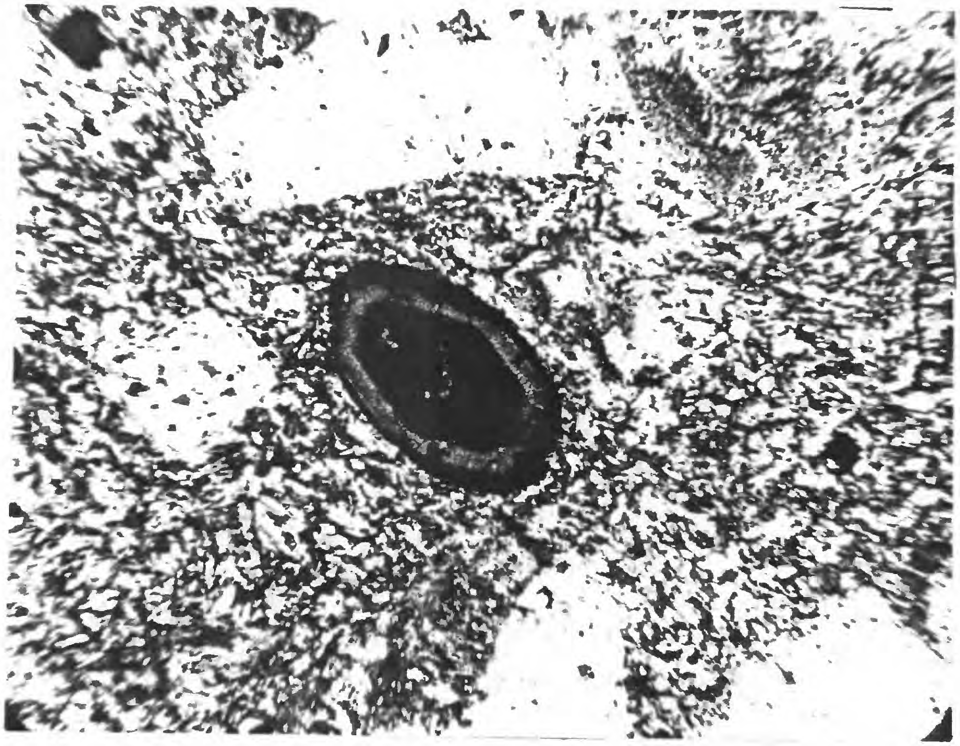
1/ Tuttle, O. F., 1951, written communication.

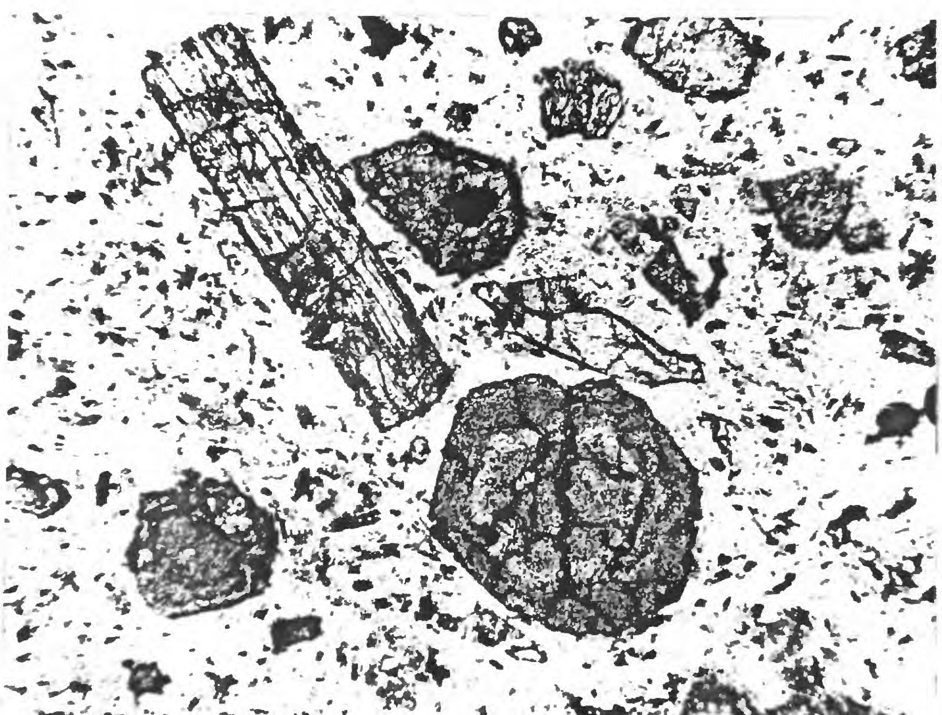
A. PHOTOMICROGRAPH OF DARK GRAY PLAGIOCLASE-AMPHIBOLE TINGUAITE FROM LINSTER PEAK DOME

Dark crystal in center is zoned sodic amphibole, hastingsite(?). Small light crystal to left of amphibole and large crystal above amphibole are andesine. Large darker-gray crystal which shows faintly at upper right is sodic pyroxene. Trachytic groundmass of alkali feldspar laths. Specimen from prominent north-trending dike in Sec. 20, T. 17 N., R. 21 E. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF CROWDED TINGUAITE PORPHYRY FROM LINSTER PEAK DOME

Large equidimensional crystal near center is zoned melanite. To the right of this is another smaller crystal of melanite. Just below large melanite is sphene. Remainder of phenocrysts are aegirine-augite. Groundmass is alkali feldspar, aegirine and magnetite. Plane-polarized light. X 58.





not "soda-sanidine." However, Tuttle [1] states that an x-ray of the feldspar heated for 1 hour at 900°C shows it to be monoclinic, and he suggests that the triclinic properties may be due to unmixed albite in submicroscopic units. The following are limiting values for indices of feldspar from four different tinguaites:

alpha = 1.521 - 1.522

beta = 1.524 - 1.525

gamma = 1.526 - 1.527

At the present state of knowledge it seems best to interpret the feldspars of the tinguaites as x-ray perthites consisting of unmixed potash and soda-lime feldspar. For the sake of simplicity these feldspars will hereafter be referred to as sanidine.

Many of the crystals show faint oscillatory zoning marked by slight changes in index and extinction (pl. 24, A). If the crystals are x-ray perthites of unmixed sanidine and albite, it seems doubtful that the zoning is the result of changes in the sodium content; possibly it is due to the presence of barium.

Pseudoleucite.--In a small tinguaite sill in the northeastern part of the mountains, there are small aggregates of potash feldspar, sericite and analcite which appear to be pseudomorphic after leucite. The replacement minerals are arranged in radial aggregates that center along the edges of the pseudomorphs and diverge toward the center.

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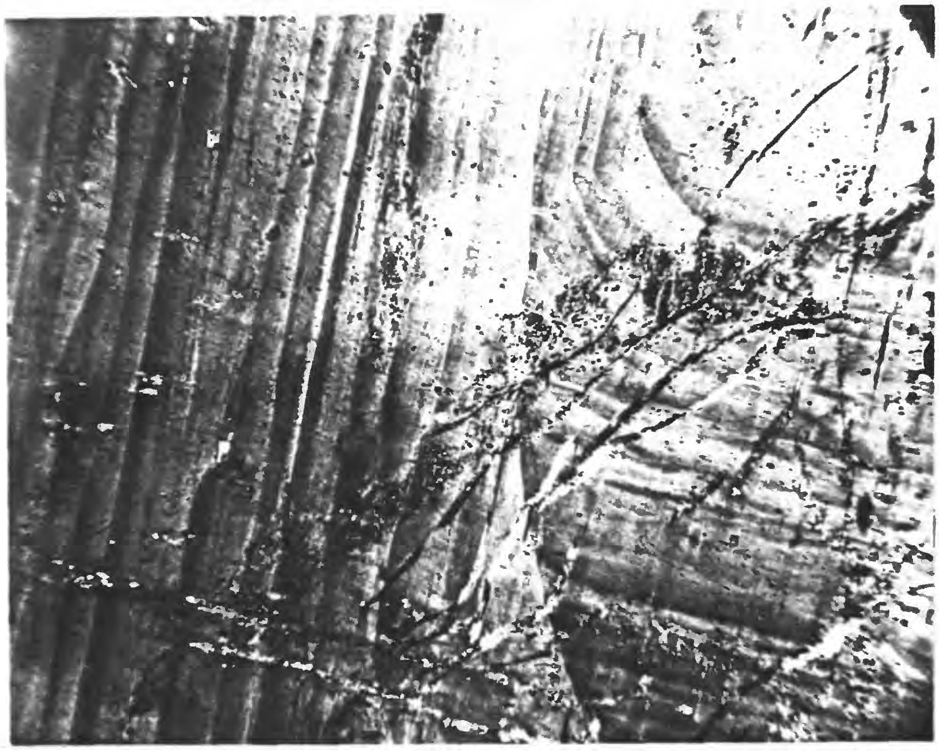
[1] Tuttle, O. F., 1951, written communication.

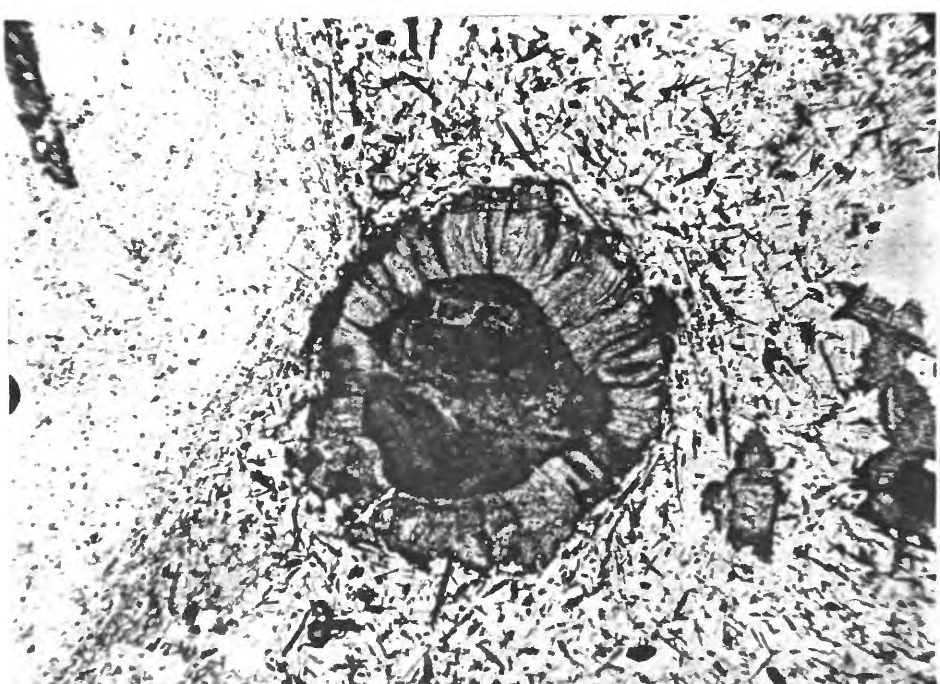
A. PHOTOMICROGRAPH OF GRAY TINGUAITE PORPHYRY FROM WEST FORK OF ARMELL CREEK

Oscillatory zoning in large sanidine phenocryst from tinguaite sill in Colorado shale on north side of West Fork of Armell Creek. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF GREEN TINGUAITE PORPHYRY FROM DIKE NORTHWEST OF MAIDEN

Dark crystal in center is altered spinel (?). Fibrous mineral of reaction rim probably belongs to epidote group. Specimen from 5,600 feet N. 17° W. of Maiden road junction. Plane-polarized light. X 50.





In the larger "crystals" the structure consists of interfingering rosettes; in small "crystals" the overall structure is roughly radial (pl. 25, A). Except for the pseudoleucite "crystals," which range in size from 0.04 to 5 millimeters, the rock is a typical green tinguaite.

Late Magmatic Reactions, --Certain of the phenocrysts in the tinguaites show effects of magmatic reaction. The amphibole phenocrysts in the plagioclase tinguaites commonly show some corrosion. Bluish-green amphibole, in a cognate feldspathic inclusion from a green tinguaite dike in the Linster Peak dome, has partly replaced aegirine-augite, and thus is a "soda uralite." This same rock contains minor amounts of biotite, replacing the amphibole and to some extent the pyroxene.

What appears to be a dark-green, almost black spinel is seen in a number of sections. These crystals are roughly equidimensional, usually much altered, and are commonly mantled by coronas of fibrous material. The fibers have both positive and negative elongation, with parallel or near parallel extinction, and interference colors which range from slightly anomalous bluish-grays to upper second order. The material is too fine grained for positive optical identification but probably belongs to the epidote group.

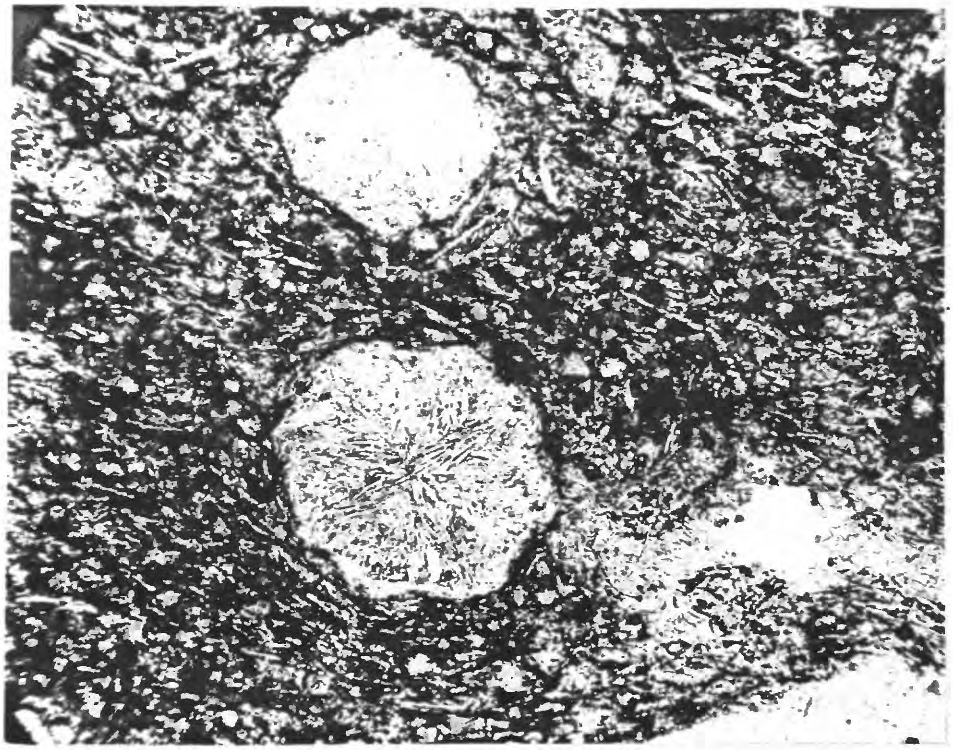
The most significant orthomagmatic reaction from a petrologic viewpoint is the conversion of leucite to pseudoleucite. The pseudomorphs are probably 75 to 90 percent potash feldspar, and no nepheline has been

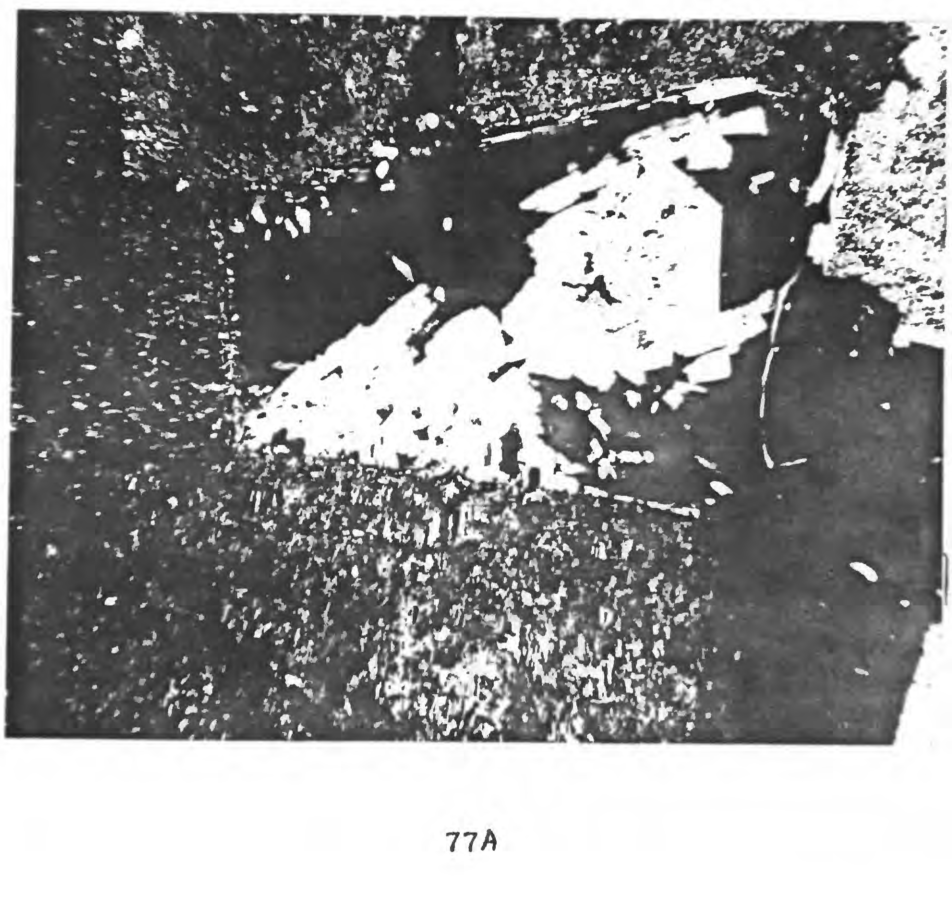
A. PHOTOMICROGRAPH OF PSEUDOLEUCITE TINGUAITE FROM NORTHEASTERN PART OF THE MOUNTAINS

"Crystals" of pseudoleucite - potash feldspar, sericite and analcite (light gray). Groundmass is sanidine (lath shaped crystals) aegirine needles, and pseudoleucite (small circular bright spots). At bottom right is edge of large pseudoleucite. Light irregular patch in groundmass just above this large pseudoleucite is analcite. Specimen from small sill in Colorado shale at east base of Lookout Peak. Plane-polarized light. X 50.

B. PHOTOMICROGRAPH OF FELDSPATHIC INCLUSION FROM GREEN TINGUAITE DIKE IN THE LINSTER PEAK STOCK

Albite overgrowths filling cavity between albitized sanidine phenocrysts in feldspathic inclusion. Specimen from dike 1,800 feet S. 28° W. of Linster Peak. Crossed nicols. X 58.





observed. Whether the sericite and analcite have replaced the "reaction" nepheline, as Bowen (1928, p. 253) believes, or whether they have formed directly from the leucite with no intermediate steps is unknown.

## Alteration

Albitization of the feldspars is similar to that observed in the monzonitic rocks, except that plagioclase is generally absent, and sanidine is the usual host. Deuteric albite also occurs in interstitial cavities as overgrowths on sanidine crystals in the feldspathic inclusion previously mentioned (pl. 25, B).

Later stage deuteric reactions are especially evident in the green tinguaites and have further altered the sanidine to analcite and natrolite. These minerals have also formed at the expense of nepheline and groundmass material (pl. 21, B). In some sections, natrolite is seen replacing the analcite and is believed to be generally later than the analcite.

Each alteration product shows some selectivity in replacement, e.g., relicts of albite (perthitic) remain in patches of analcite and natrolite that have replaced the sanidine following albitization (pl. 26).

With respect to sanidine, the deuteric minerals indicate a continued exchange of soda for potash with a progressive loss of silica and the addition of water (table 4).

A. PHOTOMICROGRAPH OF GREEN TINGUAITE PORPHYRY FROM NORTHWEST OF MAIDEN

Replacement of sanidine phenocryst by albite, analcite, and natrolite. Dark-gray (dirty) areas at left edge and top of plate are sanidine clouded with allophane. Black is analcite which has replaced sanidine. Light-gray mineral (center, and lower right) is natrolite which replaces both sanidine and analcite. Thin gray seams which cut analcite (top and left) and natrolite (bottom) are antecedent veinlets of incipient albitization. Albite replaced sanidine along fractures and cleavage cracks. Analcite and natrolite alteration which followed, replaced the sanidine, but not the albite. Specimen from dike 5,600 feet N. 17° W. of Maiden road junction. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF SAME SPECIMEN AS A

Relict veinlets of incipient albitization cut natrolite at upper left, near right margin, and diagonally across middle of plate. Cloudy gray material in lower left corner is sanidine with allophane alteration. Edges of serrations on albite veinlets are roughly parallel to cleavage directions of the sanidine. Crossed nicols. X 104.

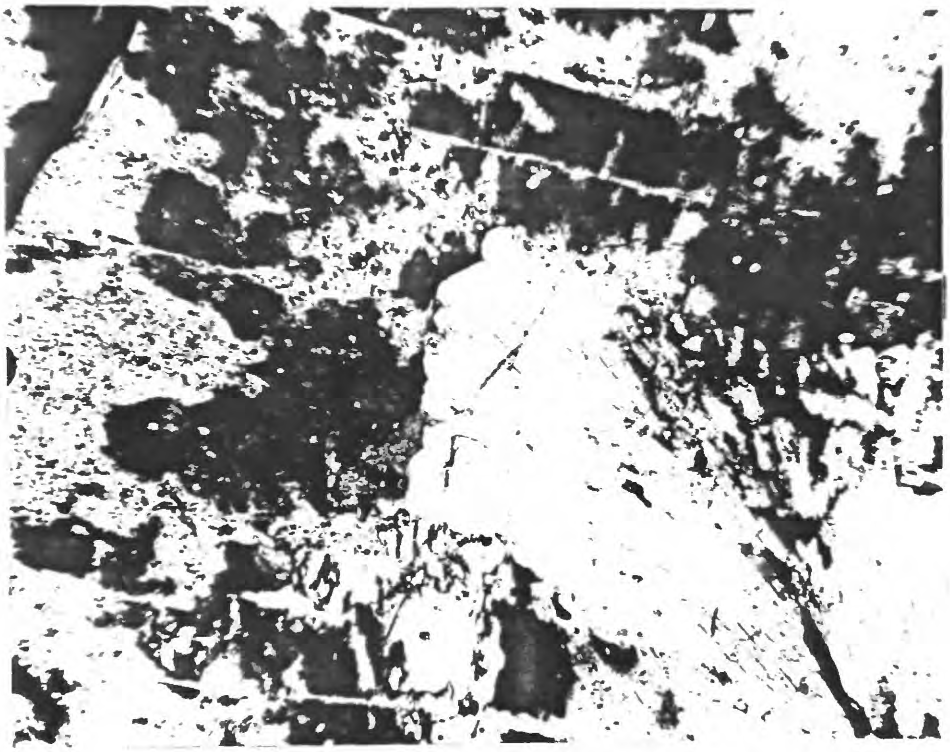


TABLE 4.--Formulae of sanidine, nepheline, and their alteration products expressed as oxides

| | | | | |
|---|---|---|---|---|
| Sanidine | ($K_2O$, $Na_2O$) | $Al_2O_3$ | 6 $SiO_2$ | - |
| Albite | $Na_2O$ | $Al_2O_3$ | 6 $SiO_2$ | - |
| Analcite | $Na_2O$ | $Al_2O_3$ | 4 $SiO_2$ | 2 $H_2O$ |
| Natrolite | $Na_2O$ | $Al_2O_3$ | 3 $SiO_2$ | 2 $H_2O$ |
| Nepheline | $Na_2O$ ($K_2O$) | $Al_2O_3$ | 2 $SiO_2$ | - |

The replacement of nepheline by analcite and natrolite requires the addition of some silica, probably derived in part from the sanidine.

In general, the replacement products seem to indicate local rearrangement of material by highly aqueous solutions rather than a large scale transfer of constituents, but some soda and water have been introduced, and potash has been removed. Minor amounts of sericite and hydromica (pl. 27, A) probably represent some of the potash, but cannot account for all of it. A series of four specimens, taken across a green tinguaite-monzonite contact gives no clue as to the site of deposition of the replaced potash. Hydrothermal alteration of the tinguaites is similar to that observed in the monzonites.

## Unidentified Minerals

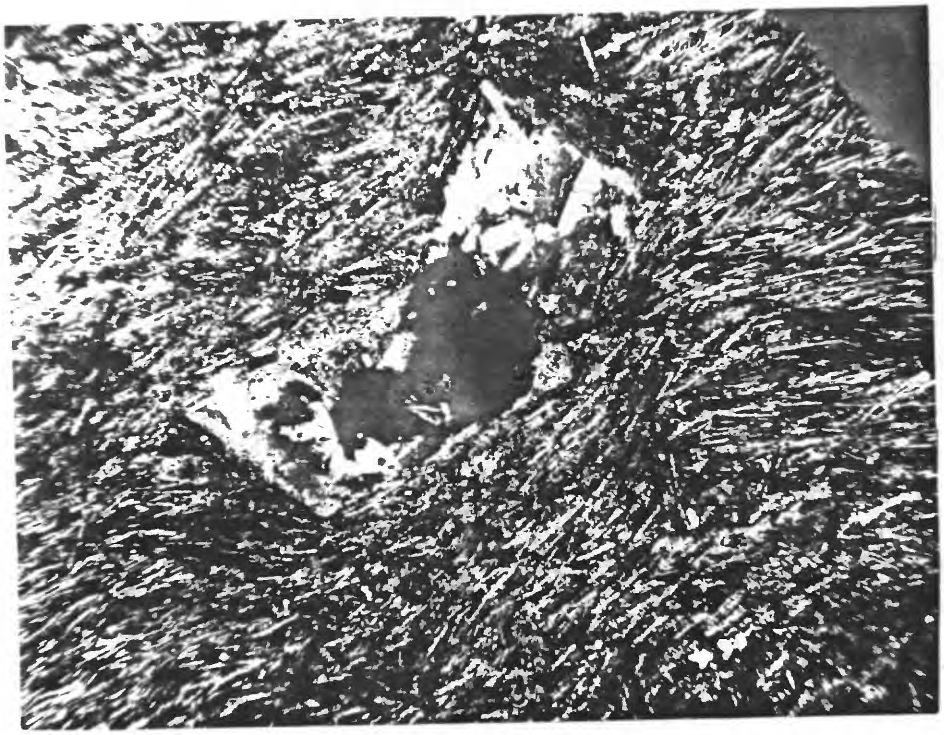
Two unidentified minerals are present in the cognate feldspathic inclusion from the green tinguaite dike in the Linster Peak dome.

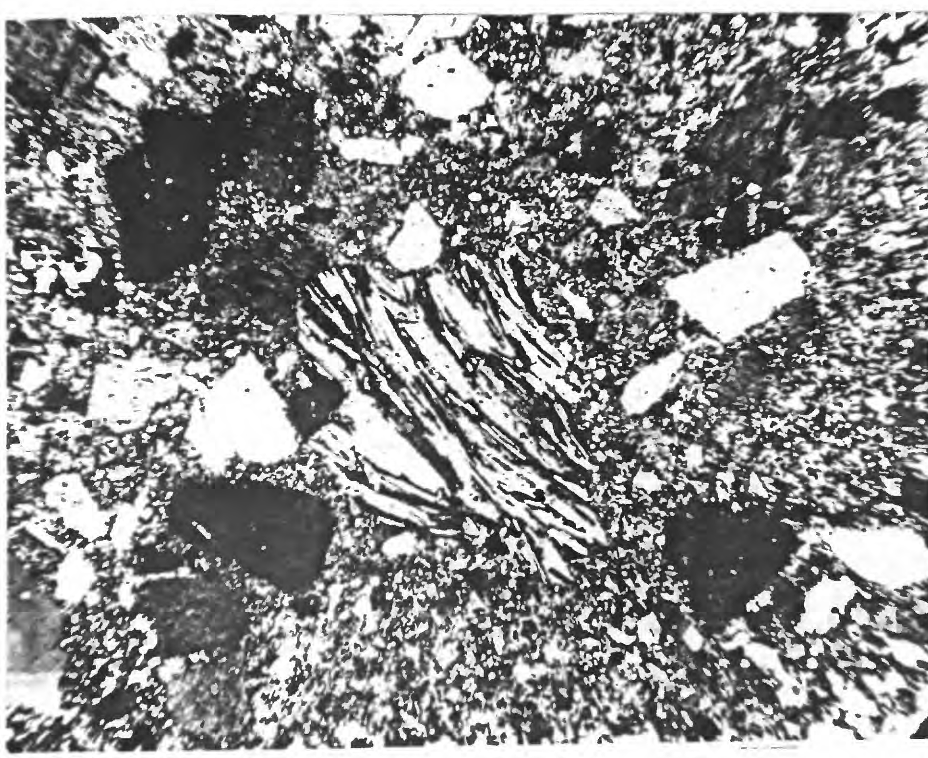
A. PHOTOMICROGRAPH OF GREEN TINGUAITE PORPHYRY FROM 1 MILE WEST OF JUDITH PEAK

Phenocryst is sanidine partly replaced by hydromica. (Clear gray area in center of crystal is hole in slide.) Groundmass is largely alkali feldspar laths and aegirine needles. Specimen from fine-grained dense green tinguaite dike with few phenocrysts 5,300 feet S. 86° W. of summit of Judith Peak. Crossed nicols. X 50.

B. PHOTOMICROGRAPH OF INTRUSION BRECCIA FROM RED MOUNTAIN

Fragment of tinguaite (center) in silicified intrusion breccia. Other fragments in plate are sanidine, but breccia also includes fragments of quartz monzonite and rhyolite. Groundmass is feldspathic but contains secondary silica. Specimen from Red Mountain pyritic alteration zone, 6,300 feet N. of Tail Holt mine. Crossed nicols. X 50.





Mineral A.

| | | |
|---|---|---|
| Occurrence | - | as open fillings associated with albite overgrowths on sanidine crystals - generally as overgrowths on the albite. |
| Form | - | massive |
| Color | - | clear, glassy |
| Birefringence | - | nil to very faint |
| Mean index | - | approximately 1.535 |
| Figure | - | biaxial (?) +, small 2V |

Mineral B.

| | | |
|---|---|---|
| Occurrence | - | generally associated with aegirine-augite |
| Form | - | small anhedral to subhedral grains and crystals |
| Cleavage | - | one excellent, one good at approximately 70° |
| Color | - | dark red in reflected light |
| Pleochroism | - | strong<br>alpha = yellow brown<br>beta, gamma = dark carmine red |
| Birefringence | - | moderate |
| Mean index | - | 1.67 |
| Figure | - | biaxial +, small to moderate 2V, dispersion, r<v, distinct |

## Rocks of the Red Mountain Complex

The Red Mountain area is a complex intrusive mass of monzonite, intrusion breccia, alkali granite dikes, and tinguaite and related silica-deficient rocks. The rocks are highly fractured and altered and the writer was unable to determine in detail the distribution and relative amounts of the various rock types. The geology of the area as shown on the map is necessarily generalized.

The monzonite and the tinguaite are, except for their extreme alteration, identical to those that occur elsewhere in the mountains;

the alkali granite dikes and the intrusion breccia are described in following sections of this paper. To be discussed here, are those rocks with alkali syenite and tinguaite affinities that are peculiar to this area.

Much of the rock debris that mantles the barren ridge crests and slopes of Red Mountain has an appearance intermediate between that of the altered tinguaites and that of the altered monzonites. Thin sections of "grab samples" of these rocks reveal the presence of quartz monzonite and two types of quartz-free rocks. In all rocks, the primary mafic constituents have been completely removed, and the accessory minerals are either destroyed or masked by the abundance of pyrite, magnetite, and finely disseminated alteration products - allophane, other clay minerals, hematite, limonite, jarosite and a little rutile.

The quartz-free rocks are all characterized by trachytic groundmass of alkali feldspar laths. In somespecimens the groundmass crystals attain a length of 3 millimeters and commonly are two to four times larger than the feldspar laths typical of the tinguaites; in some sections the groundmass is extremely fine grained. The only phenocrysts that remain in these rocks are feldspar. These vary in abundance, average 3 to 4 millimeters in length, and provide a basis for separation into two distinct rock types: (1) Those that contain only sanidine phenocrysts, and (2) Those that contain phenocrysts of both albite and sanidine. In both rocks the sanidine is slightly albitized.

The rocks containing both of the alkali feldspars appear to be essentially alkali syenites from which everything but the feldspar has been leached out; the sanidine rocks closely resemble some of the altered tinguaites. Primary quartz is present in the associated and similarly altered monzonites, and this demonstrates that the absence of quartz in the highly feldspathic rocks is not due to leaching. Whatever feldspathoids and zeolites were once present is unknown. The feldspar phenocrysts show no vestiges of zeolitic alteration, but the similarity with rocks containing silica-deficient minerals suggests that they may have been present as minor constituents. The rocks certainly were not oversaturated with respect to silica, and they may have been slightly undersaturated. Both types are rich in potash. The sanidine rocks probably contain 20 to 25 percent of the albite molecule; the albite - sanidine rocks are estimated to contain 35 to 45 percent of the albite molecule. Based on the composition of sanidine and albite, the total alkali content probably falls between 12 and 15 percent. The rocks are very similar to silica-deficient rocks seen elsewhere in the Judith Mountains and must be considered as closely related to them.

## Alkali Granite Porphyry of Judith Peak

### Distribution

Rocks of alkaline granitic composition are exposed in a roughly circular area approximately 1 mile in diameter centering on Judith

Peak. The peripheral part of this area and the entire northwestern sector are underlain by fine-grained alkali granite porphyry and associated metasomatic rocks. Within the southeastern half of the area, these rocks are cut at the surface by two bodies of coarse-grained alkali granite porphyry and two bodies of intrusion breccia.

Satellite dikes of alkali granite porphyry are found in the area southeast, east, and especially northeast of Judith Peak. A single dike of alkaline rhyolite is exposed between the monzonite porphyry and the Madison limestone on the south side of West Armell Creek, due north of Judith Peak. Several small sills lie within the limestone close to the contact.

## Age Relationships

The fine-grained facies of the alkali granite porphyry is cut by the coarse-grained facies and both are cut by the associated intrusion breccia. The dikes of alkali granite cut the quartz-free alkaline rocks and associated breccias on Red Mountain as well as dikes of green tinguaite. Tinguaite dikes occur on all sides of Judith Peak, but none have been found within the circular area underlain by rocks of alkaline granitic composition, and probably the fine-grained facies of the alkali granite porphyry is also younger than the tinguaites.

## Petrography of the Coarse-Grained Facies

The coarse-grained alkali granite porphyry is the most unusual rock in the Judith Mountains. In the hand specimen it shows conspicuous doubly terminated cyrstals of quartz which average about 10 millimeters in size, and smaller but more abundant phenocrysts of white to glassy tabular sanidine which attain a maximum length of about 7 millimeters. These are set in a fine-grained groundmass which constitutes an estimated 25 to 40 percent of the rock. Where fresh, the groundmass is a medium grayish green; on weathered surfaces the groundmass and the sanidine phenocrysts are buff-colored, and the quartz crystals, which are dark, almost smoky in color, stand out in strong contrast (pl. 28). Ferromagnesian minerals, megascopically visible, are almost entirely lacking. In a few places, the rock contains scattered crystals of aegirine as much as 5 millimeters in size. Tiny needles of aegirine as much as 0.5 millimeters long are present in the groundmass of most specimens and impart a greenish color to it.

In thin section, the groundmass has a micro-porphyritic texture with subhedral grains of albite, $Ab_{97}$, set in a quartz base containing aegirine needles and minor amounts of alkali feldspar. The albite ranges in size from 0.1 to 0.5 millimeters. Crystals that show good twinning are usually rectangular in outline with good (010) faces and irregular terminations; crystals that show only faint twinning commonly have an elliptical outline. None of the accessory minerals common to the Judith Mountain rocks have been identified.

The groundmass, exclusive of the micro-phenocrysts of albite, constitutes only a very small percent of the rock. The closely packed

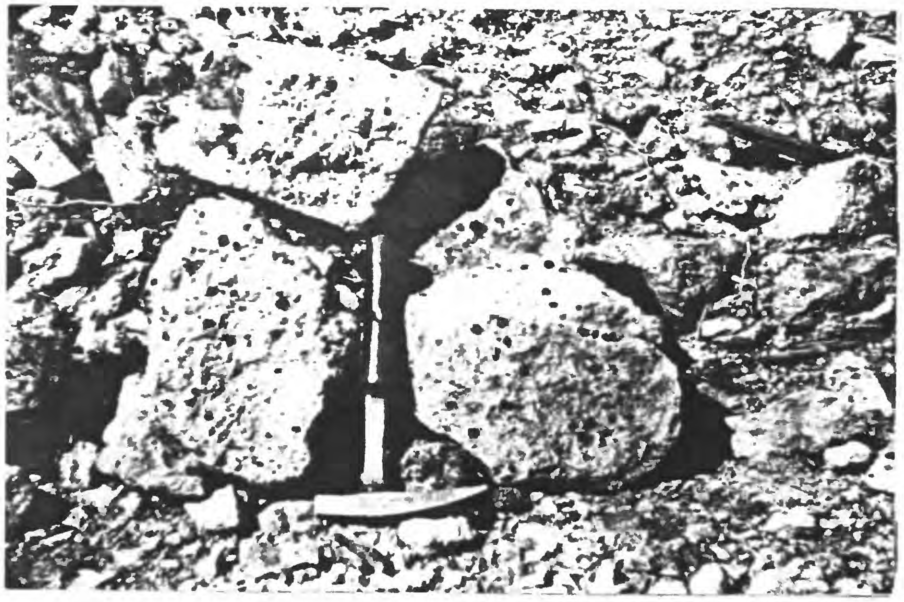
Plate 28

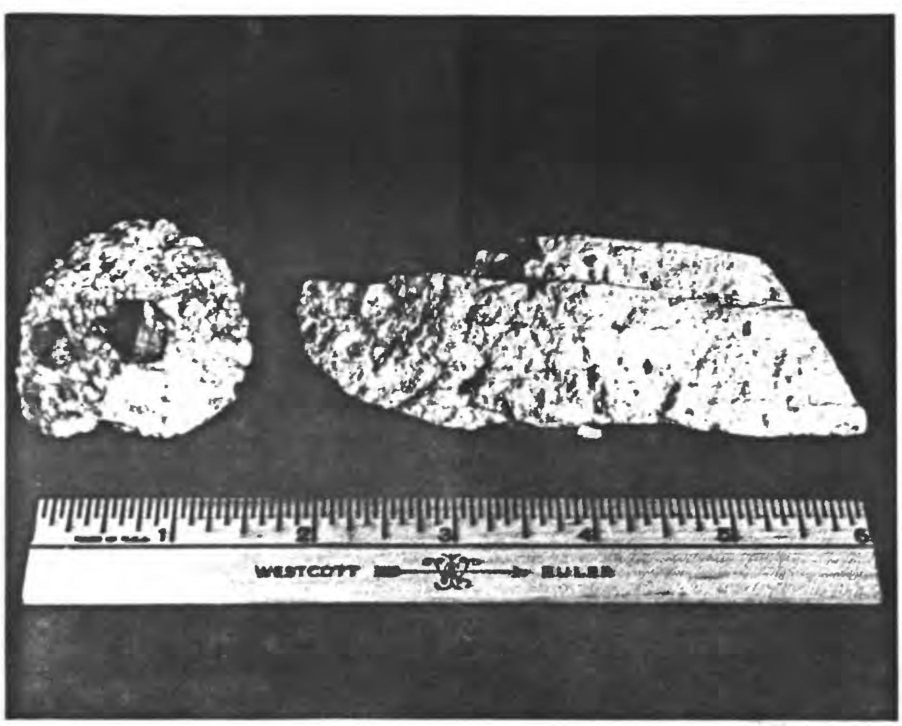
A. ALKALI GRANITE PORPHYRY OF JUDITH PEAK

Coarse grained facies of alkali granite porphyry. Dark spots are quartz phenocrysts. Picture taken along road on east side of Judith Peak.

B. ALKALI GRANITE PORPHYRY OF JUDITH PEAK

Specimen at left shows quartz phenocryst in coarse-grained facies. Specimen at right is sheared and silicified fine-grained alkali granite porphyry from 2,100 feet S. 55° W. of Judith Peak, near contact with quartz monzonite.

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crystals of quartz, sanidine, and albite (pls. 29, 30, A, and 31, B) strongly suggest that the magma was subject to some filter press action. In some of the associated granite porphyry dikes, similar phenocrysts are well separated in the groundmass (pl. 40, B). Further evidence of filter pressing is found in the presence of bent and ruptured crystals of sanidine and quartz. The fractures are filled with albite or quartz or both, which appear to have been forced into the openings (pls. 30, B, and 31, A).

Quartz.--The quartz phenocrysts are doubly terminated with equally developed positive and negative rhombohedrons, and except for a short prism zone, commonly less than one-fourth the length of the crystal, are identical in habit with bi-pyramidal quartz so common in many rhyolites. The crystals are unique because of their size, and in the coarse-grained facies they attain a maxiumum length along the *c* axis of approximately 3 centimeters. The quartz is glassy on freshly broken surfaces, but crystal faces are finely frosted and lack the high luster typical of quartz. Most crystals are dark gray in color; some are milky, but this is due to fracturing and disruption of the crystal. In thin section such crystalsshow irregular granulated edges with interiors of diversely oriented quartz joined along sutured boundaries.

At several places along the road that traverses the east side of Judith Peak the quartz crystals weather out of the granite and may be

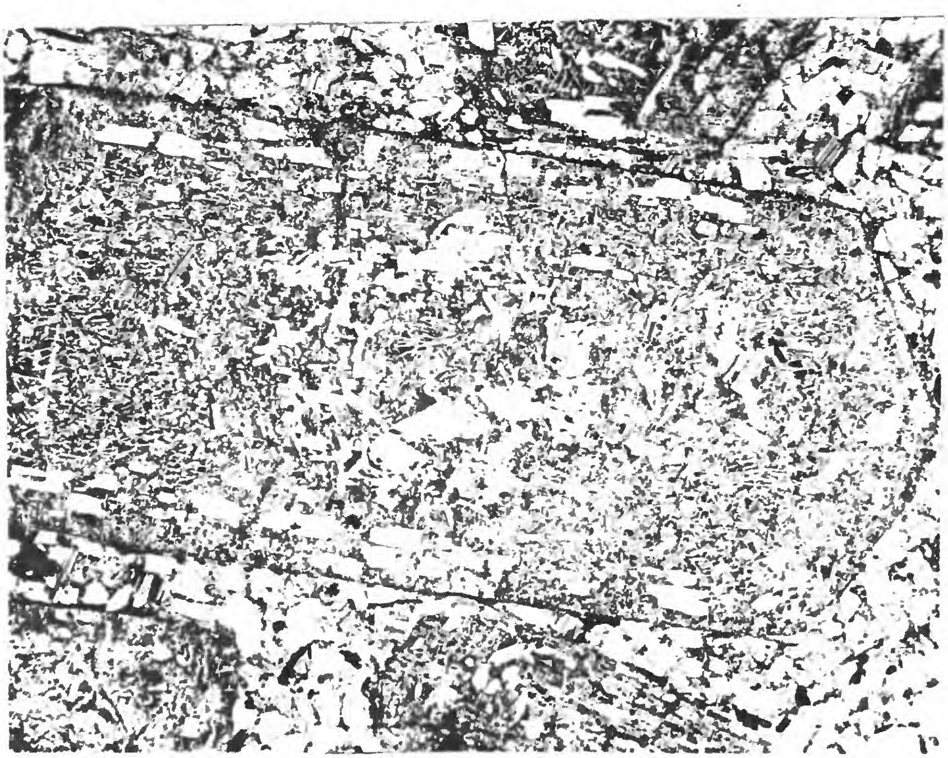
Plate 29

A. PHOTOMICROGRAPH OF COARSE-GRAINED ALKALI GRANITE PORPHYRY FROM EAST SLOPE OF JUDITH PEAK

Large white crystal is quartz phenocryst. Zoned appearance of some crystals in hand specimen is due to oriented inclusions of albite and groundmass material (largely torn out of slide). Small light clear areas are other quartz crystals. Dark crystals are sanidine with inclusions of albite. Note small laths of exsolution albite in central part of sanidine crystal at bottom right center. Groundmass is albite micro-phenocrysts with quartz, aegirine and alkali feldspar. Crossed nicols. X 7.

B. PHOTOMICROGRAPH OF SAME SPECIMEN AS A

Sanidine phenocrysts with oriented and zonally arranged albite inclusions. Irregular light patches in central part of crystal are replacement quartz. Note absence of exsolution albite laths in peripheral part of crystal. The same thing shows in sanidine crystal at top right center. Note the close packing of the albite micro-phenocrysts in the groundmass. Crossed nicols. X 16.



A. PHOTOMICROGRAPH OF COARSE-GRAINED ALKALI GRANITE PORPHYRY FROM SOUTHEAST SLOPE OF JUDITH PEAK

Dark area at left is crystal of sanidine. Note the rectangular albite inclusion half in and half out of sanidine along right edge of crystal. Exsolution albite laths are confined to central part of sanidine phenocryst. Crossed nicols. X 97.

B. PHOTOMICROGRAPH OF COARSE-GRAINED ALKALI GRANITE PORPHYRY FROM NORTHEAST SLOPE OF JUDITH PEAK

Bent and broken sanidine phenocryst. Dark color of sanidine is due to allophane. Fractures are filled with quartz. Dark needles in groundmass are aegirine. Specimen from near the Bolivia tunnel. Plane-polarized light. X 31.

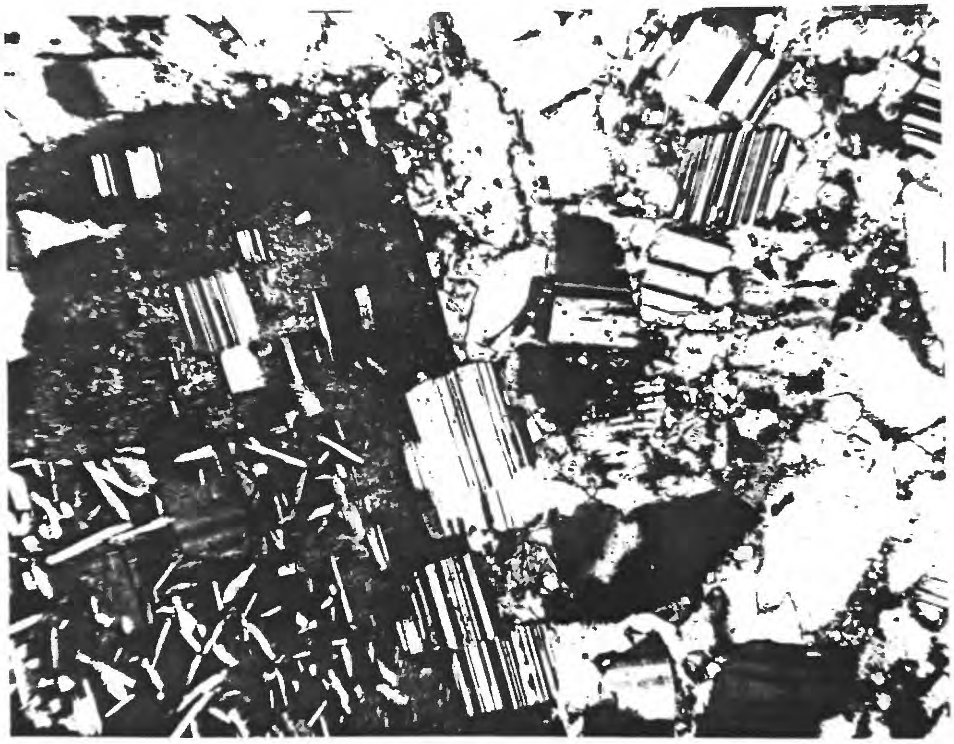


Plate 31

A. PHOTOMICROGRAPH OF COARSE-GRAINED ALKALI GRANITE PORPHYRY FROM SOUTHEAST SLOPE OF JUDITH PEAK

Fracture in quartz phenocryst filled with rectangular albite grains identical to those found in the groundmass. Crossed nicols. X 24.

B. PHOTOMICROGRAPH OF SAME SPECIMEN AS A

Fracture in sanidine phenocryst filled with quartz. Light clear areas in groundmass are albite. Note small amount of interstitial material - quartz, aegirine, and alkali feldspar. Plane-polarized light. X 53.

picked up in quantity. A number show small reentrants between prism faces and between positive and negative rhombohedrons, indicating penetration twins - with the twinning axis parallel with c. One specimen shows two divergent apicies at one end, and a single termination at the other, with a composition plane parallel with the third order rhombohedron.

A number of broken crystals show a parting parallel with one or more of the prism faces; one or two crystals show a preferred parting direction parallel with one of the rhombohedral faces.

Etch figures or growth figures were found on a number of these crystals. Many show corrosion, especially at the terminations, and the symmetrical markings on the faces are probably the result of differential solution along certain directions. These markings and various other features of the quartz phenocrysts are shown on plate 32, A.

Some crystals show zoning, visible even in the hand specimen. In thin section, the major zonal structures are seen to be elongate inclusions of fine groundmass material, aligned parallel with crystal faces (pl. 29, A). In some of the phenocrysts, groups of albite crystals show similar orientation. Under high power, other oriented and zonally arranged inclusions are evident. "Bubble trains" of tiny negative crystals are common, and some crystals contain minute needles of an unknown mineral concentrated in zones parallel with crystal faces. Each zone consists of a cross hatch of needles with individual needles oriented parallel with the a axes of the crystal.

Plate 32

A. QUARTZ PHENOCRYSTS FROM ALKALI GRANITE PORPHYRY

Far left - rounded edges and apices indicate corrosion. Lines (striations) on faces are probably etch figures, but may be growth figures.

Middle left - crystal flattened along one of the a axes.

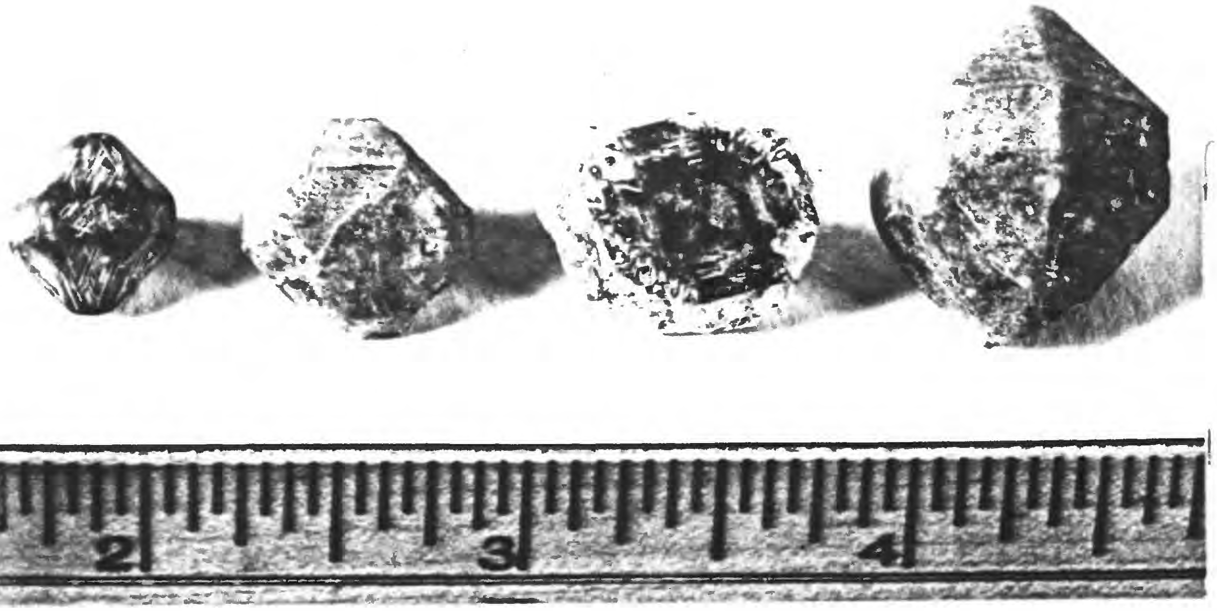
Middle right - exposed surface is "cleavage" plane parallel with c. Note zoning.

Far right - this crystal, with broken terminations, measures 2.7 centimeters along c.

Crystals gathered from road along east side of Judith Peak.

B. PHOTOMICROGRAPH OF FINE-GRAINED ALKALI GRANITE PORPHYRY FROM NORTHEAST SLOPE OF JUDITH PEAK

Slightly crushed fine-grained alkali granite porphyry. Dark needles which wrap around sanidine phenocrysts (light gray) are aegirine. Light areas are rectangular albite grains and replacement quartz. Plane-polarized light. X 31.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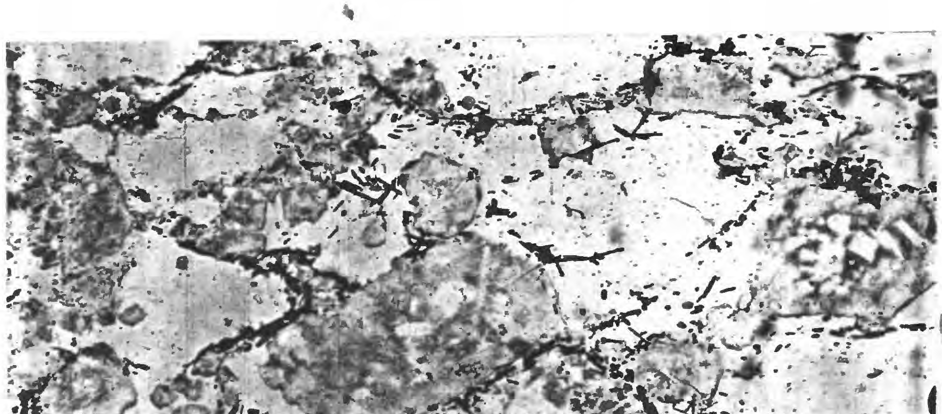


Feldspar.--The sanidine phenocrysts are tabular, elongated parallel with a and flattened parallel with (010). They are similar in habit and optical properties to many of those seen in the tinguaites. With the hand lens, many of the sanidine crystals from the alkali granite show curved or bent crystal faces. This distortion may be due to the abundance of included material.

In thin section, the sanidine phenocrysts are seen to be crowded with inclusions of rectangular to elliptical albite which tend to be oriented parallel with the crystal faces of the host, and in some crystals are zonally arranged (pls. 29 and 30, A). A few phenocrysts contain irregular clots of albite crystals in the core. The albite is identical to that in the groundmass, and in some sections crystals are observed one half within the sanidine, the remainder projecting into the groundmass (pl. 30, A).

Albite is also present as fine elongate laths from 0.1 to 0.4 millimeters in length, which occur within the central parts of the sanidine phenocrysts. The larger laths show fine polysynthetic twinning, and extinction angles and the mean index indicate a composition close to pure albite, thus approximately the same as that of the rectangular inclusions, $Ab_{97}$. The laths are not present in the groundmass as are the albite inclusions. The genetic significance of the two types of albite is discussed on page 153.

Aegirine.--The aegirine is associated with the late quartz, which constitutes the bulk of the micro-groundmass (pls. 30, B and 31, B).

Some specimens show small crystals and clusters of needles embedded in sanidine, but again, these are usually associated with quartz, which replaces the sanidine (pl. 33, A). In a few sections the aegirine needles wrap around the sanidine phénocrysts (pl. 32, B). Some specimens contain a few scattered stubby prisms of aegirine as much as 5 millimeters long. In thin section these have a poikilitic-like structure and commonly show ragged edges. Disconnected segments have identical extinction positions.

The textural relations described above indicate that the formation of the aegirine began late in the orthomagmatic stage and extended into the deuteric stage.

## Petrography of the Fine-Grained Facies

Mineralogically, the fine-grained facies resembles the coarse-grained facies. Primary textures are similar, but have been modified in the fine-grained facies by mild cataclastic deformation. As is common, quartz is one of the first minerals to yield. The phenocrysts are deformed and broken into diversely oriented segments joined along sutured boundaries. Undulatory extinction is not pronounced, but most sections normal to c show biaxial figures. In more severely deformed specimens the phenocrysts are strung out into spindle shaped mosaics of granulated quartz (pl. 33, B).

The sanidine phenocrysts show granulation along shear fractures. Many have ragged boundaries, and some are broken into two or more

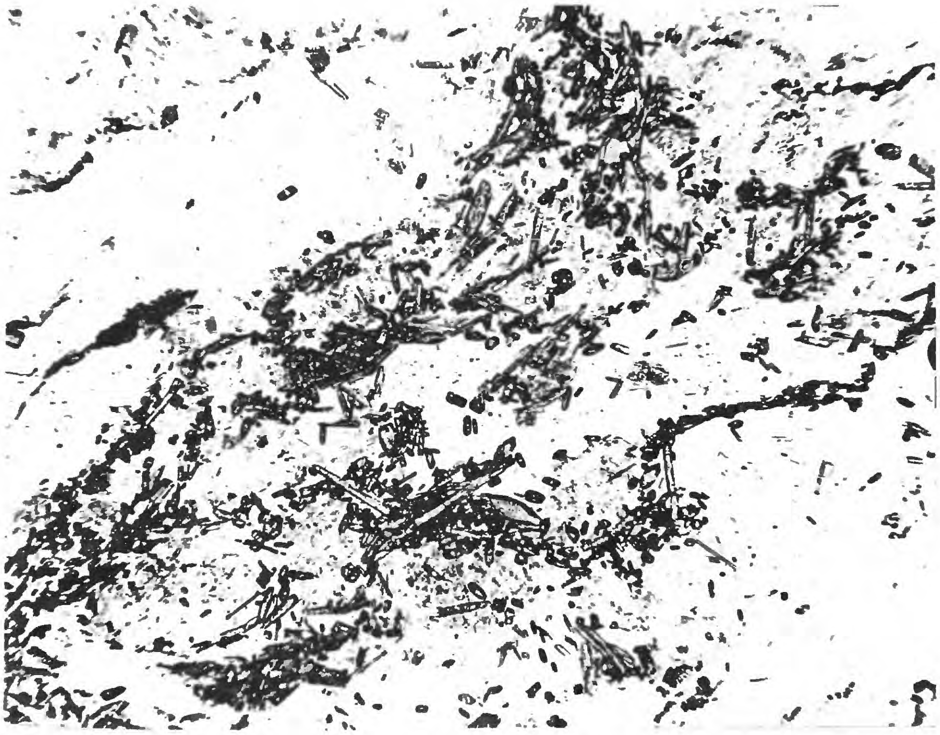
Plate 33

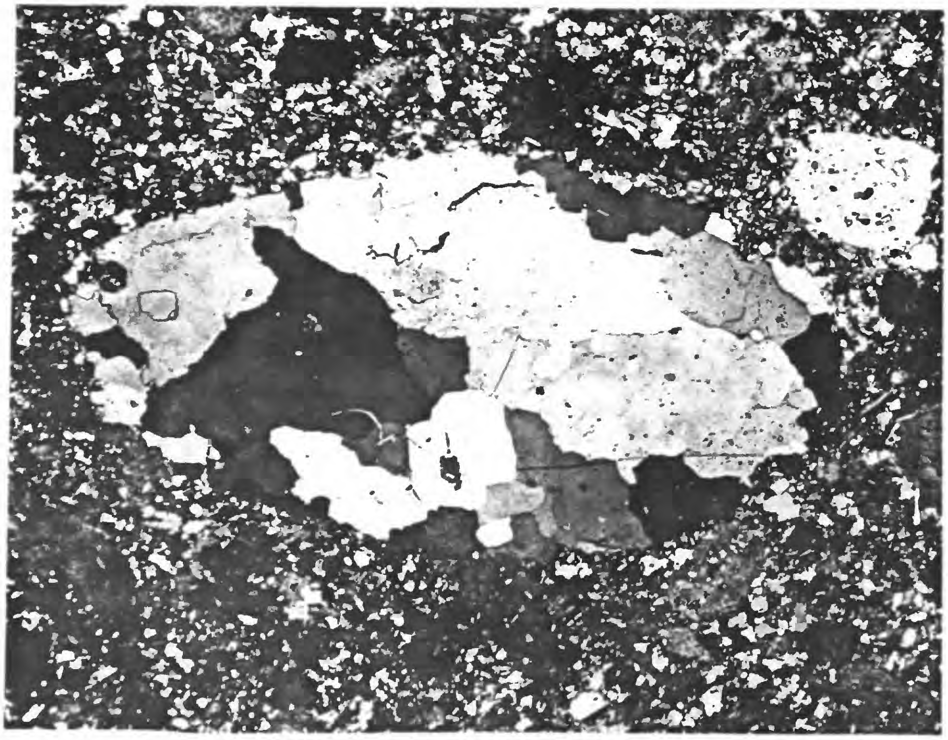
A. PHOTOMICROGRAPH OF CRUSHED AND SILICIFIED FINE-GRAINED ALKALI GRANITE PORPHYRY FROM NORTHEAST SLOPE OF JUDITH PEAK

Light gray areas are sanidine with allophane alteration. Dark crystals replacing sanidine are aegirine. Light clear areas are albite grains and replacement quartz. Plane-polarized light. X 57.

B. PHOTOMICROGRAPH OF SHEARED AND SILICIFIED FINE-GRAINED ALKALI GRANITE PORPHYRY FROM SOUTHWEST SLOPE OF JUDITH PEAK

Quartz mosaic in center is crushed and drawn out phenocryst. Remainder of slide is sanidine, albite and interstitial quartz. Specimen from 2,400 feet S. 57° W. of Judith Peak. Crossed nicols. X 16.





separated fragments. Cracks and voids in crystals thus broken are commonly filled with quartz, or small crystals of albite or both (pl. 34). The albite crystals are little disrupted probably because of their small size; a few show bent or displaced twinning lamellae.

Much of the fine-grained facies is highly fractured and cut by numerous veinlets and stringers of quartz. This is especially true of rocks in the peripheral areas (pl. 36, A). The adjacent monzonitic rocks show similar features (pl. 35).

The relative ages of the fine- and coarse-grained facies and the textures described above suggest that the coarse-grained facies was forcibly injected into the fine-grained facies at the stage just prior to the complete solidification of the fine-grained facies. The chilled peripheral parts of the fine-grained alkali granite and the adjacent monzonitic rocks fractured. These fractures were filled with silica-rich interstitial material squeezed out of the coarse-grained facies and the incompletely solidified parts of the fine-grained facies by filter press action. Filter pressing left the coarse-grained alkali granite as a crystalline mush and resulted in some bent and broken crystals. In the adjacent portions of the fine-grained alkali granite these effects were more pronounced, producing the cataclastic textures.

## Petrography of the Alkali Granite Porphyry Dikes

The alkali granite porphyry dikes vary greatly in appearance, both megascopic and microscopic, but all have certain mineralogical

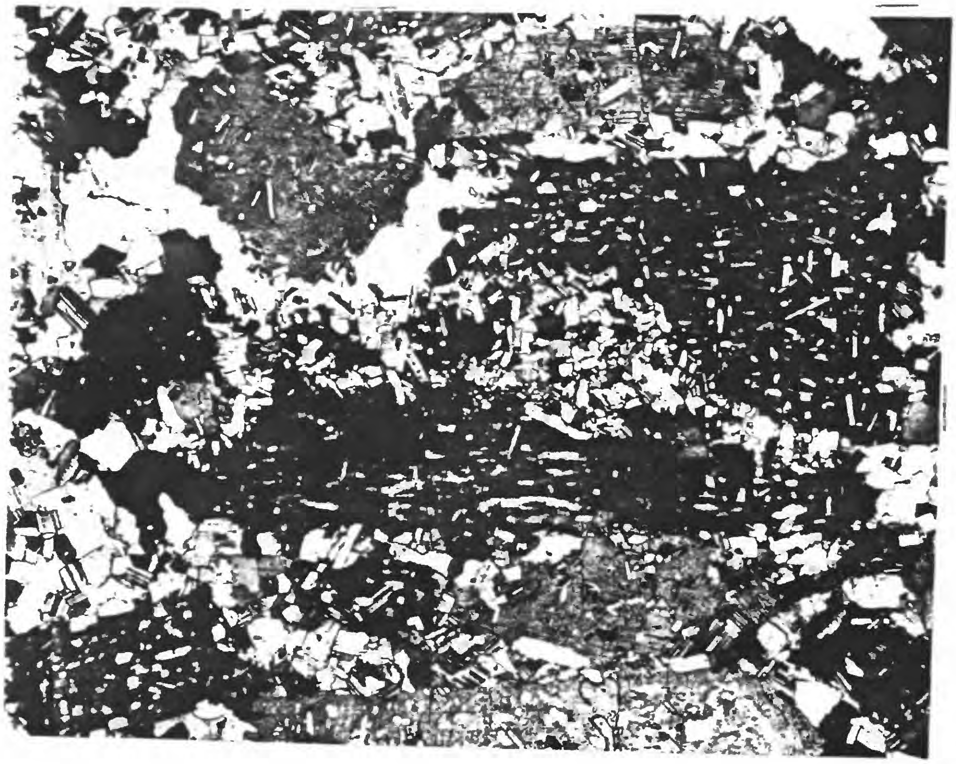
Plate 34

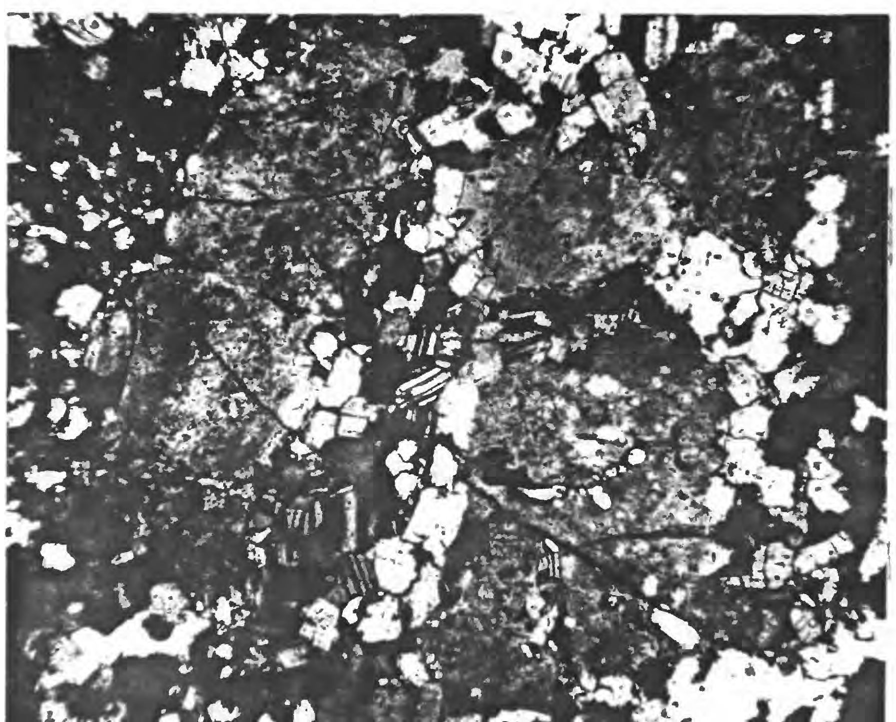
A. PHOTOMICROGRAPH OF CRUSHED, FINE-GRAINED ALKALI GRANITE FROM SUMMIT OF JUDITH PEAK

Large dark-gray areas in center are parts of a single sanidine crystal which has been broken into separate segments. Opening between segments is packed with small albite grains identical with those which occur as micro-phenocrysts in groundmass. Minor amounts of quartz fill interstices between albite grains. Irregular band of light clear material at upper left center is quartz. Crossed nicols. X 31.

B. PHOTOMICROGRAPH OF SHEARED AND SILICIFIED FINE-GRAINED ALKALI GRANITE FROM EAST SIDE OF JUDITH PEAK

Cloudy, medium-gray areas are separate segments of disrupted sanidine crystal with allophane alteration. Breaks between segments filled with small albite crystals. Specimen from 2,300 feet S. 80° E. of Judith Peak. Crossed nicols. X 60.



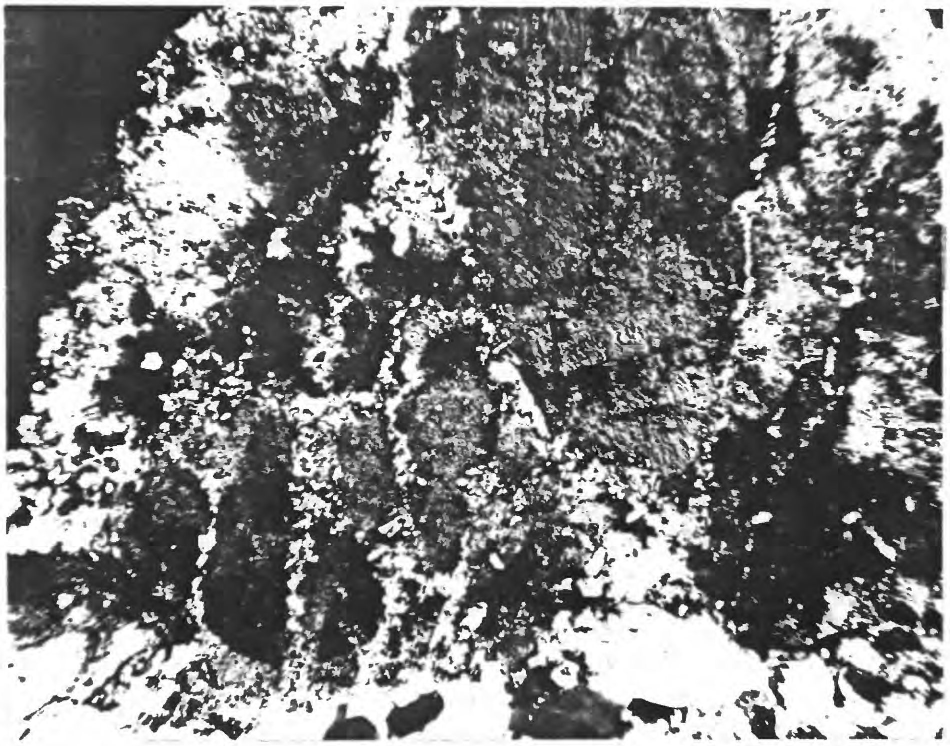


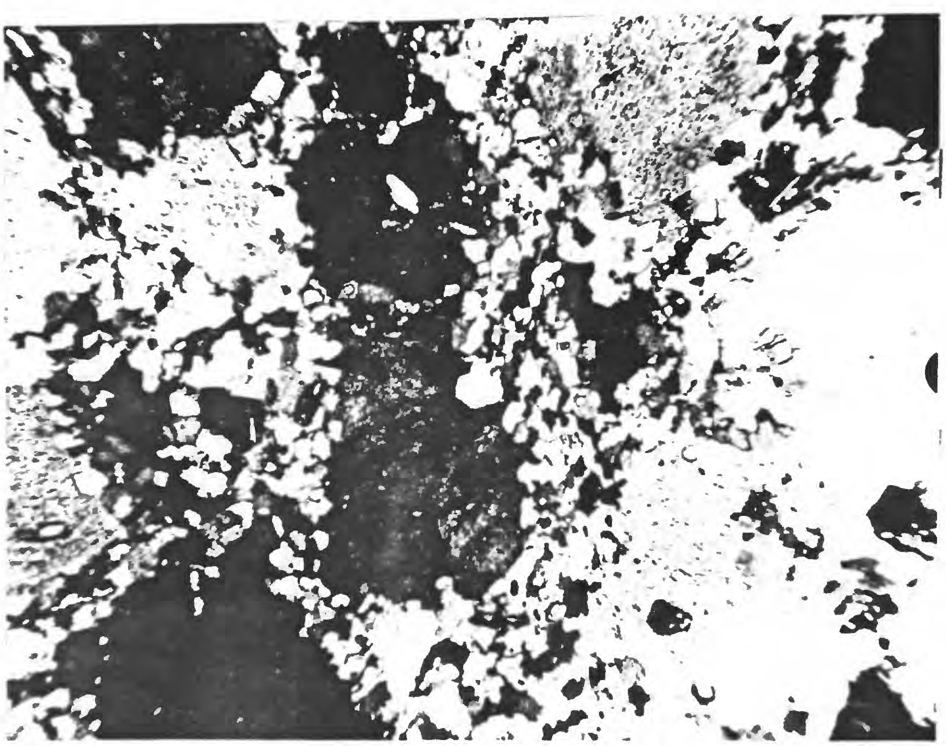
A. PHOTOMICROGRAPH OF SHEARED AND SILICIFIED QUARTZ MONZONITE PORPHYRY FROM CONTACT ZONE BORDERING FINE-GRAINED ALKALI GRANITE ON EAST SIDE OF JUDITH PEAK

Dark-gray areas are segments of a single sanidine crystal. Fine irregular bands with light-colored mosaic texture are granulated sanidine along shear fractures in the broken crystal. Light area along bottom of slide is quartz. Specimen from 3,000 feet S. 80° E. of summit of Judith Peak. Crossed nicols. X 53.

B. PHOTOMICROGRAPH OF SAME SPECIMEN AS A

Large areas (various shades of gray) with uniform extinction are fragments of sanidine phenocrysts. Fine-grained mosaic material is granulated sanidine with minor amounts of quartz. Crossed nicols. X 56.





and textural features which relate them definitely to the parent intrusives occurring on Judith Peak. All those examined contain both euhedral quartz crystals and sanidine phenocrysts with albite inclusions.

The principal differences are grain size, and the relative amounts of groundmass and phenocrysts. All dikes belong to the same general period of irruptive activity and all were injected to approximately the same levels within the crust. Differences in texture are accounted for by two conditions, present singly, or in combination: (1) Withdrawal of dike magma from the parent magma chamber at slightly different stages of crystallization of the parent magma. (2) Filter press action, both at the source and within the dikes following their emplacement.

Three textural types will be discussed and for convenience these will be called types A, B, and C. Photomicrographs of the three types are shown respectively on plates 36, B, 37, and 38, A.

Type A.--contains small phenocrysts of quartz and sanidine with albite inclusions, and micro-phenocrysts of albite. These are set in an aphanitic groundmass of quartz, alkali feldspar and aegirine. The groundmass constitutes an estimated 30 to 40 percent of the rock, and the composition of the rock is believed to approximate that of the magma from which it crystallized. In contrast, types B and C probably did not crystallize from liquids of their own composition.

Plate 36

A. PHOTOMICROGRAPH OF SHEARED AND SILICIFIED FINE-GRAINED ALKALI GRANITE FROM SOUTHEAST SIDE OF JUDITH PEAK

Large dark areas are sanidine phenocrysts cut by quartz stringers (bands with mosaic texture). Specimen from S. 29° E. of summit of Judith Peak. Crossed nicols. X 53.

B. PHOTOMICROGRAPH OF ALKALI GRANITE PORPHYRY DIKE (TYPE A) FROM SOUTHEAST SLOPE OF JUDITH PEAK

Large white crystal at lower right is quartz. Other phenocrysts are sanidine with albite inclusions. Groundmass contains micro-phenocrysts of albite set in fine aggregate of quartz, alkali feldspar and aegirine. Specimen from 1,300 feet N. 50° W. of Tail Holt mine. Crossed nicols. X 21.

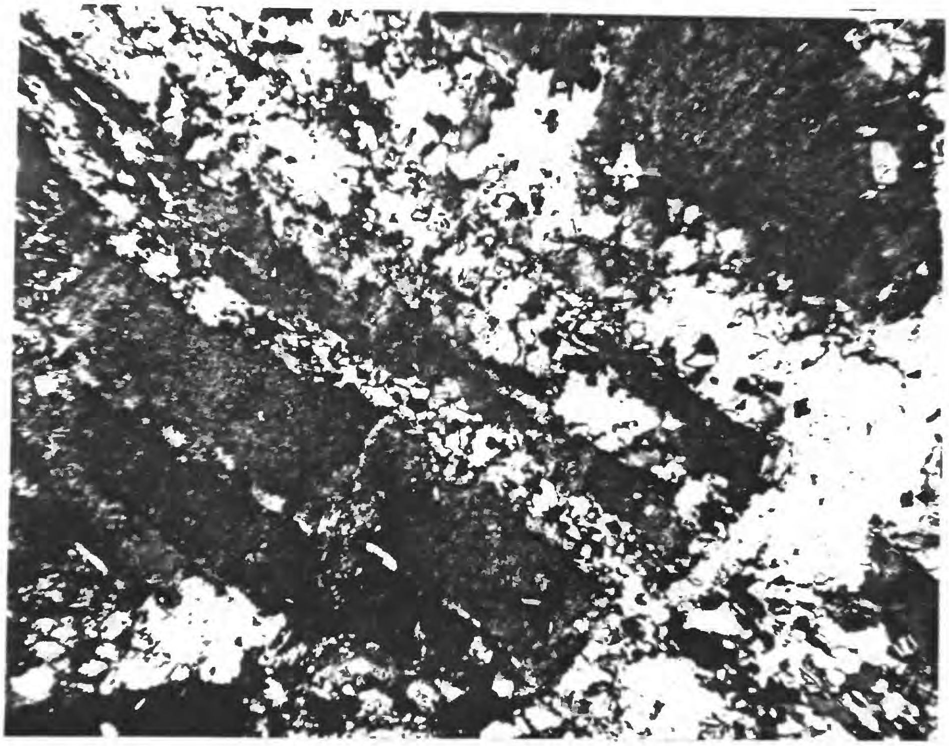


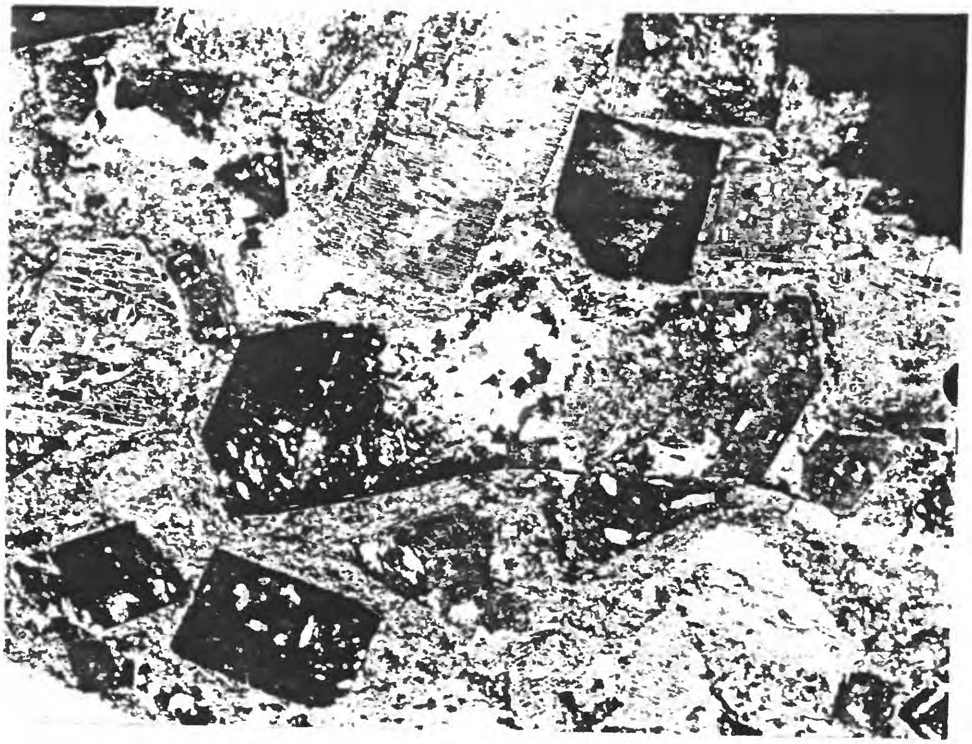
Plate 37

A. PHOTOMICROGRAPH OF ALKALI GRANITE PORPHYRY DIKE (TYPE B) FROM COLLAR GULCH

Phenocrysts are sanidine with allophane alteration. Albite crystals occur as inclusions in sanidine and in quartz phenocrysts (not shown) but are very rare in groundmass. Groundmass is quartz, alkali feldspar, and aegirine. Note abundance of phenocrysts and relatively small amount of groundmass material. Specimen from bottom of Collar Gulch east of Judith Peak. Crossed nicols. X 14.

B. SAME AS A BUT IN PLANE-POLARIZED LIGHT

Light area in center of large bent sanidine crystal is quartz (white) and albite (light gray). Note that flow lines in groundmass, (shown by aegirine) do not point into the break in the sanidine crystal. Plane-polarized light. X 14.

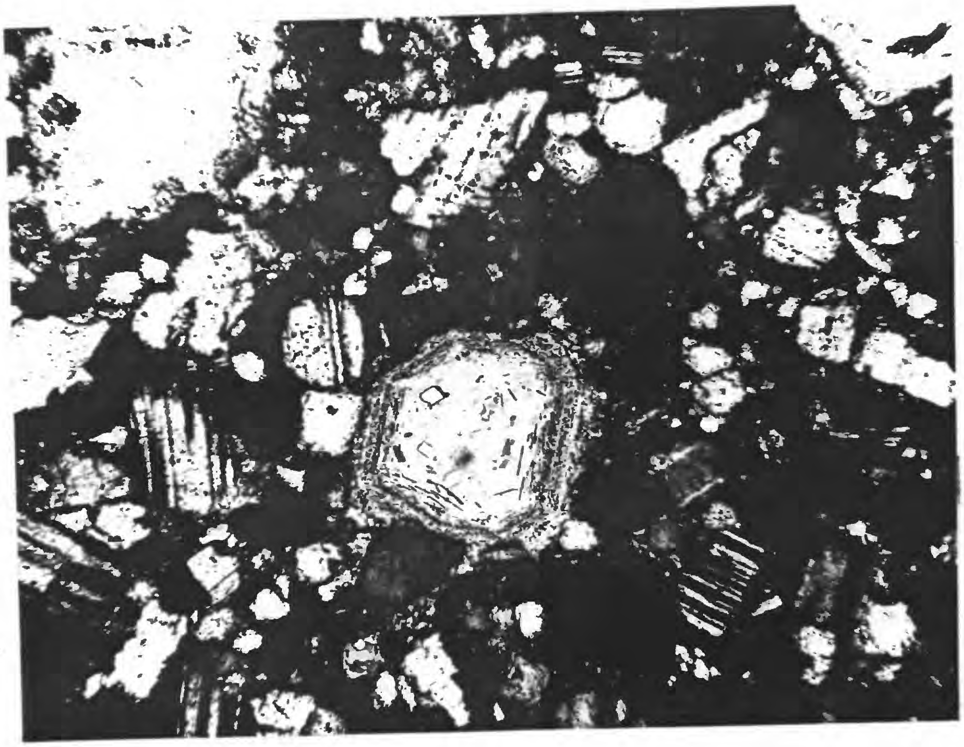


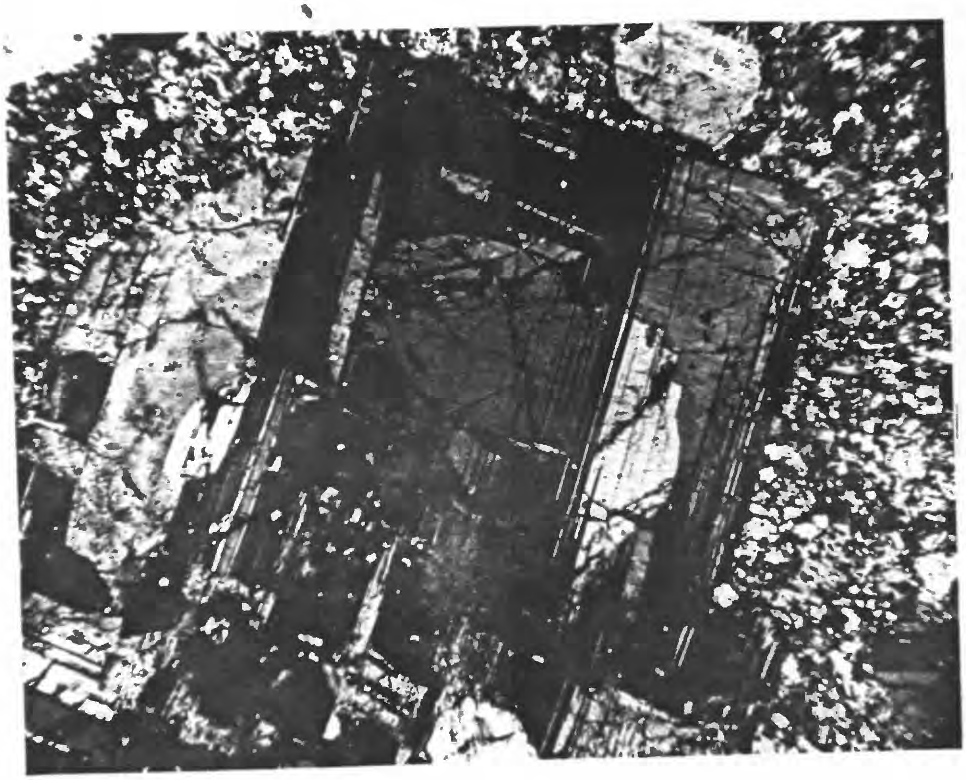
A. PHOTOMICROGRAPH OF ALKALI GRANITE PORPHYRY DIKE (TYPE C) FROM RED MOUNTAIN

Light-gray crystal in center is quartz with inclusions of aegirine (dark needles crowded around periphery) and albite (small light spots in interior). Albite also present as small phenocrysts (twinned crystals). Small equant light spots are tiny quartz crystals, smaller but otherwise similar to crystal in center. Crystal form tends to be obscured by parallel overgrowths, but form is shown by oriented inclusions of aegirine. Note especially, circular white spot in upper right center (small quartz crystal with oriented inclusions of aegirine and parallel overgrowth of quartz). Large white area at upper left is quartz with unoriented aegirine needles. Specimen from saddle between east and west peaks of Red Mountain. Crossed nicols. X 88.

B. PHOTOMICROGRAPH OF QUARTZ MONZONITE PORPHYRY FROM WEST SIDE OF PORPHYRY PEAK

Zoned plagioclase. Irregular core is $Ab_{52}$. Outer shell is $Ab_{81}$. Specimen from coarse-grained facies 5,400 feet N. 7° W. of summit of Porphyry Peak. Crossed nicols. X 50.





Type B, --as compared with both type A and type C, is relatively rich in potash and poor in soda. It consists of closely packed crystals of sanidine with albite inclusions, set in a fine groundmass of quartz, alkali feldspar and aegirine, but it contains very few albite micro-phenocrysts.

Filter press action on the dike is suggested by the small amount of groundmass and by the scarcity of the albite micro-phenocrysts in the groundmass. They are present in the sanidine phenocrysts and presumably were present in the magma from which the sanidine crystals were separating. Removal of most of these small crystals with the supporting liquid during filter pressing seems to be the best explanation to account for their scarcity. Some of the sanidine phenocrysts are broken, and the breaks filled with groundmass.

An earlier period of crystal deformation (type B) is evidenced by the large "horizontal" phenocryst in the center of plates 37, A and B. It is bent down along the bottom with a corresponding break along the upper edge which has been filled, in part by replacement, with quartz and albite. The flow lines, shown by clots of aegirine needles do not point toward the filled break. Clearly, the crystal was broken and healed prior to its inclusion in the dike.

Type C, --is relatively rich in silica and poor in potash. Sanidine phenocrysts are smaller and much less abundant than in type A; volumetrically, they probably do not represent more than 30 percent of the sanidine phenocrysts in an equivalent sized specimen of type B. The groundmass consists of albite, quartz, aegirine, and alkali feldspar.

In addition to the sanidine phenocrysts, Type C contains small crystals of quartz, commonly less than 1 millimeter in size. Under the microscope in plane-polarized light, these appear as euhedral crystals whose form is outlined by countless tiny needles of aegirine concentrated along the crystal margins and oriented parallel with the crystal faces. With crossed nicols, the perfection of form is less apparent. The crystals are mantled by irregular overgrowths of optically parallel quartz which fill the contiguous interstices.. The shape of the optically continuous masses of quartz is thus quite erratic, but the grouping of the aegirine inclusions demonstrates the euhedral form of the original quartz crystals.

The groundmass contains numerous tiny crystals of quartz, as small as 0.04 millimeters, which are identical in every respect, except for size, to those described above (pl. 38, A). These and minor amounts of anhedral alkali feldspar are packed between the sanidine phenocrysts, the larger crystals of quartz and the subhedral albite crystals.

Fine-grained quartz is a universal constituent of the groundmass of non-glassy extrusive and hypbyssal salic rocks. But its occurrence in euhedral crystals as the major constituent of such a groundmass is unique in the writer's knowledge. The writer can offer no entirely satisfactory explanation, but one sequence of events which might account for the peculiar texture is presented below.

The dike magma (Type C) separated from the parent magma early in the crystallization of the parent magma. This is indicated by the relatively small size of the sanidine phenocrysts - 1 to 3 millimeters. The paucity of the sanidine phenocrysts compared with Type A, and the alkali granite porphyry of Judith Peak, suggests that this separation was accomplished by filter pressing. That is, all but a few of the sanidine phenocrysts were strained out of the dike magma. The relatively small albite crystals, and the quartz crystals, just starting to form, were carried along in the filtrate.

Following emplacement of the dike, the dike magma was subjected to a second period of filter pressing which extracted much of the fluid from the magma, and left a crystalline residue with minor amounts of interstitial fluid. The compressive forces responsible for this filter pressing were applied slowly enough to prevent flushing out the finer crystalline material with the liquid fraction.

This was followed by the final crystallization of the residuum. The silica contained in the interstitial fluid found numerous centers of crystallization available in the form of euhedral quartz crystals, on which to deposit as parallel overgrowths. Aegirine, found as a product of agpaitic crystallization in the alkali granite porphyry of Judith Peak, crystallized at this stage and thus is found concentrated around the peripheral parts of the quartz crystals. Inclusions of feldspar within the quartz, chiefly albite, are not concentrated near the margins (pl. 38, A). Scattered pockets of residual liquid crystallized as irregular patches of quartz containing aegirine needles set at random (pl. 38, A). The alkali feldspar in the rest solutions took up whatever space remained.

## Granitized Sedimentary Rocks

Within the area shown on the map (pl. 1) as fine-grained alkali granite porphyry are three separate localities where fragments of granitized sedimentary rocks are abundant. These rocks were first discovered late in the field season of 1951 during the course of a geochemical investigation of the area, and time did not permit more than a cursory examination of the occurrences. The significance of banded rock fragments was not recognized at the time Judith Peak was mapped, and it is possible that much of the area originally thought to be underlain by sheared and silicified fine-grained alkali granite contains appreciable amounts of granitized sediment.

The largest single inclusion is on a spur 2,000 feet S. 50° E. of the summit of Judith Peak and covers a surface area approximately 20 by 50 feet. This inclusion consists of highly altered beds of sandstone and shale of unknown age; structural and stratigraphic evidence indicates that these rocks may represent material from the Kootenai formation.

The appearance of the granitized sediments varies with the degree of transformation. Some rocks resemble granite gneiss, others show only scattered porphyroblasts of sanidine, and some are banded migmatic rocks. The porphyroblasts have grown partially by replacement and partially by spreading apart the enclosing rock layers (pls. 39, and 40, A). Even the migmatites show evidence of replacement rather than forceful injection of igneous material. The widest parts of many thin migmatite layers result from the spreading of the walls by growing crystals, and in thicker migmatite bands, the porphyroblasts along the margins have similarly pushed aside the confining rock layers. Under the microscope, replacement is further indicated by the presence of relict bedding within the migmatite bands.

Transformation of the sediments has proceeded by stages. The first stage was the introduction of potash feldspar, particularly to the more arenaceous layers. One specimen from the center of the inclusion was thought to represent an original sandstone fragment, but when examined microscopically, it proved to be almost entirely potash feldspar. In thin section, the rock shows a fine, somewhat directional mosaic of sutured potash feldspar grains with scattered porphyroblasts of sanidine as much as 3 millimeters across.

The second stage, represented by specimens collected nearer the margins of the inclusion, was the introduction of albite as small subhedral grains; in places these lie across the grain boundaries of

A. GRANITIZED SEDIMENTARY ROCKS FROM SOUTHEAST SIDE OF JUDITH PEAK

In upper specimen, "groundmass" is fine-grained aggregate of xenoblastic potash feldspar, small albite crystals, and aegirine-augite (concentrated in dark layers) and minor quartz. Note how the sanidine porphyoblasts (light spots) have spread the bedding (see pl. 40, A). Small reverse fault which dips to right on face of specimen is filled with quartz.

Lower specimen is similar to above, but with band of migmatite (see B).

Both specimens from inclusion in fine-grained alkali granite, 2,000 feet S. 50° E. of summit of Judith Peak.

B. PHOTOMICROGRAPH OF LOWER SPECIMEN SHOWN IN A

Section is cut from right end of lower specimen in A. Upper half is fine mosaic of sutured potash feldspar grains with albite crystals and bands of aegirine-augite. Quartz is rare except for veinlet (light colored) which cuts diagonally across relict bedding at right edge. Bottom half shows migmatite layer with potash feldspar porphyroblasts set in "groundmass" of fine potash feldspar, albite, quartz, and aegirine-augite. Crossed nicols. X 9.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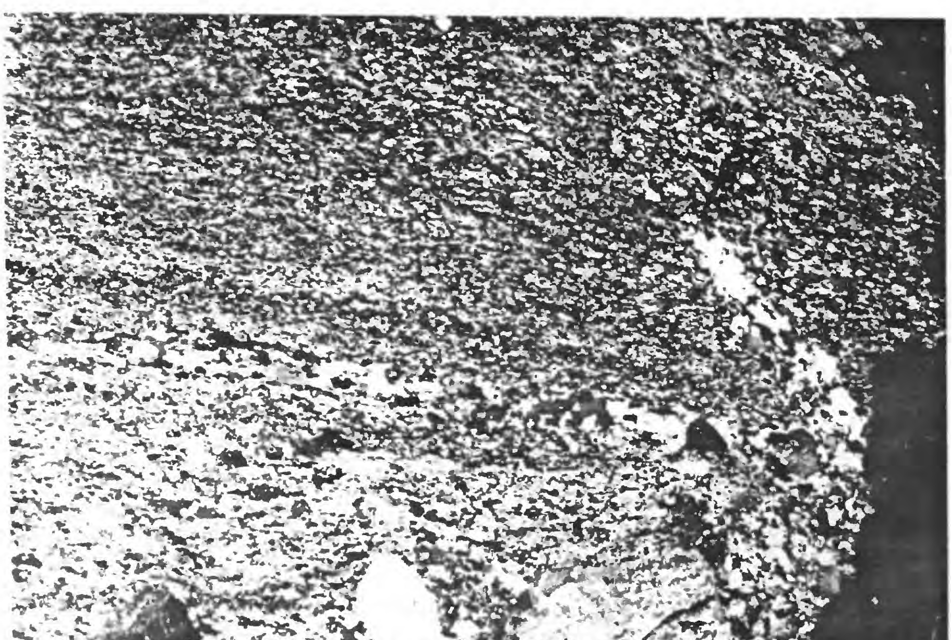


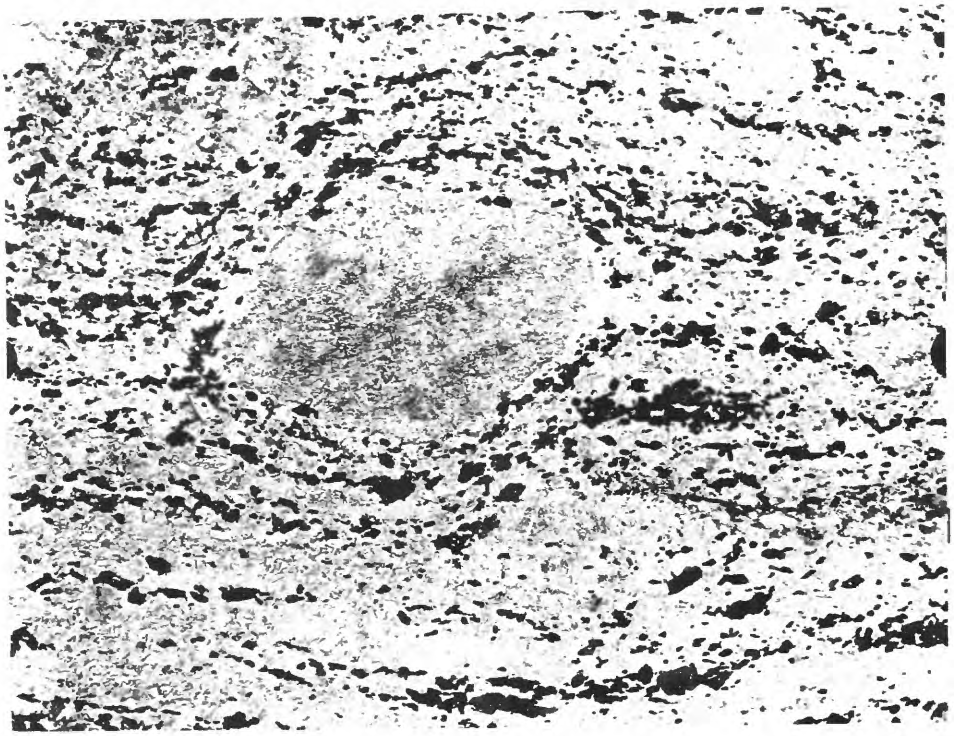
PLATE 40

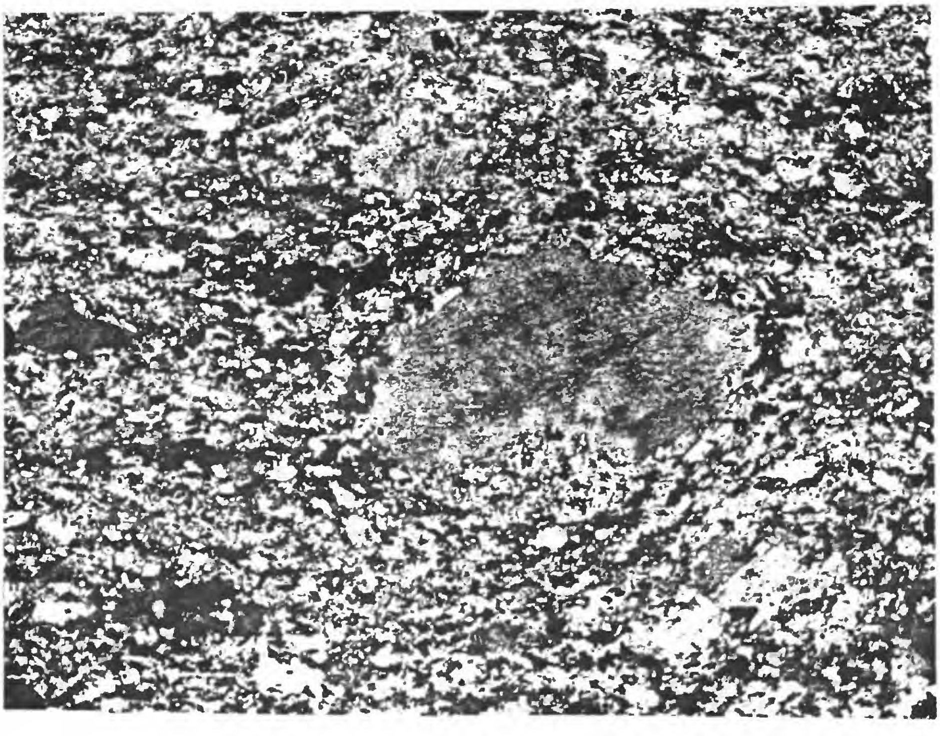
A. PHOTOMICROGRAPH OF GRANITIZED SEDIMENTARY ROCK OF PLATE 39 A.

Large crystal in center is potash feldspar which has spread bedding, shown by dark bands of aegirine-augite. "Ground-mass" is mixture of potash feldspar, albite, and quartz. Section is cut from upper specimen in plate 39, A. Plane-polarized light. X 23.

B. SAME AS A, BUT WITH CROSSED NICOLS

Note how upper part of potash feldspar porphyroblast has been replaced by aggregate of albite and quartz. Crossed nicols. X 23.





of the potash feldspar (pl. 41, A). In the shaly layers, the introduction of soda resulted in the formation of extremely fine grained aegirine-augite (pl. 40, A). In the hand specimen, this mineral gives the original bedding surfaces a dark-green color. Some of this material was separated with heavy liquid, and the optical identification verified by x-ray by Alfred Levinson, research assistant of the University of Michigan.

The third and final stage was the introduction of quartz which in part replaces the potash feldspar, but not the albite (pls. 40 and 42). This stage is best shown by sandstone fragments which were not strongly attacked by the potash- and soda-bearing solutions. Such specimens contain only scattered sanidine porphyroblasts and a few widely separated bands of feldspathic material, and the permeable sandstone was readily transformed to an orthoquartzite by silica bearing solutions (pl. 41, B).

The silica apparently traveled further than the alkalies, and south of Judith Peak, near the alkali granite-sedimentary rock contact, is a belt, approximately 400 yards long, of exceptionally hard orthoquartzite with no megascopic feldspar. This material is thought to be silicified Cat Creek sandstone at the base of the Colorado shale.

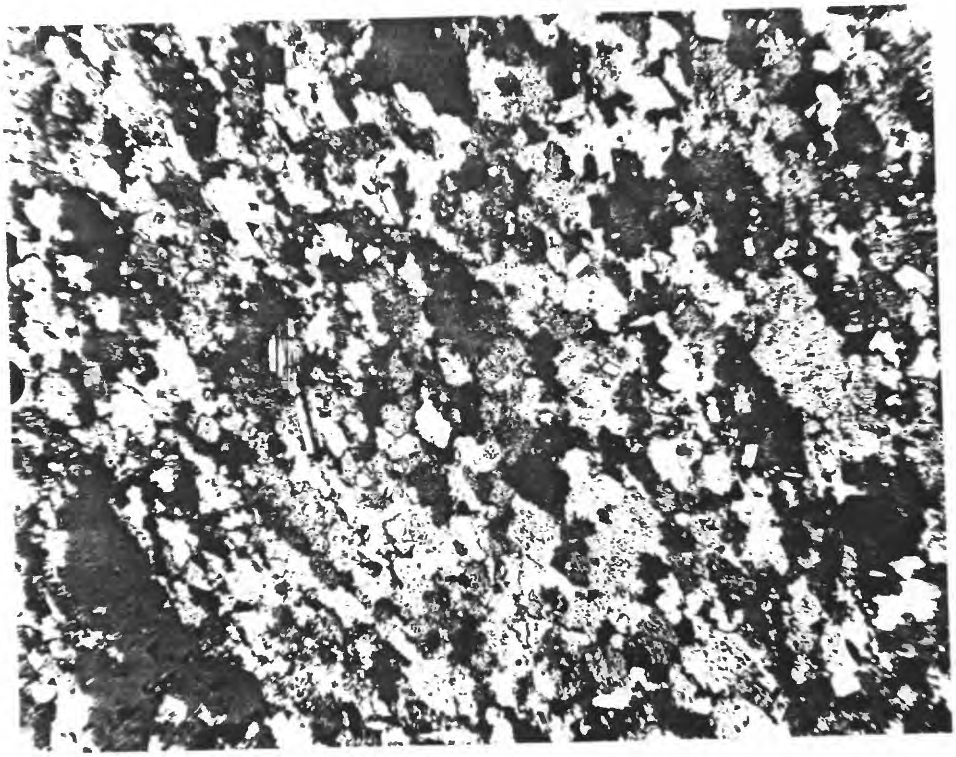
A large part of the quartz in the silicified and granitized sediments was probably introduced during the period when late siliceous juices were being extracted from parts of the alkali granite by filter pressing. Some sections of granitized rock show evidence of deformation.

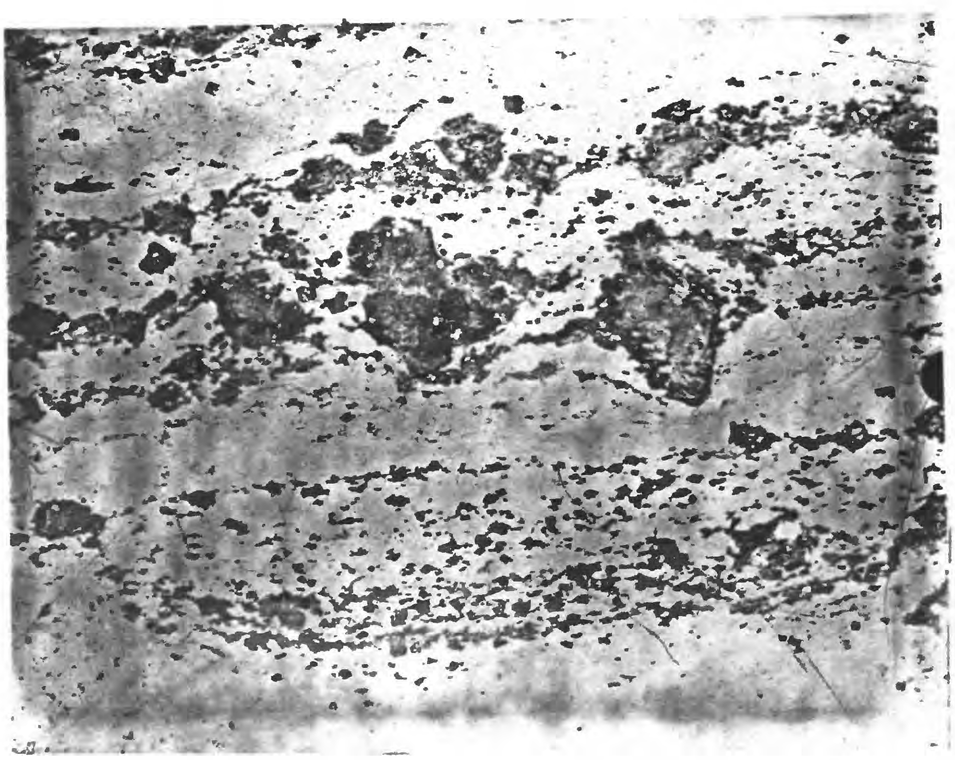
A. PHOTOMICROGRAPH OF GRANITIZED SEDIMENTARY ROCK OF PLATE 39, B

Enlarged view of area in upper part of plate 39, B, showing fine mosaic of potash feldspar. Albite (twinned, and clear rectangular areas) lies across the grain boundaries of potash feldspar, cloudy with allophane. Thus albite is later than potash feldspar. Note absence of quartz. Crossed nicols. X 57.

B. PHOTOMICROGRAPH OF GRANITIZED SEDIMENTARY ROCK FROM SOUTHEAST SIDE OF JUDITH PEAK

Gray is metasomatic potash feldspar partly replaced by later quartz (light). Several relict porphyroblasts show in center. Small dark spots are aegirine-augite. Plane polarized light. X 7. Thin section is of fragment collected 2,500 feet S. 40° E. of summit of Judith Peak.





Granulation of potash feldspar preceded introduction of and replacement by quartz (pl. 42). This agrees with the sequence suggested in the filter press origin of the silica.

The three stages described above are not sharply separated, but are overlapping, especially the albite - aegirine-augite and the quartz stages.

## Intrusion Breccia

### Distribution and Age Relationships

Major bodies of intrusion breccia are found in the Burnette Peak stock, the Alpine Gulch stock, and in the Judith Peak-Red Mountain area. Minor bodies occur as satellitic intrusions to the larger bodies, and as small irregular dikes and plugs scattered throughout the mountains. A single sill of intrusion breccia approximately 3 feet thick and 200 feet long is associated with several small plugs and dikes that cut the Colorado shale in Ross Pass.

Genetically, the intrusion breccias may be divided into three principal types: (1) Those associated with the rhyolites (2) Those associated with the quartz-free alkaline rocks found on Red Mountain (3) Those related to the alkali granite porphyry of Judith Peak. Some intrusion breccia may be related to the monzonites, but no breccia in which the cementing material and related primary phenocrysts are of monzonitic composition has been identified.

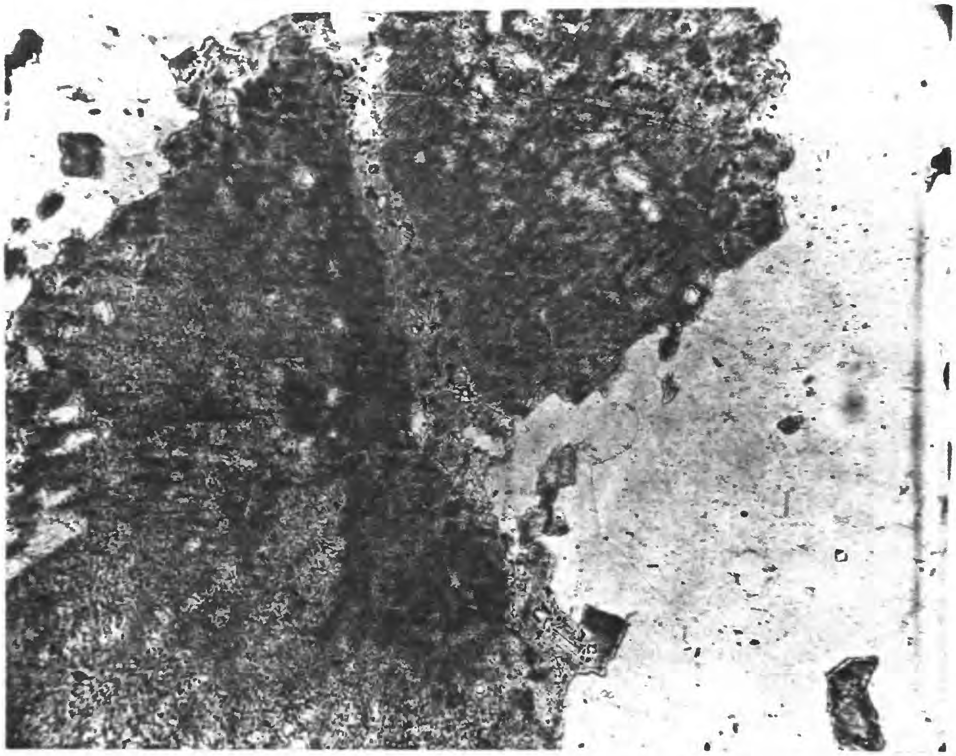
Plate 42

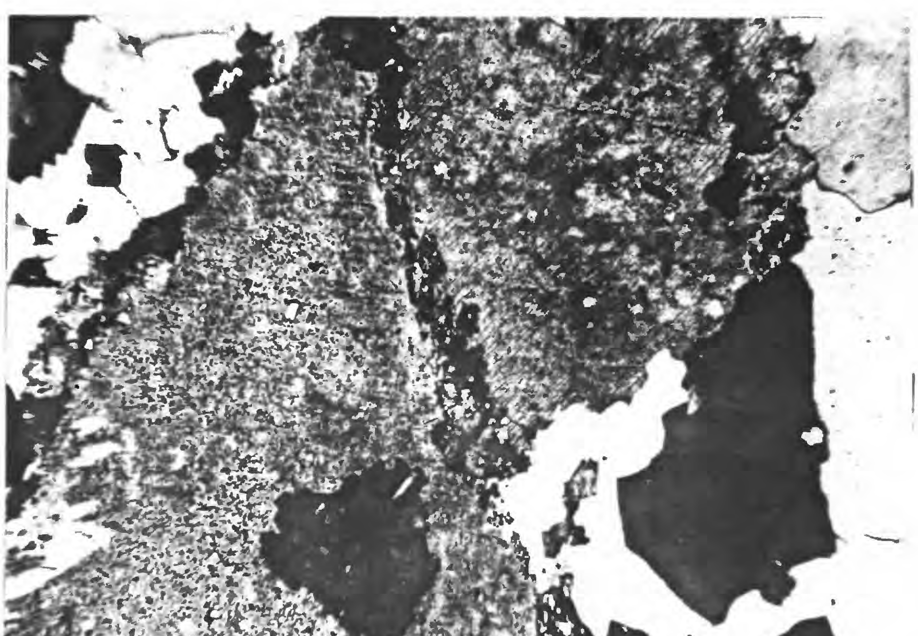
A. PHOTOMICROGRAPH OF GRANITIZED SEDIMENTARY ROCK FROM SOUTHEAST SIDE OF JUDITH PEAK

Gray is potash feldspar porphyroblast with allophane alteration. Light-gray band which runs across porphyroblast is fracture "filled" with granulated potash feldspar. White is replacement quartz. Specimen from large inclusion in fine-grained alkali granite 2,000 feet S. 50° E. of summit of Judith Peak. Plane-polarized light. X 53.

B. SAME AS A, BUT WITH CROSSED NICOLS

Note how late quartz replaces potash feldspar across fracture, but is not itself fractured. Crossed nicols. X 53.





The intrusion breccias are grouped together merely because they have similar textures and modes of formation. In age, distribution and composition, the three types are related to their respective "parent" rocks, but not to one another.

The intrusion breccias in the Burnette Peak and the Alpine Gulch stocks are associated with rhyolite. They are rhyolitic in composition and are younger than the rhyolite. How much younger is unknown, but it seems very probable that they belong to the same phase of irruptive activity as the rhyolites. The same may be said of the bodies of rhyolitic breccia that cut the rhyolite and adjacent rocks in the Warm Spring Creek dome, in the area north of Maiden, in the Gold Hill stock, and in the rhyolite plug east of the mountains.

The alkaline breccias of the Red Mountain area are cut by alkali granite porphyry dikes, but include many fragments of tinguaite rocks (pl. 27, B). Thus the intrusion of these breccias is restricted to the period of time between the injection of the gray tinguaites and the emplacement of the alkali granite porphyry. Contact relations are obscure, but in several places the breccia seems to be cut by green tinguaite dikes. Probably some of this breccia is older than some of the green tinguaites. The breccia on Judith Peak contains numerous fragments of the alkali granite porphyry and is the youngest igneous rock in the mountains.

One other type of breccia should be mentioned here. This is the breccia, usually of mixed rhyolite porphyry and limestone, that forms the ore zones in the more productive mines of the Judith Mountains - the Gilt edge, Maginnis, Spotted horse, and Cumberland mines. The breccia zones occur along the contact of the rhyolite and the Madison limestone and are in part tectonic.

## Petrography

The intrusion breccias exhibit all gradations from compact material in which individual fragments are spaced 2 to 5 centimeters apart and are supported by the igneous matrix, to somewhat friable and porous material in which closely packed fragments are held together with a minimum of cementing material. The matrix is invariably fine grained and many of the fragments consist of fine-grained igneous material of earlier rocks. Thus it is often difficult to distinguish matrix from fragment, especially where the breccia shows two or more periods of brecciation. Most thin sections are clouded with alteration products, and it is equally difficult to determine the composition of the fine-grained matrix once it has been identified as such.

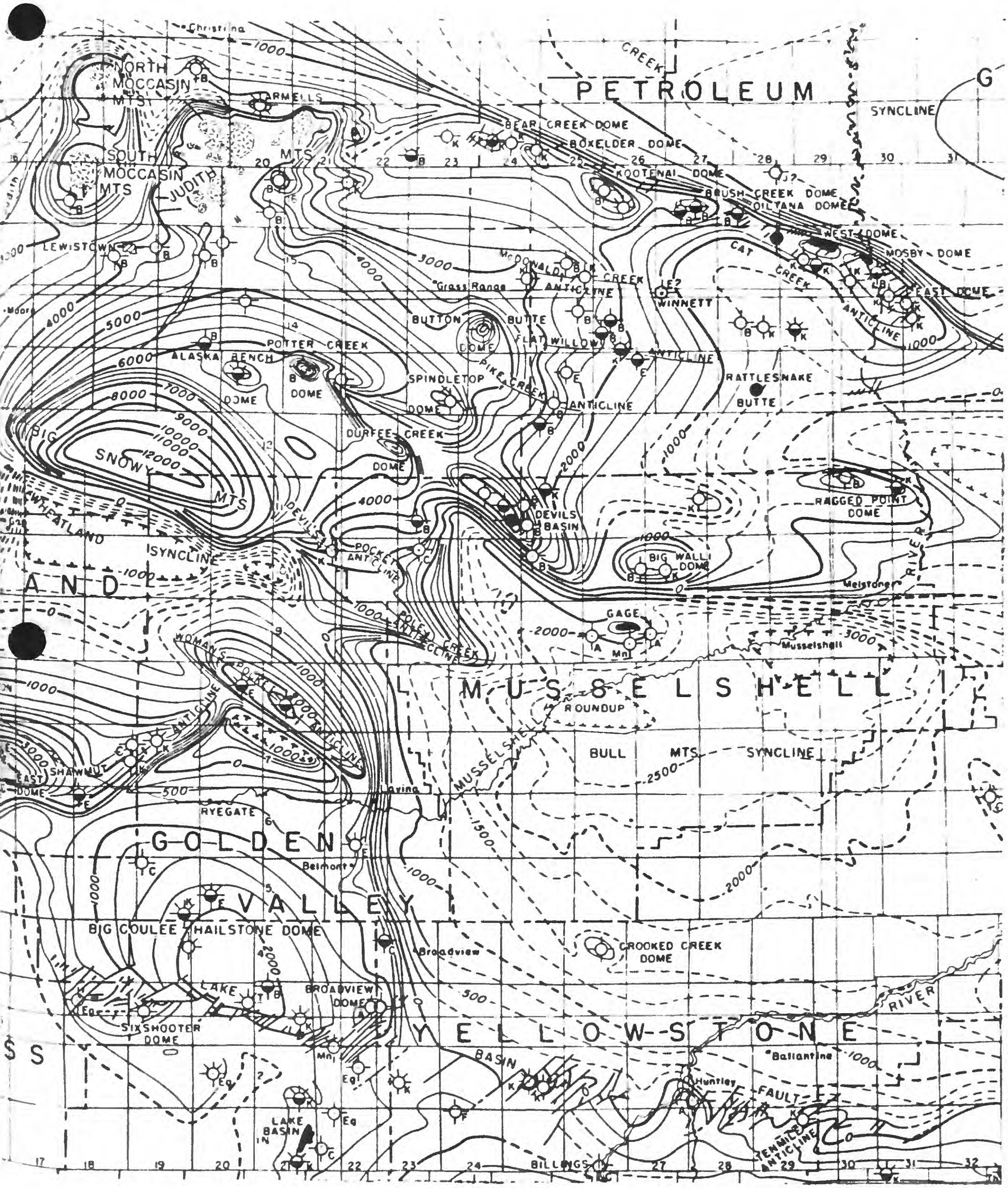
In general, the composition of the matrix material corresponds to the three principal types mentioned above - rhyolitic, trachytic, and alkaline granitic. Probably there is very little difference in the matrix composition of the rhyolite breccias and the alkali granite breccias. However, the threefold division is retained because of the genetic association. The small body of breccia which cuts the rhyolite on the south flank of Judith Peak is rhyolitic, and is much older than the alkaline granitic breccias that are found on Judith Peak.

Because of the close spatial relationship of the breccias to their "parent" rocks, many of the breccias contain a high percentage of fragments that are similar in composition to the matrix.

## STRUCTURE

### Regional Structure

Two major structural trends have been recognized in central Montana, and these are shown on the Structure Contour Map of the Montana Plains (Dobbin and Erdmann, 1946). Part of this map is reproduced in plate 43. A N. 75° W. trend is exhibited by the Cat Creek anticline, the Big Snowy dome and numerous other domes and anticlines, and the Lake Basin fault zone. A N.-NE.-trend is shown by the abrupt termination of these structures on the northwest, and by two faults mapped by Reeves (1931) in the Big Snowy Mountains. The Judith Mountains, and the neighboring North and South Moccasins lie at the northwest corner of a large uplifted block outlined by these two trends, and Goddard (1950) suggests that the Judith Mountains are localized at the intersection to two major fracture systems in the pre-Cambrian basement, which only locally reach as high as the present surface and elsewhere are exhibited as prominent folds.




Part of Structure Contour Map of the Montana Plains
(after Dobbin and Erdmann, 1946).

## Local Structure

### Major Structural Trends

The most important structural feature of the Judith Mountains is the Warm Spring Creek fault, a strong normal fault, which strikes N. 75° W., parallel to one of the regional trends, and dips 45° - 85° N. Throughout most of its length within the Judith Mountains, it lies beneath the alluvium of Warm Spring Creek valley. East of Maiden, it swings north around Crystal Peak and dies out in the bedding on the east flank of the Crystal Peak dome.

This irregular fault bisects the mountains and has dropped the northern part 800 to 1,500 feet. Stratigraphic relationships indicate that a large part of this movement took place between Mississippian and Jurassic time (p.127), but the fault was active again in early Tertiary time, coincident with the intrusion of the porphyry masses. The arcuate segment of the fault around the Crystal Peak dome is a trap door fault, formed by the intrusion of the Gold Hill stock. The complex fault pattern east of Maiden is due to the joining of this fault with the re-opened pre-Jurassic fault at this point.

In addition to the Warm Spring Creek fault, a general westerly trend is also reflected by the alignment of the porphyry bodies along the northern edge of the mountains, by faults along the south side of the Burnette Peak dome and the Alpine Gulch dome, and by the faults east and west of Black Butte.

The N.-NE.-trend is exhibited in the Judith Mountains by the alignment of the rhyolite dikes within the Alpine Gulch stock (pl. 46), and by a parallel alignment of large irregular rhyolite and monzonite dikes along the east side of the Burnette Peak and Alpine Gulch stocks.

## Domal Structures

The basic structural pattern of the Judith Mountains is a group of coalescing domes. The individual domes are well shown on the geologic map by the concentric outcrop pattern of the sedimentary formations and by the roughly circular or hexagonal fault systems which break and partly surround some of the domes. The initial and major doming in the mountains was caused by the intrusion of the monzonitic porphyries, the dominant rock type of the mountains. Minor domes, in some places superimposed on the earlier structures, were formed largely by the intrusion of rhyolite and syenite.

Goddard (1950) has discussed in detail the various stages in the development of the domal structures. The simplest form is illustrated by the small dome just north of the Warm Spring Creek dome (pl. 1). Although no porphyry is exposed in this structure, its close association with porphyry-cored domes strongly suggests that this dome was formed by an igneous intrusion. Additional evidence for this mode of origin is found in a similar but unmapped dome in the Colorado shale approximately 1 mile east of the rhyolite plug on the east flank of the mountains. No igneous rock is exposed in the dome, but records on file with the

Texas Company in Lewistown reveal that a hole drilled in the top of the structure bottomed in porphyry. In some places the simple domes have been modified by bedding faults in the flanking sediments.

More advanced stages are shown by trap-door faults, exemplified in the Kelly Hill structure (pl. 1, section D-D'-D''-D'''), and by bysmaliths or punch structures illustrated by Pyramid Peak (pl. 1, section B-B') and Black Butte (pl. 1, section E-E'-E''). The evolution of these structural types is outlined below. The sediments are first domed by a rise of the magma in the crust. Continued or renewed thrust, especially if the igneous core has cooled sufficiently to form a solidifed cap, raises the overlying strata beyond the limit that can be accommodated by simple arching, and the sedimentary roof is broken in a roughly hexagonal or circular pattern. An uneven distribution of the vertical forces results in the tilting of the roof block along a "hinge" and the development of a trap-door structure.

Further upward thrust opens tension fractures in the roof, and the sedimentary block begins to break up. Finally, in the extreme case, the corners of the block are worn off by brecciation and shearing, and a bysmalith is formed - a circular or elliptical plug-like body surrounded by nearly vertical faults.

## Form of Major Intrusive Masses

Weed and Pirsson (1898) mapped the Judith Mountains in 1896, and interpreted most of the major intrusive bodies as laccoliths.

Detailed mapping of the present study shows that nearly all the large porphyry masses are stocks, though in a few places there appear to be floored intrusives which are laccolith-like in form. Four main lines of evidence clearly indicate that the major domal uplifts are not underlain by laccoliths: (1) Contacts in many places show cross-cutting relationships, especially in the northern part of the mountains. (2) Nearly all the primary flow structures have steep rather than moderate dips as would be expected in laccoliths. (3) Simple domes have been ruptured by upward movement of the solidified igneous core. As shown on section E-E'-E'' of plate 1, vertical displacement at Black Butte is more than 1 mile. (4) The major intrusive bodies are composite stocks containing different compositional and textural varieties of igneous rock.

The syenite mass of Maginnis Mountain is the largest floored intrusive in the mountains, but the discordant contacts at the surface show that it is not a true laccolith. The generally concordant base, as shown on plate 1, sections A-A' and C-C'-C'', is inferred from the strike and dip of the foliation and the plunge of the lineations. These primary structures are fairly flat and indicate that the magma rose from beneath the Elk Peak dome. The crude tabular shape of the intrusion is further suggested by poorly developed columnar jointing seen on the south side of Maginnis Mountain.

Three other floored intrusives are shown on the structure section sections of plate 1: the rhyolite in the Warm Spring Creek dome (section C-C'-C''), the syenite of Lewis Peak (section E-E'-E'') and the syenite mass exposed along Log Gulch and in the area west of Lookout Peak (section E-E'-E''). These intrusives more nearly resemble laccoliths and are best described as thick sill-like bodies with slightly arched roofs, injected into previously tilted strata, and fed by wide "feeder dikes." The sill-like nature of the two syenite intrusives is shown by the contacts, especially along the western margins, and by the extremely flat flow structures. The movement displayed by the steep peripheral fault which bounds Lewis Peak on the north and east indicates a strong upward force from beneath the Lewis Peak mass, and a wide "feeder dike" seems necessary to account for this movement.

The syenite intrusives described above do not form the igneous cores of domes, but occur as relatively minor masses, emplaced on the flanks of pre-existing domes. The rhyolite body in the Warm Spring Creek dome crops out in the center of the structure and thus occupies at the surface, a position similar to that of the major stocks. The rhyolite is a homogeneous fine-grained rock with few phenocrysts and exhibits no flow structure. There is no direct evidence for a floor to the rhyolite body, and its presence is inferred solely from the general igneous sequence observed elsewhere in the mountains. With the exception of a single specimen of monzonite with an inclusion of rhyolite, all known rhyolite is younger than monzonite. The monzonite mass of Bald Butte transects the edge of the Warm Spring Creek dome. Thus, if the Warm Spring Creek dome were formed by the intrusion of rhyolite, it is a reversal of the "normal" irruptive sequence shown throughout the rest of the Judith Mountains.

## Structural Sub-provinces

The Judith Mountains are divided into two structural sub-provinces a northern and a southern, roughly separated by the Warm Spring Creek fault. Both sub-provinces are clearly shown on the geologic map (pl. 1), and are readily distinguished by the striking difference in outcrop pattern north and south of the Warm Spring Creek embayment. These differences are outlined below.

Within the southern sub-province:

1. The Madison limestone is exposed in a broad belt surrounding the igneous cores of the coalescing domes, and forms the most extensive outcrops of any rock in the sedimentary sequence. Outcrops of the Colorado shale are restricted to the foothill belt far out on the flanks of the domes.
2. At and near the surface, the major intrusive bodies are roughly concordant. The contacts are irregular in detail, but the sediments dip away from the intrusive centers on all sides.

3. The major bodies of monzonitic rocks are restricted to the cores of the primary domal structure - the Burnette Peak, the Alpine Gulch, and Crystal Peak domes.

Within the northern sub-province:

1. The Madison limestone crops out only in four widely separated areas - on Elk Peak, along the West Fork of Armell Creek, on Black Butte, and 1 1/2 miles north of Porphyry Peak. Beds of Colorado shale cover much of the area, and crop out along more than 50 percent of the exposed porphyry-sediment contacts.
2. Discordant contacts are common. In many places, the sedimentary beds dip toward the porphyry bodies or are cut off along strike.
3. Large bodies of monzonitic rock are not restricted to the central parts of primary domal structures.

The differencesin structure noted above are due to a difference in the mode of intrusion in the two sub-provinces. This in turn is related to a difference in depth beneath the surface of the Madison limestone in the areas north and south of the Warm Spring Creek fault at the time of intrusion -- a difference brought about by the pre-intrusive structural and erosional history of the Judith Mountain area.

## Pre-intrusive Structural and Erosional History in Relation to Stratigraphy

At the time of intrusion, the Madison limestone was more deeply buried beneath the northern sub-province than it was beneath the southern part of the mountains. This condition resulted from two separate periods of crustal movement - one pre-Jurassic, and the other early Tertiary.

### Pre-Jurassic Uplift and Faulting

The sedimentary sequence in northern and central Montana is broken by a major disconformity between the Ellis group of Jurassic age and beds of Carboniferous age. According to Gardner, [1] the southern limit of this disconformity lies close to the Lake Basin fault zone, which trends N. 75° W. about 70 miles south of Lewistown (pl. 43). In the southern part of the state, the Pennsylvanian Tensleep sandstone, the Permian Embar formation, and the Triassic Chugwater formation are exposed in the Big Horn and Prior Mountains. Thom (1923, p. 7) reports that the Chugwater formation terminates just south of the Lake Basin fault zone. In the central and north-central part of the state, these formations are absent, and the Jurassic beds rest on older formations - the Pennsylvanian-Mississippian Amsden formation, and the Big Snowy group and the Madison limestone of Mississippian age.

The profound disconformity over much of central Montana represents an erosional interval of major geologic proportions.

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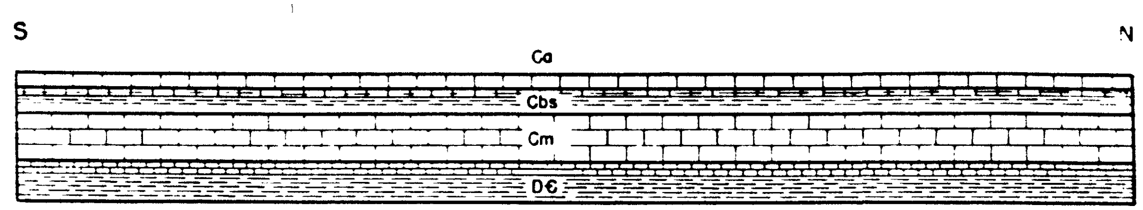
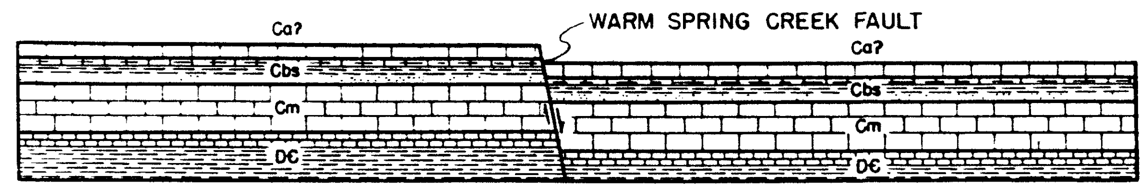
[1] Gardner, L. S., 1950, Oral communication.

Dobbin and Erdmann (1934, p. 698), speaking specificially of the hiatus represented by the disconformity over the Sweet Grass arch, state that, "The time value probably includes Lower Jurassic, Triassic, Permian, and possibly late Pennsylvanian." Certainly central Montana was a positive area during much of the post-Amsden - pre-Ellis interval.

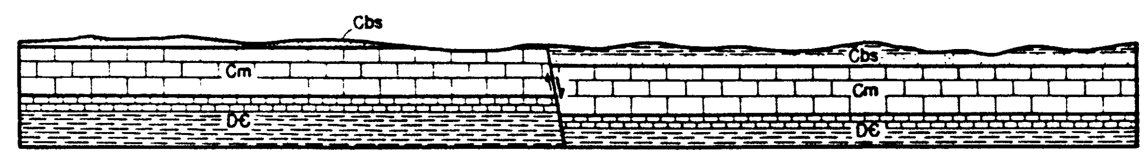
The structural trends of central Montana reflect lines of weakness in the pre-Cambrian basement that developed or at least were active during the pre-Jurassic uplift. The pre-Jurassic existence of these regional trends is indicated by the abrupt change in the stratigraphic section north and south of the Lake Basin fault zone (Tertiary) and by a smaller, but no less striking change north and south of the Warm Spring Creek fault where it cuts the Warm Spring Creek dome at the western edge of the Judith Mountains. On the north side of the dome, the Jurassic Ellis group overlies the Heath formation, the upper formation of the Big Snowy group. Two thousand feet distant, on the south side of the fault, the Ellis group rests on the Kibbey sandstone, the basal formation of the Big Snowy group. In both places, the Ellis group is in sedimentary contact with the underlying beds, but the Big Snowy group is from 500 to 800 feet thicker on the north side of the dome (pl. 1, section C-C'-C''). Post-Mississippian - pre-Jurassic movement along this fault dropped the north side 500 to 800 feet. Displacement was followed by erosion sufficient to reduce both blocks to a common level prior to the deposition of Jurassic sediments (pl. 44, sections 1, 2, 3, and 4).



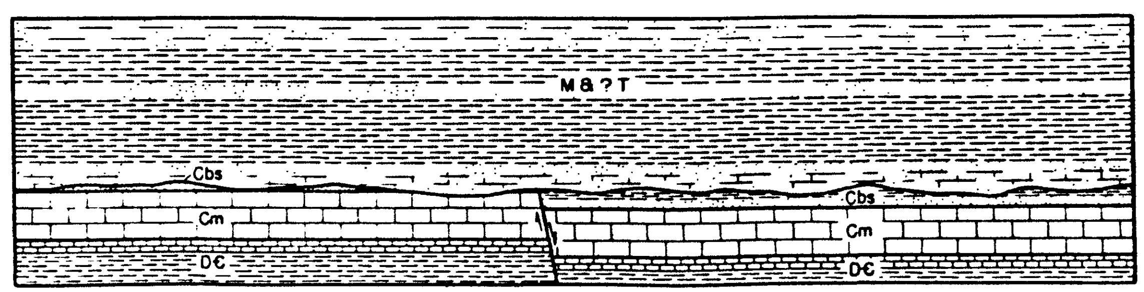

1. LATE MISSISSIPPIAN, (?) EARLY PENNSYLVANIAN – SEDIMENTATION




2. POST-MISSISSIPPIAN, (?) EARLY PENNSYLVANIAN – UPLIFT AND FAULTING



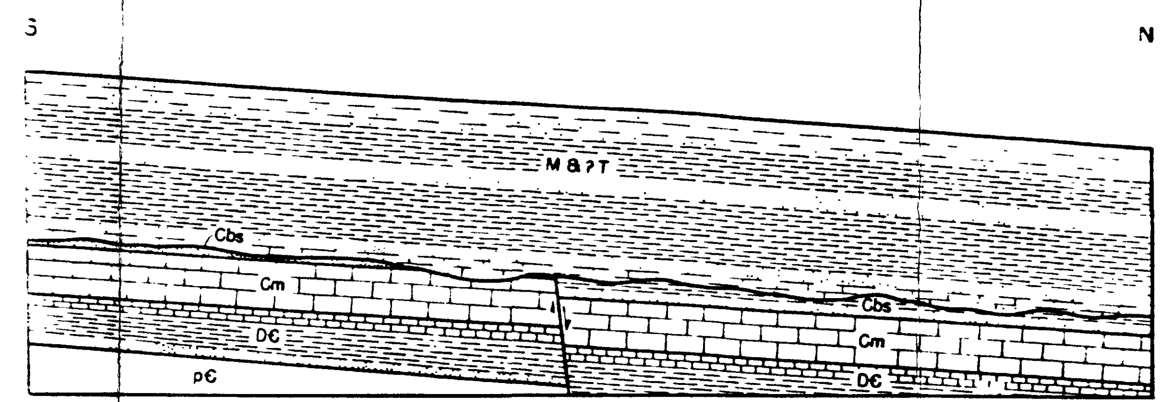

3. POST-FAULTING – PRE-JURASSIC EROSION



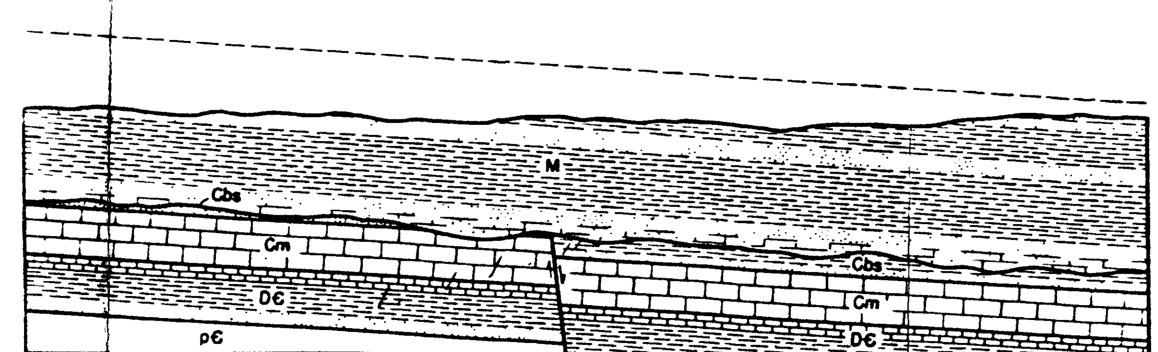

4. BURIAL OF PRE-JURASSIC EROSION SURFACE BY MESOZOIC AND (?) TERTIARY SEDIMENTS

# DIAGRAMMATIC SECTIONS SHOWING EFFECT OF PRE-INTRUSIVE STRUCTURAL AND EROSIONAL HISTORY ON THE MODE OF INTRUSION

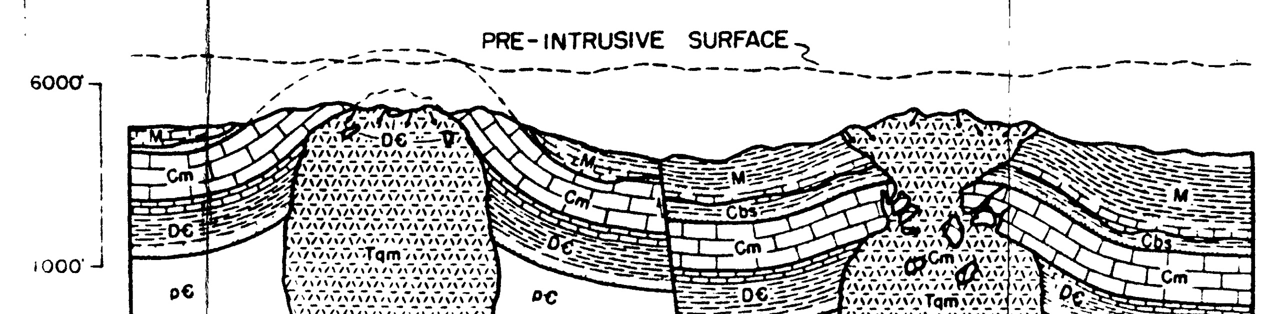
LENGTH OF SECTIONS —— 15 MILES VERTICAL EXAGGERATION —— x2½




5. LATE PALEOCENE, (?) EARLY EOCENE – UPLIFT AND TILTING




6. POST-TILTING – PRE-INTRUSIVE EROSION




7. INTRUSION OF PORPHYRY STOCKS, (?) LATE EOCENE – AND SUBSEQUENT EROSION

Tqm, QUARTZ MONZONITE PORPHYRY; M & ? T, MESOZOIC AND POSSIBLY EARLY TERTIARY; Ca, AMSDEN FORMATION, MISSISSIPPIAN; Cbs, BIG SNOWY GROUP, MISSISSIPPIAN; Cm, MADISON LIMESTONE, MISSISSIPPIAN; D€ DEVONIAN AND CAMBRIAN (UNDIVIDED); p€, PRE-CAMBRIAN

The thickness of the uneroded part of the Big Snowy group is quite variable, but in general it is thicker in the northern part of the mountains. The Heath formation is exposed at six different localities north of the Warm Spring Creek fault. Although exposures of the Big Snowy group are much more extensive south of the fault, the Heath formation is present at only one locality - on the south side of the Burnette Peak dome. At several places the Ellis group rests on the basal Kibbey sandstone, and along the southeastern flank of the Crystal Peak dome, the entire Big Snowy group has been removed by pre-Jurassic erosion.

## Early Tertiary Tilting

The pre-Jurassic structures are parallel to the more recent folds shown on the Structure Contour Map of the Montana Plains contoured on the base of the Colorado shale (pl. 43).

According to Dobbin and Erdmann (1934, p.698), "The principal tectonic movements causing the development of the structural features of the region took place some time in the Eocene subsequent to the deposition of the Fort Union formation. These movements, which belong to the Laramide revolution, were preceded by several oscillatory movements which are clearly recorded by the character of the late Upper Cretaceous and early Tertiary strata throughout the region."

This general period of crustal warping probably imparted a slight northward tilt to the sediments in the immediate vicinity of the Judith

Mountains. South of the mountains, the highest beds stratigraphically belong to the upper part of the Kootenai formation and the lower part of the Colorado shale. Along the northern edge of the mountains, the formations exposed are the Eagle sandstone and the Claggett shale, roughly 2,000 to 2,500 feet higher in the section. Surface elevations are approximately the same in both localities. Further north, still younger beds crop out - the Judith River formation and the Bearpaw shale. Successive steps in the depression of the Madison limestone beneath the northern part of the mountains are shown on plate 44.

## Mode of Intrusion

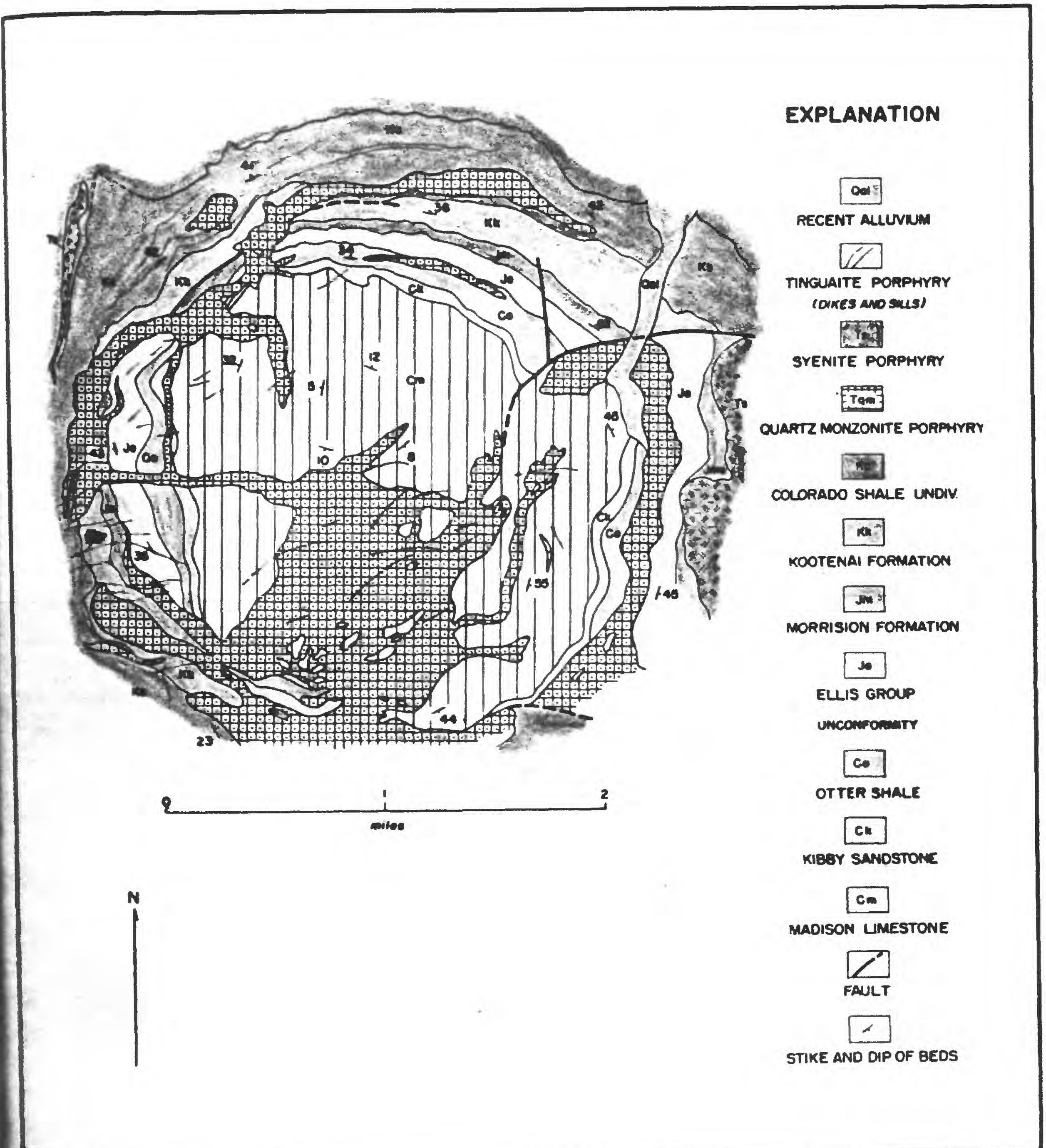
As noted on page 125, the contrast between the two structural sub-provinces is due to dissimilar modes of intrusion in the northern and southern parts of the mountains. The difference in the intrusive mechanism involves only the final stages of emplacement within the upper levels of the crust, and is related to a difference in altitude of the Madison limestone underlying the two sub-provinces at the time of intrusion. The minimum difference in depth to the Madison limestone north and south of the fault is estimated as 300 to 500 feet; the maximum difference probably did not exceed 2,500 feet.

The influence of the Madison limestone on the mechanism of intrusion is illustrated in section 7 of plate 44. South of the Warm Spring Creek fault, the monzonite magma rose through the crust largely by stoping the overlying country rock. This process was augmented by slight doming and fracturing of the superincumbent rock, especially after the magma had penetrated to the Lower Paleozoic strata. Emplacement continued in this manner until the magma reached the Madison limestone, which is a thick, massive, and competent formation. It prevented further penetration of the magma through the crust, and emplacement was completed by doming of the Madison limestone and overlying sediments, with the Madison forming the sedimentary roof over the magma chamber. The dips of the strata beneath the Madison were probably increased by continued pressure from below combined with relief of load by the lifting of the Madison limestone. It is possible that many sill-like bodies were emplaced marginal to the main stocks, in "structural vacuums" created by the lifting of overlying strata.

North of the Warm Spring Creek fault the monzonite magma rose through the crust by the same processes until it reached the Madison limestone. This formation resisted penetration just as it did in the area to the south, and some doming occurred. However, the magma encountered the Madison limestone at greater depth, and the weight of the sediments overlying the Madison was greater than in the area to the south. It is thought that this additional load prevented complete doming, and that the magma eventually broke through the Madison limestone by stoping. However, it is possible that the doming was of the same magnitude as that in the southern sub-province. In this case, the magma would nevertheless stand at a lower level within the crust in the northern sub-province after the doming had occurred. If the "driving force" of the magma were approximately the same throughout the mountains, the magma directly beneath the domed Madison limestone in the northern sub-province would have a greater "emplacement energy" than that beneath the domes to the south. That is, the relief in pressure obtained by the doming of the sediments in the northern part of the mountains would be insufficient to prevent the continued rise of the magma to higher levels, and rupture of the Madison would result.

In either case, complete penetration of the Madison limestone was accomplished. Once the Madison limestone was breached, the magma rose easily through the soft overlying shale formations (pl. 44, section 7). The irregular shapes and positions of the igneous bodies thus formed are shown in plan and in section on plate 1. Geologic evidence for this mechanism of emplacement is abundantly displayed in the northern part of the mountains by the major discordance along many contacts and by primary flow structures. In many places lineations in the monzonites indicate contacts which flare upward and outward from some constriction at depth.

The most striking evidence is shown by the vestiges of two former domes which have "foundered" and been engulfed in the magma. One lies just north of Porphyry Peak, and the other is adjacent to the first, just north of Judith Peak (pl. 1). The large igneous mass which




Geologic map of the Elk Peak dome.

extends far beyond the intrusive centers illustrates that magma has escaped from the confines of the primary domal structures.

The largest area of Madison limestone north of the Warm Spring Creek fault is found on the Elk Peak dome. Plate 45 is a detailed map of this structure and illustrates an arrested stage in the destruction of a dome by stoping. The outcrop pattern suggests the operation of two separate processes. The irregular dikes and the numerous inclusions in the porphyry in the south-central part of the dome indicate penetration by the magma along fractures as the sedimentary roof begins to break up. The arcuate bodies around the periphery resemble ring dikes and illustrate a step in the large-scale stoping of the entire dome. Several of the "ring dikes" are shown on the geologic sections of plate 1. The magma rose along circular faults or fractures as dikes. In places the magma spread into the bedding, especially where dips were steep, and thus some of the arcuate bodies are sills.

The rhyolite in the Warm Spring Creek dome and the syenite bodies exposed in Log Gulch and on Lewis Peak were probably emplaced in this manner (pl. 1, sections C-C'-C'' and E-E'-E''). The assymetry of the Linster Peak stock, shown by primary flow structures and the attitude of the flanking sediments, may be due to a similar mechanism (pl. I, section D-D'-D''-D'''). That is, the "overhang" on the west side of the stock may represent an arcuate fracture along which the magma rose. If so, the dike and sill pattern were obliterated as the magma continued to rise and coalesced with the main stock. Indirect evidence of ring-fracture stoping is found in the form of an irregular but roughly arcuate mass of coarse-grained porphyry which is exposed along the western margin of the stock. The outline of the coarse-grained facies conforms to that of a modified ring dike, and the large phenocrysts suggest that this facies is slightly younger than the main stock.

## HYPOTHESES ON THE ORIGIN OF ALKALINE ROCKS

Any logical discussion of the origin of alkaline rock must begin with an exact statement of what is meant by the terms, alkaline rock and alkaline magma. Because of the many definitions proposed in the past, and by reason of the various connotations given when no definition was stated, there is today no universal agreement among petrologists as to the significance of these terms. The writer prefers the restricted and precise definition proposed by Shand (1922) who limits the alkaline rocks to those in which the molecular percentage of the alkalies exceeds the 1:1:6 ratio (alkali oxides:alumina:silica) of the alkali feldspars, either alumina or silica or both being deficient.

The chemical relations noted above have endowed many of the alkaline rocks with unusual mineral assemblages. Partly for this reason, and partly because the alkaline rocks are so rare, they have been regarded as abnormal types, and many theories have been advanced to explain their origin. Some of these theories are reviewed briefly below. The close association in time and space of alkaline and calc-alkaline rocks necessitates for most occurrences a common parent magma. For this reason, those theories which take as their point of departure, a special and unrelated alkaline magma, are not included.

### HARKER

Harker (1911 and 1918) proposed a "wine press" mechanism with squeezing out of interstitial fluids enriched in the alkalies by either progressive crystallization or progressive fusion. The method by which such liquids become impoverished in silica is not stated.

## GILLSON

Gillson (1928) believed that the process of albitization furnished a key to the genesis of some alkaline rocks. He suggested that the transfer of volatiles to and their accumulation in the cupola areas of large igneous bodies might under favorable circumstances concentrate the alkalies, desilicate the magma, and give rise to alkaline rocks. Again, the mechanism by which the magma is desilicated is not made clear.

## SMYTH

Smyth (1913) also stressed the role of volatiles in the genesis of alkaline rocks. He believed that a high concentration of water plus such elements as fluorine, sulfur, chlorine, and zirconium is responsible for a re-grouping of the ions into compounds characteristic of alkaline rocks, and that these compounds would tend to be segregated from the parent granitic liquids.

## BOWEN

Bowen (1915) suggested that phonolitic liquids might be generated from granitic magmas by the separation of early formed quartz from the magma at the stage just prior to its resorption as shown by the corroded crystals in many rhyolites. He proposed an additional method of desilicating the magma by the action of volatiles. A high concentration of volatiles, principally water, is assumed to cause the breakdown of the polysilicate molecules (feldspars) to orthosilicate molecules (micas) with a freeing of silica. Evidence is found in the development of biotite in biotite granites. Precipitation of biotite and quartz results in a concentration of $NaAlSiO_4$ in the liquid, and separation of this liquid from crystals by gravity or filter pressing yields a phonolitic differentiate.

If the separation of early quartz can extract from the magma sufficient silica not only to prevent the subsequent precipitation of quartz, but also cause the formation of silica-deficient minerals, then there should exist some few "rhyolites", chilled just prior to the period of quartz resorption, with numerous but uncorroded crystals of quartz set in a feldspathic base containing a small percentage of feldspathoids. No such rocks are known.

Bowen (1928, pp. 234-257) pointed out a similar objection, and although he did not abandon the theory, he proposed an alternative hypothesis based on the incongruent melting of potash feldspar. The first essential is the existence of a liquid from which leucite will separate. This liquid must be rich in potash, relatively poor in the albite molecule in relation to the anorthite molecule, and with no more than a slight excess of silica.

The generation of this liquid from a parental basaltic magma requires rather special conditions of cooling. In the temperature range through which olivine crystallizes there must be either rapid cooling so that no olivine forms, or extremely slow cooling so that complete equilibrium is attained between the olivine and the liquid. There can be no separation of solid and liquid phases either by sinking or filter pressing until the reaction point, forsterite-enstatite is reached, and all the olivine resorbed. If the olivine is segregated, it must be the olivine-rich fraction - again cooled slowly with complete equilibrium - that gives rise to the phonolitic differentiate. If the magma cools thus, it will be relatively poor in silica, and Bowen believes that some basic feldspathoid liquids may develop at this stage, and that these may possibly give rise to phonolitic types without the benefit of the pseudo-leucite reaction.

Failure of the magma to cool in the manner outlined above will result in an enrichment in silica due to the precipitation of olivine in excess of its stochiometric proportions and the incongruent melting of enstatite. The result is that later derivative liquids will crystallize without encountering the leucite field.

The same effect is achieved if the magma is enriched in soda. If the magma has been appropriately cooled through the olivine forming temperature range, subsequent differentiation may result in a trachytic liquid. Pyroxene is removed and soda is suppressed relative to potash and lime by suitable fractionation of the plagioclase.

With further cooling this liquid will then precipitate leucite. If there is no differential movement of liquid and crystals, all of the leucite will be made over into potash feldspar at the leucite-orthoclase reaction point, and no nepheline will form. To precipitate nepheline, there must be a separation of liquid and solid phases after leucite starts to crystallize, but before the temperature of the leucite-orthclase reaction is reached. If these conditions are met, the fraction with excess crystals will still contain some undestroyed leucite after the leucite-orthoclase reaction point is passed, and at a still lower temperature, these crystals will react with the liquid to yield pseudoleucite, a mixture of orthoclase and nepheline. Very slow cooling at this stage may result in the solution of leucite and the precipitation of nepheline and orthoclase about separate nuclei without the formation of the usual nepheline-orthoclase pseudomorphs, thus giving rise to a nepheline syenite.

If leucite crystals are separated at a certain stage in the course of crystallization, the liquid may precipitate orthoclase, albite and nepheline without any pseudoleucite reaction. But the separation of nepheline would nevertheless depend upon the former presence of leucite and upon cooling curves defined in part by the pseudoleucite reaction (Bowen, 1928, pp. 246-247).

This theory is as complex as it is ingenious; it requires very special and delicate control of physical-chemical conditions throughout the crystallization period of the magma. The required control is such that all conditions necessary for the development of a phonolitic liquid will not often be satisfied. This, of course, is in general agreement with the observed scarcity of alkaline rocks, and it seems probable that some rocks of phonolitic composition have originated by this mechanism.

To explain some of the more basic alkaline types, Bowen (1928, pp. 269-273) proposed another mechanism based on fractional resorption. Crystals of hornblende and biotite are assumed to sink into a hotter, more basic portion of the magma and are destroyed by reaction with the liquid. The destruction of these phases is not a simple solution, but a reactive solution, with the simultaneous precipitation of earlier minerals of the reaction series - olivine, pyroxene, and perhaps calcic plagioclase, The liquid thus becomes enriched in those elements present in hornblende and biotite, but absent or present in lesser amounts in the substituting mineral phases. Thus, resorption of biotite would add potash to the magma, and resorption of hornblende would lead to an increase in soda. The result is a liquid relatively rich in iron and the alkalies, yet still poor in silica, and filtration at this point will yield magmas of alkali basaltic composition - nepheline leucite basalts and related rocks. Some phonolites are believed to result from continued differentiation of these magmas (Bowen, 1928, p. 272).

If hornblende and biotite are concentrated by gravity in a suitable environment, it seems possible that the resorption of biotite may bring about an enrichment of the liquid in potash; but it seems doubtful that resorption of hornblende, a mineral notably poor in sodium, can enrich the melt in soda.

## DALY

Daly (1910) published a theory on the origin of alkaline rocks based on the syntexis of limestone. The original statement has been amplified, both by Daly in his later works (1918 and 1933), and by Shand (1922 and 1945), who has in general supported Daly so vigorously that his name is as closely linked with limestone syntexis as is Daly's.

The generation of silica-deficient alkaline magmas from basaltic or granitic calc-alkaline magmas involves three distinct processes:

1. Assimilation of limestone leading to direct formation of feldspathoids by desilication of feldspar molecules.
2. Extraction of silica from the magma by the formation of heavy lime silicates and their removal from the system by sinking.
3. Concentration of the alkalies by:
    a. Upward displacement of residual alkaline fraction in response to gravity.
    b. Formation, in the presence of lime and resurgent carbon dioxide, of alkaline carbonate fluxes which rise toward the top of the magma chamber.

Variations in composition of original magma, degree of reaction with carbonate material, and differentiation of resulting hybrid magma are believed adequate to account for sub-silicic alkaline rocks of all compositions. Daly does not suppose that all alkaline rocks can be explained by limestone syntexis, but with Bowen and others, believes that some trachytic and phonolitic differentiates may be formed from the residual portions of an olivine basalt magma by fractional crystallization.

Bowen (1928, pp. 216-223) objects to the syntectic theory on the grounds that most magmas, particularly granitic magmas, do not have sufficient superheat to cause simple solution of appreciable quantities of limestone. Bowen also presents evidence indicating that reactive solution can only result in a change in the relative amounts of phases essentially the same as those the magma is already capable of precipitating. That is, no new phases, e.g., the feldspathoids, will result.

But Bowen's arguments are based on conditions existing in anhydrous melts, and it seems significant that in so many theories on the origin of alkaline rocks, volatiles have been assigned an important, though often somewhat ill-defined role. Smyth (1913) and Bowen (1915) believed that a high concentration of volatiles would promote a re-grouping of the ions into alkaline compounds, which if segregated would yield alkaline rocks. Gillson (1928) emphasizes the effect of volatiles in concentrating the alkalies. Tomkeieff (1937) invoked the process of "alkali-volatile diffusion differentiation" to account for the trachytic and phonolitic differentiates of olivine basalt in the Permo-Carboniferous igneous rocks of Scotland. Ross (1926) recognized the influence of "water and other mineralizers" in the generation of a nephelite - hauynite alnoite from Winnett, Montana. Holmes (1937 and 1945) and Backlund (1932) rely in part on volatiles to produce certain types of alkaline rocks. Rittman (1933) employed gaseous transfer to concentrate potash in certain of the alkaline rocks erupted from Vesuvius. Many others have recognized the importance of volatile constituents in the genesis of certain alkaline rocks, and it seems to the writer that volatiles, so important to the reaction rate in such geologic processes as replacement and metamorphism, may greatly increase the capacity of a melt to digest limestone.

At Scawt Hill, County Antrim, Ireland (Tilley and Harwood, 1931), chalk at the intrusive contact with a dolerite boss contains wollastonite and the rare high temperature silicates, spurrite, larnite, and merwinite. Tilley and Harwood (1931, p. 446) note the importance of solutions in "--- effecting a rapid rise in temperature in the limestone, apart from conduction." But the mineral assemblage suggests a temperature environment of perhaps 1300° - 1500°C., which seems high even for a doleritic magma, and an alternative or perhaps dual role of the solutions may have been a lowering of the temperature required for the formation of the observed reaction products. In any case, volatiles seem to have been important in promoting reaction with the chalk.

In applying this concept to Daly's hypothesis, it should be noted that Daly derives a large part of the volatiles by the action of resurgent carbon dioxide. That is, the volatiles are in part dependent upon the solution of limestone and not vice versa. But magmas are not dry melts; all contain some juvenile volatiles which may initiate reaction. Hybrid vesiculated rocks at the margin of the Scawt Hill intrusive indicate that reaction took place while the dolerite was still a magma. The vesicles represent either juvenile gases, available for reaction with the chalk, or resurgent carbon dioxide, indicating reaction. Once the breakdown of $CaCO_3$ has started, it is quite possible that resurgent carbon dioxide may accelerate the reaction. Morey's (1952, p. 70) recent work shows that the gaseous solubility of many substances is affected by a mixture of water (94 percent) and carbon dioxide (6 percent) at temperatures as high as 600°C. and pressures as high as 2,000 bars. Morey [1/] reports that the solubility of $CaCO_3$ was increased many fold. Thus, the abundance of volatiles in alkaline magmas noted by so many investigators may be the result of such a "chain reaction."

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1/ Morey, G. W., 1953, written communication.

## COMPLEX INTRUSIVE RELATIONSHIPS

The major igneous bodies are complexes of various types of rock whose textural and compositional differences record successive irruptions of magma. A few of these irruptions resulted in the emplacement of rocks whose appearance and structural relations are such that they can be easily mapped as separate units. The green tinguaites for example, are readily distinguished from the monzonites, and in many places occur as well defined dikes which occupy joints and fractures in the early porphyries. These dikes appear late in the igneous sequence and were intruded as tabular bodies at a stage when the earlier porphyries had cooled sufficiently to have the properties of a solid throughout a considerable range.

The results of those phases of irruptive activity that followed more closely the initial intrusion of magma are much less apparent. Many of the recurrent surges of magma are marked only by textural differences with little or no change in bulk composition, i.e., the different textural varieties of the monzonites.

The distribution of the various textural facies of the monzonitic rocks is imperfectly known. In some places there are large units of a single type which can be separated from adjacent units of different texture. For example, a large irregular crescent-shaped area of coarse-grained monzonite porphyry forms a border facies along the western margin of the Linster Peak stock. Comonly the textural units are smaller, they exhibit random distribution within the stocks, and contacts are both gradational and highly irregular.

The facies pattern of the monzonites is broken by bodies of rock of different composition. In contrast to the textural facies, which can be distinguished by appearance, many of the different compositional types are extremely difficult to detect, and some rocks with significant chemical differences appear almost identical. The presence of different rock types in igneous bodies which appeared uniform in the field was discovered by the microscopic study of specimens collected as being typical of a general area. Nothing is known of the size and shape of the various igneous bodies represented. They are recognized solely from a number of fortuitously located samples, and certainly there are many similar anomalies which remain undiscovered.

The writer spent three days mapping three fairly distinct facies in the southwest corner of the Alpine Gulch stock. The three facies distinguished were:

1. Quartz monzonite porphyry, undivided
2. Coarse-grained rhyolite porphyry
3. Fine-grained rhyolite porphyry

The three types were separated on the basis of the size and relative abundance of quartz phenocrysts; a sketch map of their distribution is shown on plate 46. Specimens of the three types were collected, examined in thin section, and found to correspond to the field designations. The mapping was done largely on float, and although it certainly fails to show the detailed relationships, it does reveal the complexity of the intrusive pattern.

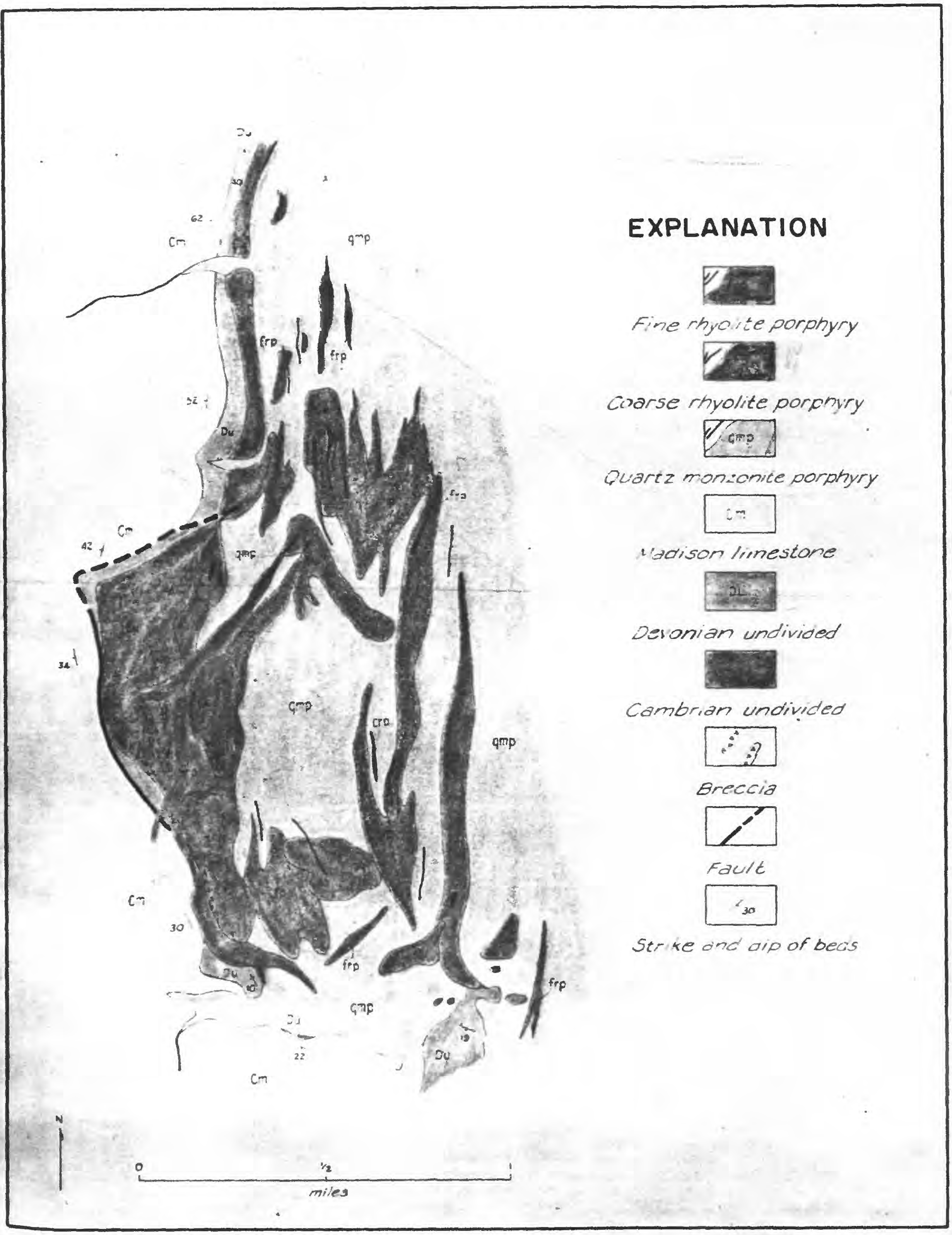
## PETROGENETIC SIGNIFICANCE OF THE FELDSPARS

### Evidence of Mixed Magmas

The chemical and mineralogical similarity between different facies of the monzonitic rocks assigns them to a common magma which had little time to differentiate between successive periods of irruption. The spatial relations and the gradational contacts suggest that the early facies were in a semi-solid state, probably as a crystalline mush, at the time that later facies were injected.

The change in composition of the magma from monzonitic to rhyolitic occupied a t.me interval during which the hood zones of the quartz monzonite stocks cooled and solidified sufficiently to sustain fractures. This is shown in the case of the Alpine Gulch stock, by the dikes of rhyolite which definitely transect the earlier quartz monzonite, and by the preferred orientation of the irregular rhyolite bodies in a general north-south direction (pl. 46).

At some time either late in the monzonite stage or early in the rhyolite stage, certain rocks were injected which seem best explained as hybrids formed by the mixing of two separate magmas.




**Sketch map showing distribution of rhyolite and quartz monzonite in the southwest part of the Alpine Gulch stock.**

Evidence pointing to the mixing of magmas is found in the presence of certain incompatible mineral phases within single specimens. Four specimens, all from different localities, contain plagioclase phenocrysts which are not in equilibrium with one another. Differences in composition range from 12 to 29 percent Ab. Zoned plagioclase is common in the Judith Mountain rocks, but the zoning is oscillatory and the maximum difference observed in any one crystal with regular oscillatory zoning is approximately 8 percent Ab. The variations noted above thus seem too great to be explained by the usual zoning, and it is noteworthy that in three of the four specimens with incompatible feldspars, the crystals exhibit only faint zoning. The more calcic plagioclase crystals in these three specimens show little resorption and are not mantled with more sodic rims; apparently the magma was chilled soon after mixing. A thin section of the fourth specimen contains a single large crystal of $Ab_{52}$, mantled by $Ab_{81}$ (pl. 38, B). The calcic core is rounded, indicating some reaction between the time of mixing and final consolidation. Unfortunately, the groundmass in all specimens is a fine grained aggregate of alkali feldspar and quartz, and the composition of the groundmass feldspar cannot be compared with the composition of the plagioclase phenocrysts.

Larsen and Irving (1938, pp. 227-257) describe similar anomalies in the feldspars of the San Juan lavas and attribute them largely to mixing. Other mechanisms considered are crystal accumulation by floating or sinking, and reaction with inclusions. As they point out, the density relations pretty well negate the required gravitational separation. They consider reaction with inclusions an effective mechanism in some cases, but this requires that the magma be more basic than the inclusions (Bowen, 1922, pp. 513-567 and 1928, pp. 175-223). The relative abundance of sodic over calcic feldspars in the two plagioclase rocks of the Judith Mountains, the presence of basic plagioclase cores, mantled by more sodic rims, but not vice versa, and the general sequence of irruption all point to an origin other than by reaction with inclusions less basic than the magma. The evidence suggesting the emplacement of certain facies before previously injected magma had completely solidified supports the concept of mixed magmas.

The writer feels that mixed magmas may be far more common than generally realized, although evidence will probably be lacking except among the extrusive and hypabyssal rocks. Even in these rocks, indications of mixing can be expected in only a small percentage of the total rocks sampled. But in any area where different irruptive phases of differentiating magma are closely related in time and space, some mixing should be considered as "normal" and not as unusual.

## Fractionation by Mantling

A specimen taken from the Tail Holt mine contains crystals of two plagioclase feldspars which differ in composition by 38 percent Ab. However, there are certain features of the rock which suggest that the two plagioclases do not indicate the mixing of magmas, but rather are the result of fractionation by mantling. The specimen shows prominent sanidine phenocrysts as much as 12 millimeters long, and smaller crystals of plagioclase which average 3 to 4 millimeters in length. These are set in a fine-grained groundmass of alkali feldspar and quartz. Accessory minerals are magnetite, apatite, and sphene. The original mafic minerals are altered to calcite, magnetite, and clay minerals, and the entire rock shows the effects of strong alteration. Fluorite and secondary quartz are present, and abundant sericite and allophane have developed at the expense of the feldspars.

The two plagioclases present are $Ab_{56}$and $Ab_{94}$. Both form euhedral crystals of approximately the same size, but all of the andesine crystals are armored with potash feldspar rims. The albite phenocrysts have no orthoclase mantles.

When the two plagioclases are plotted on Bowen's (1913, pp. 577-599) familiar equilibrium diagram of the system, Albite-Anorthite, the possibility of explaining the incompatible feldspars as a result of fractionation by mantling becomes apparent (fig. 2). Point A represents the composition of the armored plagioclase, $Ab_{54}$. The composition of the liquid in equilibrium with solid $Ab_{54}$ is shown by B. If this liquid were separated from the plagioclase which it was precipitating, and allowed to crystallize under conditions of equilibrium, the resulting plagioclase would have the composition of C, $Ab_{91}$. Point D represents the composition of the sodic plagioclase in the specimen, $Ab_{94}$ - only

3 percent removed from $Ab_{91}$, the theoretical resultant composition. The development of potash feldspar mantles around the early-formed plagioclase, $Ab_{54}$, would remove it from the plagioclase solid solution series just as effectively as if actual separation had occurred. The Tail Holt specimen seems to represent fractionation by mantling rather than the mixing of two magmas.

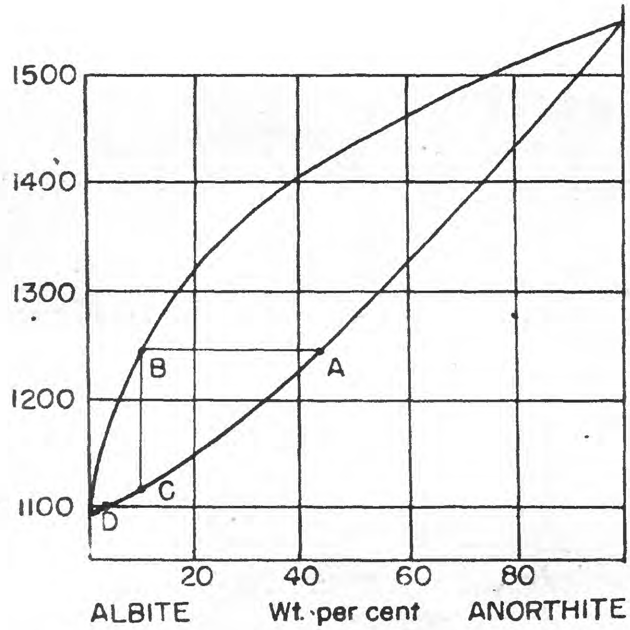



Figure 2. --Equilibrium diagram of the system, Albite-Anorthite. (after Bowen)

Exsolution Perthite in the Alkali Granite

Two different forms of albite were noted in the coarse-grained facies of the alkali granite porhyry of Judith Peak (p. 94 ): (1) rectangular to elliptical subhedral crystals which occur as inclusions in the sanidine phenocrysts and in the groundmass, and (2) elongate laths which occur only within the sanidine crystals, and which are not present in the groundmass. The albite laths have an entirely different habit than do the rectangular and elliptical albite inclusions, and, unlike the inclusions, commonly exhibit a random orientation even though they are extremely non-equidimensional. Clearly two separate modes of origin are required. The textural relations noted earlier (p. 94) indicate that the elliptical to rectangular albite inclusions are orthomagmatic minerals; the laths are believed to be exsolution albite.

Equilibrium relations between the alkali feldspars show that when both are precipitating simultaneously from the same melt, each will be saturated with the other to the limit of miscibility for the particular temperature of formation.

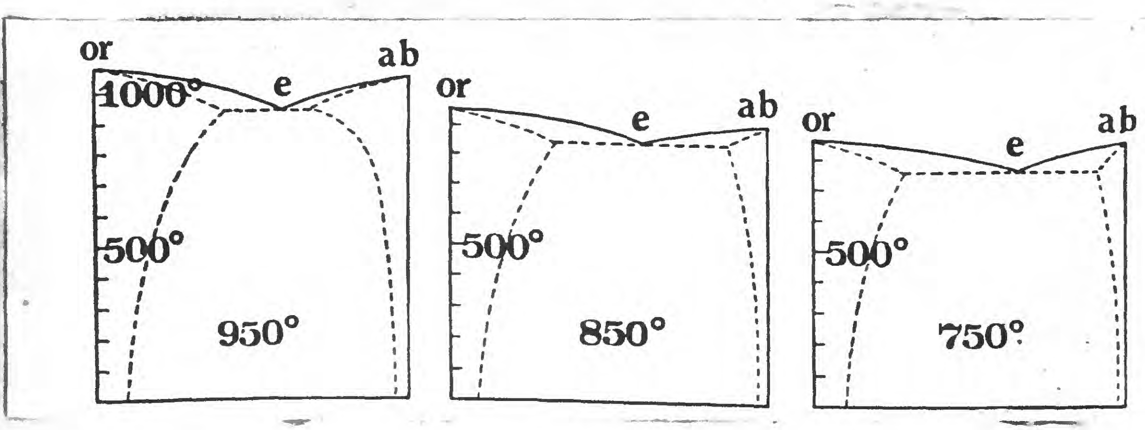



Figure 3.--Crystallization of Or-Ab melts showing decrease in Or-Ab miscibility and change in position of eutectic with falling temperature - 950°, 850°, and 750°C. Crystallization temperature decreases with increasing amounts of volatile components. (after Vogt, 1926, p. 68)

As shown in figure 3, the limits of mutual solubility decrease with falling temperature of formation. These diagrams were constructed for the initial crystallization of the feldspars under different conditions of temperature and pressure, but the same general relations apply to early-formed crystals existing in a changing physical-chemical environment during the cooling of the magma. Thus, homogeneous phases formed at high temperatures tend to unmix at lower temperatures - especially if cooled slowly through certain critical temperature ranges. The lath-shaped albite crystals present in the sanidine phenocrysts of the coarse-grained facies are believed to have formed in this manner. Certain indirect lines of evidence support this belief: (1) The absence of these laths in the fine-grained facies and, (2) the distribution of the laths within the sanidine phenocrysts of the coarse-grained facies.

The rectangular albite inclusionsare found in the sanidine of both the coarse and fine-grained facies, and there can be little doubt that the sanidine crystals of both facies were saturated with the albite molecule at the time they formed. The development of the albite laths in the sanidine crystals of the coarse-grained facies (but not in the sanidine of the fine-grained facies) must therefore be due to some difference in environmental conditions subsequent to the formation of the sanidine crystals of the two facies.

In the fine-grained alkali granite, both the sanidine and the quartz phenocrysts are smaller, by a factor of about three, than in the coarse-grained alkali granite. This suggests a shortened period within the metastable region of crystallization which agrees with the observed age relations of the coarse and fine-grained facies. The absence of the albite laths in the sanidine of the fine-grained facies seems best explained as a consequence of rapid cooling through the temperature range favorable for the exsolution of albite. This contrasts with slower cooling in the coarse-grained facies - slower cooling which would promote the required unmixing.

Additional evidence for an exsolution origin of the albite laths is their distribution within the sanidine crystals of the coarse-grained facies. The laths are never seen in the peripheral parts of the sanidine crystals and this suggests that the sanidine crystals are zoned. An explanation of the zoning and its significance is discussed below.

A common consequence of crystallization is an increase in the volatile constituents of magma. As shown in figure 3, such an increase will lower the Or-Ab eutectic, decrease miscibility, and promote unmixing. These conditions, or conditions producing a like effect, probably existed in the magma of the coarse-grained facies during the later stages of intratelluric crystallization. During this period, the sanidine crystals would continue to grow, but the material crystallizing would contain much less soda. If complete equilibrium were reached, the early formed phenocrysts would be made over into more potassic crystals of uniform composition. The other alternative is zoned crystals with more potassic rims. No direct evidence of zoning, e.g., differences in indices, or extinction angles are seen, but in albite-sanidine mixed crystals such differences would be slight. If present, they are masked by allophane which commonly clouds the potash feldspar of the alkali granite porphyry (pl. 31, B). If the crystals are zoned, then unmixed albite should not develop in the peripheral parts of the phenocrysts, i.e., those portions in equilibrium with the melt. In general, the albite laths conform to this distribution (pls. 29 and 30, A). Again, this is negative evidence, but the absence of the laths in the border zones of the sanidine phenocrysts, suggests that the laths in the interior of the crystals are due to exsolution.

Evidence for a Reaction Relation between Alkali Feldspars

Bowen (1928, p. 229) noted a difference in the relationship between potash feldspar and sodic and calcic members of the plagioclase group. The general Or-Ab relations are essentially the same as those presented by Vogt (1926, p. 68), i.e., a eutectic bounded on either side by regions of limited miscibility. Between potash feldspar and anorthite (and extending to approximately $An_{50}$) Bowen postulated a reaction relation. To support this view, Bowen noted the frequent occurrence of potash feldspar mantles (reaction rims) on basic plagioclase and the lack of such mantles on sodic plagioclase.

In the alkali trachyte from Collar Gulch, in some of the quartz-free rocks from the Red Mountain area, and in the alkaline rhyolite from the West Fork of Armell Creek, albite is armored with potash feldspar (pl. 47). If such mantles are cited as evidence to support a reaction relation between basic plagioclase and potash feldspar, then the same may be said of the more acid plagioclases mentioned above.

Bowen and Tuttle (1950) presented phase diagrams showing that high temperature modifications of potash and soda feldspars are completely miscible (fig. 4).

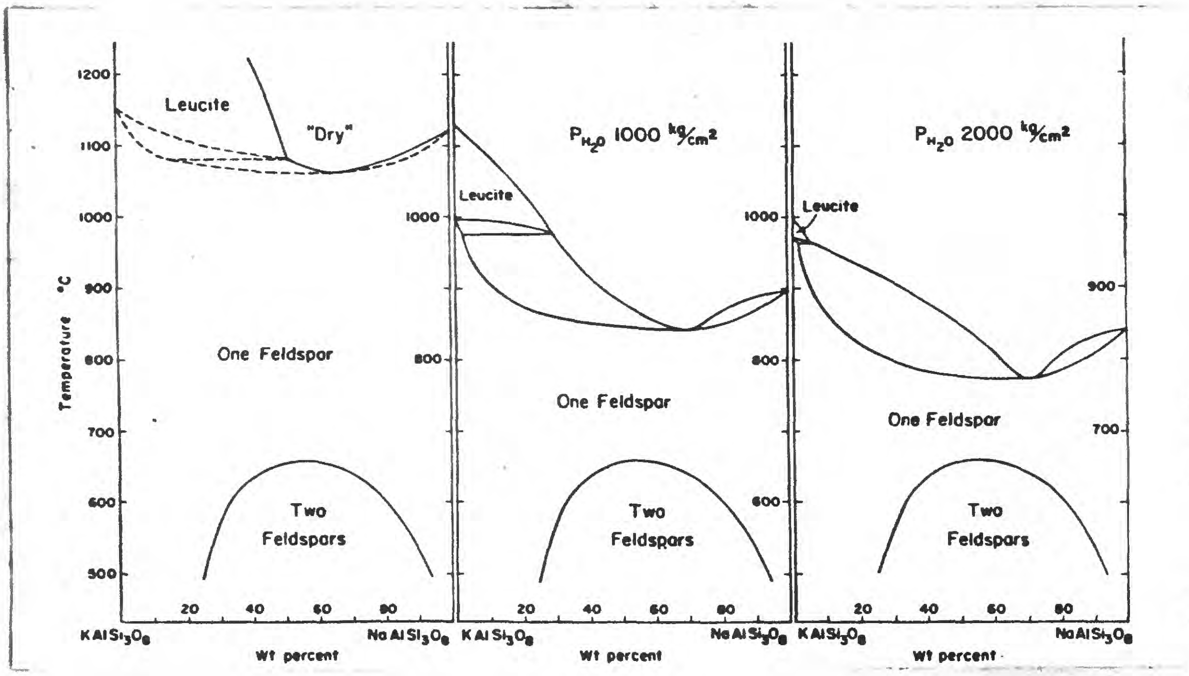


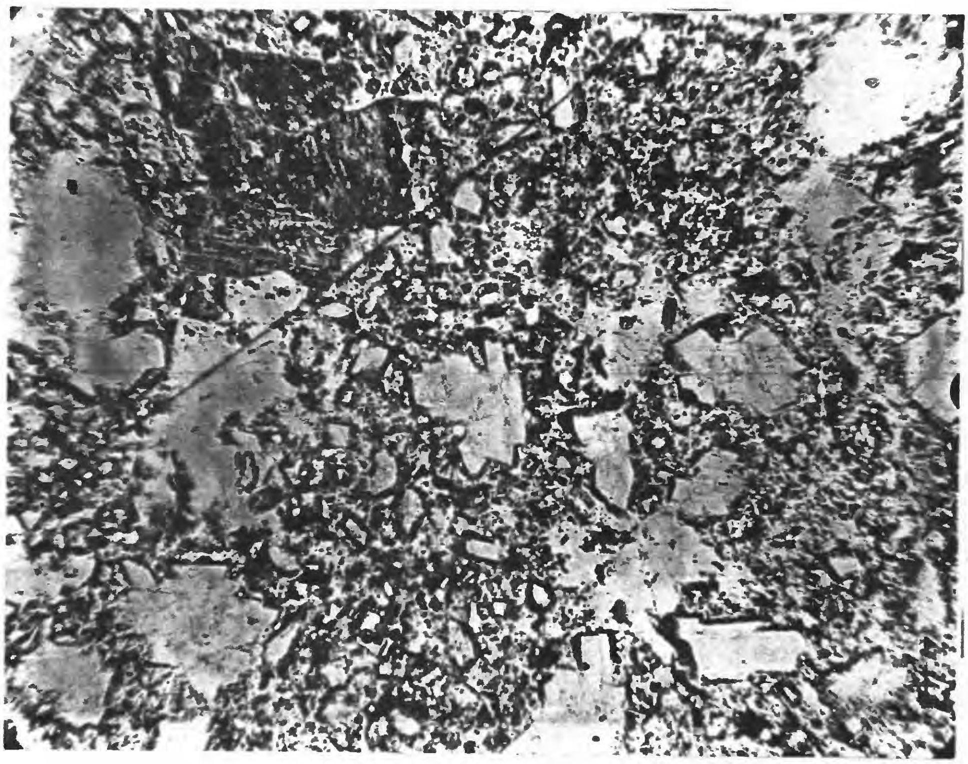

Figure 4.--Isobaric equilibrium diagrams for the alkali feldspars in dry melts and at 1,000 kg/cm² and 2,000 kg/cm² pressure of $H_2O$. (after Bowen and Tuttle, 1950)

If the incongruent melting of potash feldspar is neglected, the liquidus and solidus curves describe a binary system showing a complete series of solid solutions with a minimum melting temperature. In the lower part of the diagrams, a solvus curve appears, below which two separate

Plate 47

PHOTOMICROGRAPH OF ALKALI RHYOLITE NORTH OF JUDITH PEAK

Large gray area (upper left) is a group of sanidine crystals with strong allophane alteration. Small clear areas with angular outlines and dark borders are albite mantled with potash feldspar. Dark color of potash feldspar rims is due to allophane. Groundmass is quartz, alkali feldspar, and aegirine. Specimen from sill in Madison limestone near contact with quartz monzonite 4,400 feet north of Judith Peak. Plane-polarized light. X 50.



feldspars crystallize. Of this region Bowen and Tuttle (1950, p. 500) have this to say, - "Instead, there will form two series of solid solutions with a hiatus and a eutectic or a reaction relation, depending upon the manner of encounter of the solidus and the solvus. The indications are that it will first be a reaction relation which at still higher pressures gives way to a eutectic relation." The Judith Mountain rocks containing albite mantled with potash feldspar rims may illustrate in natural feldspars a reaction relation between potash feldspar and sodic plagioclase.

Evidence of a Eutectic Relation between Alkali Feldspars

The absence of albite in the tinguaites, and the perthitic (x-ray perthites) nature of the sanidine suggest that the tinguaites crystallized at high temperatures within the mixed crystal range. The dark-gray tinguaites contain both sanidine and plagioclase, but the plagioclase is andesine, and not albite. There is no reason to believe that these rocks crystallized at any lower temperature than the other tinguaites, and it seems probable that an appreciable content of CaO in the magma destroys the Or-Ab solid solution relationship and results in the formation of two feldspars, even at high temperatures. Tuttle (1952, p. 121), discussing the crystallization of granitic magmas, noted - "---from granitic magmas containing appreciable lime, two feldspars will crystallize in the early stages".

Albite and sanidine are both present in the alkali granite porphyry of Judith Peak, and the texture strongly suggests a eutectic relation between the two minerals (pls. 30, A and 36, B). The lime content, as a factor producing the simultaneous crystallization of two feldspars, fails completely in the case of the Judith Peak granite (analyzed CaO-0.05 percent). As previously noted, Bowen and Tuttle (1950, p. 500) in speaking of the relation Or-Ab below the solvus, state: - "The indications are that it will first be a reaction relation which at still higher pressures gives way to a eutectic relation." As shown in figure 4, the presence of volatiles tends to lower the temperature of crystallization. The abundance of volatiles in the alkali granite porphyry magma is well attested to by the granitization and silicification associated with its intrusion, and the simultaneous separation of two feldspars from this lime-poor magma seems best explained by these volatiles.

## ORIGIN OF THE INDIVIDUAL ROCK TYPES

### Evidence for Two Lines of Descent

The oldest rocks in the Judith Mountains are the quartz monzonite porphyries. Later igneous rocks represent two lines of descent: (1) A more siliceous type represented by rhyolite, and (2) Rocks relatively poor in silica and high in the alkalies, best exemplified by the tinguaites. The youngest rock, the alkali granite porphyry is rich in both silica and the alkalies, and is believed to represent a union of the two separate lineages (pl. 2).

Quartz monzonite is the dominant rock and forms major intrusive bodies in both the northern and southern structural sub-provinces. The rhyolites are abundant in the southern part of the mountains but are almost entirely absent in the northern sub-province. . Tinguaite, alkali syenite, and syenite are restricted to the area north of the Warm Spring Creek fault.

The distribution of rock types outlined above delineates two petrographic sub-provinces which correspond to the two structural sub-provinces: (1) A southern sub-province which contains only calc-alkaline rocks, and of these perhaps 40 to 50 percent are highly siliceous, i.e., the rhyolites, and (2) A northern sub-province which contains both calc-alkaline and alkaline rocks. Only a small percentage (probably less than 1) percent of the calc-alkaline rocks are rhyolites. Most of the late igneous rocks are silica-poor.

The chemical and corresponding normative compositions of 10 specimens representing the major rock types of the Judith Mountains are shown in tables 2 and 3. Table 5 gives the weight percentage ratios of alumina to total alkali oxides for the same ten rocks. The ratios fall into two distinct groups: (1) 1.63 to 1.84 - the calc-alkaline rocks, and (2) 1.16 to 1.38 - the alkaline rocks.

TABLE 5.--Weight percentage ratios of alumina to combined soda and potash.

| | Weight percent $Al_2O_3$ | Weight percent $K_2O + Na_2O$ | Ratio Alumina : Total alkali oxides |
|---|---|---|---|
| 1 | 16.30 | 8.93 | 1.83 |
| 2 | 15.74 | 8.72 | 1.81 |
| 3 | 14.58 | 7.98 | 1.83 |
| 4 | 13.88 | 8.52 | 1.63 |
| 5 | 16.60 | 9.02 | 1.84 |
| 6 | 14.54 | 11.90 | 1.22* |
| 7 | 17.14 | 12.58 | 1.38* |
| 8 | 15.63 | 8.78 | 1.78 |
| 9 | 16.74 | 14.41 | 1.16* |
| 10 | 13.44 | 10.49 | 1.28* |

* Alkaline rocks

1. Coarse-grained quartz monzonite porphyry from east slope of Porphyry Peak.
2. Coarse-grained quartz monzonite porphyry from Alpine Gulch, 1 1/2 miles southwest of Maiden.
3. Medium-grained quartz monzonite porphyry from near top of Black Butte.
4. Rhyolite porphyry from near top of Pyramid Peak.
5. Fine-grained syenite porphyry from northeast base of Maginnis Mountain along East Fork of Ford Creek.
6. Coarse-grained gray tinguaite porphyry from sill on northeast side of Armell Creek 2 1/2 miles northwest of Judith Peak.
7. Gray tinguaite (crowded) porphyry from north side of Lookout Peak.
8. Fine-grained syenite porphyry (Lewis Peak type) from dike that cuts gray tinguaite sill 1 1/4 miles southwest of Lookout Peak.
9. Green tinguaite porphyry from dike 1 mile northwest of Maiden.
10. Coarse-grained facies of the alkali granite porphyry from the east spur of Judith Peak.

Figure 5 is a Larsen triangular diagram constructed on the basis of normative composition (Larsen, 1938). The plot of the 10 specimens falls into two groups which coincide, in part, with the two groups shown on table 5. The quartz monzonites and the rhyolite are shown by the dashed lines, which have a positive slope (slope to the right), and the tinguaites, the alkali granite and the syenites by the solid lines with a negative slope. The positive lines represent the calc-alkaline rocks; the negative lines include all the alkaline rocks, both silica-rich and silica-deficient, and the syenites. On table 5, the syenites fall within the calc-alkaline group, but in figure 5 they plot with the alkaline rocks. The negative slope of their lines is due to a relatively high total femic content with respect to the anorthite content of the feldspar.

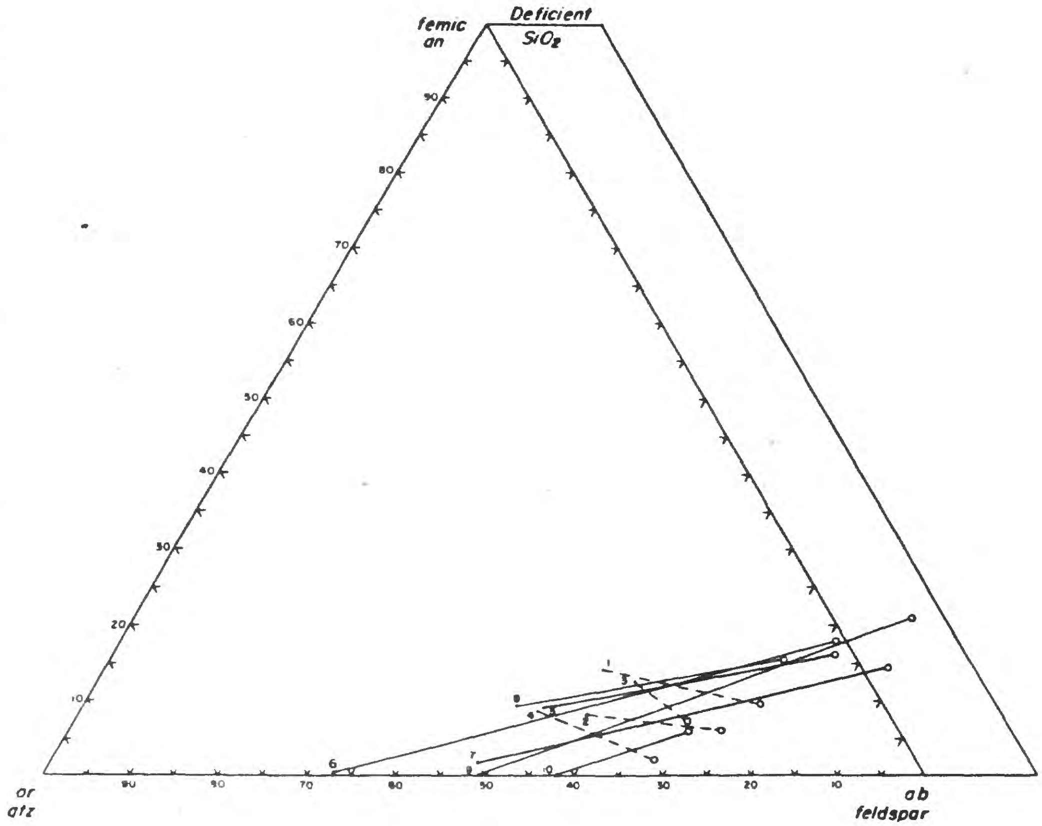
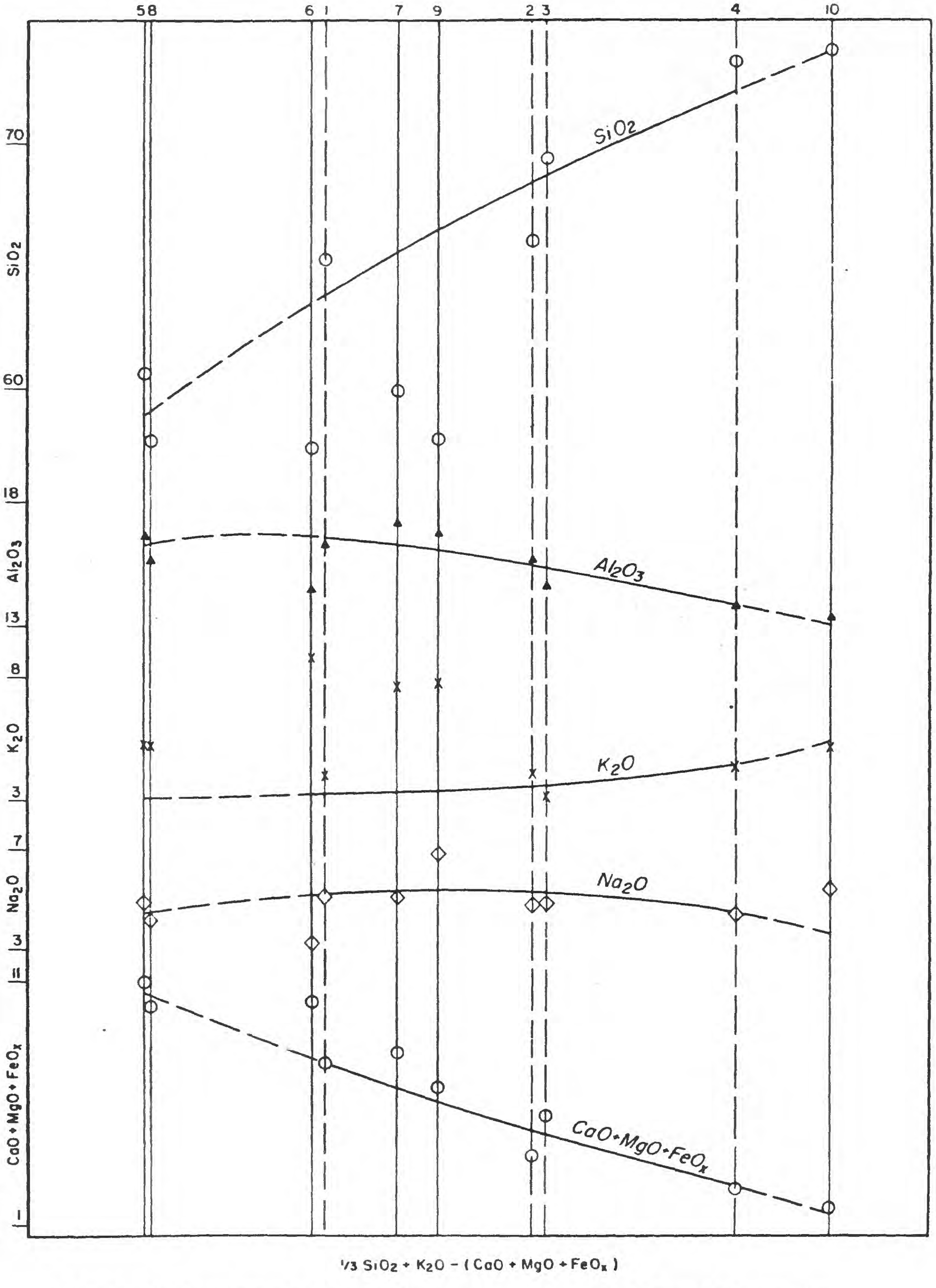



Figure 5.--Larsen triangular diagram of Judith Mountain rocks. Dashed lines are the monzonitic rocks and rhyolite. Solid lines are the tinguaites, syenites, and the alkali granite. Dots represent the composition of the normative feldspar. Circles show the relative amounts (normative) of total feldspar, quartz, and femic constituents.

The group with the positive slope lines is believed to represent rocks of a "normally" differentiated series; the rocks whose lines slope to the left are believed to have crystallized from contaminated magmas.

On plate 48, the chemical analyses of the rocks have been plotted on a modified Larsen variation diagram (Larsen, 1938). The significance of the diagram is limited by three factors: (1) The number of analyses from which the curves are constructed is small. (2) The curves represent only intermediate to acid rocks, and therefore are incomplete. (3) The rocks are all porphyritic and may not have crystallized from liquids of their own composition. With these limitations in mind we may examine plate 48 for any evidence of two lines of descent.

The figures across the top refer to the 10 specimens and correspond to those plotted on the triangular diagram and with the numbers shown in tables 2, 3, and 5. These numbers indicate the approximate sequence of irruption. The dashed vertical lines, 1, 2, 3, and 4, are the three quartz monzonites and the rhyolite. The oxide curves were constructed to fit these analyses as closely as possible and to conform in shape and slope to curves presented by Bowen, Harker, Larsen and others to illustrate liquid descent of a normally differentiated series. The close correspondence of the quartz monzonite and rhyolite analyses with the curves indicates such an origin, i.e., by fractional




Modified Larsen variation diagram of Judith Mountain rocks. Curves based on analyses 1, 2, 3, and 4. Dashed vertical lines are the monzonitic rocks and rhyolite. Solid vertical lines are the tinguaites, syenites, and the alkali granite.

crystallization. It is true that the curves are based on these analyses, but it is significant that the curves, thus defined, agree so well with the expected changes in liquid composition. Specimens 1, 2, 3, and 4, then, belong to one line of liquid descent, that of the intermediate to acid calc-alkaline rocks.

The rocks which plotted with negative slope lines on the triangular diagram are shown on plate 48 by the solid vertical lines, and several significant departures from the oxide curves are apparent. The tinguaites - 6, 7, and 9 - are markedly low in $SiO_2$ and high in $K_2O$. Values for $Na_2O$ are erratic - 6, below the curve, 7, on the curve, and 9 above the curve. The two syenites, 5 and 8 - are slightly high in $K_2O$, but otherwise fit the curves fairly well. But the syenites as plotted, do not fall in the proper part of the diagram in relation to their position in the igneous sequence.

On page 161, the post-monzonitic rocks were referred to two lines of descent. Certainly the quartz monzonites - rhyolites represent one line. But in a restricted sense, the syenites, alkali syenites, and the tinguaites do not seem to represent the other line of liquid descent; rather they form a group whose composition departs from that shown by the curves for the calc-alkaline rocks.

On the triangular diagram, the alkali granite porphyry of Judith Peak is represented by number 10. Although highly siliceous, it plots with the silica-poor - silica-deficient group. As shown on the variation diagram, the alkali granite fits the oxide curves well with the exception of the value for $Na_2O$. Not shown on the diagram is the extremely low value, even for a granite, of CaO - 0.05 percent. The silica content is close to that of the rhyolite, but the remarkably low lime content, and the high percentage of soda clearly separate this rock from the rhyolite, the late siliceous differentiate of the calc-alkaline series.

In summary, the chemical and normative analyses and the diagrams constructed from them reveal the following: (1) The quartz monzonites and the rhyolites seem to represent rocks that crystallized from liquids whose composition changed in an orderly fashion according to the laws governing the usual course of fractional crystallization of a calc-alkaline magma. (2) The syenites and the tinguaites are not a part of this series. If more analyses were available, the syenite-tinguaite rocks might exhibit some systematic change, and thus establish another series; but with the present data, they constitute simply a separate group. (3) The alkali granite porphyry seems to be related to both the quartz monzonite-rhyolite line and the syenite-tinguaite group.

The writer believes that the tinguaite, the alkali syenite, the syenite, and the alkali granite have crystallized from contaminated magmas. The fact that these rocks do not fit into the monzonite-rhyolite series, does not prove that they are hybrid rocks. It merely illustrates that they do not lie in the direct line of calc-alkaline liquid descent.

## Quartz Monzonite and Rhyolite

Evidence has been presented indicating that these rocks have originated by fractional crystallization from some parental calc-alkaline magma. Rocks representing this parental magma are not exposed in the area, but extrapolation of the quartz monzonite-rhyolite variation curves beyond the "basic" end points toward a magma with the composition of a basalt.

## Syenite, Alkali Syenite and Tinguaite

The syenites, alkali syenites and the tinguaites comprise a group in which the members are genetically related and they are therefore discussed together. The syenites and the alkali syenites are older than the tinguaites, but in this section the tinguaites are considered first as they are believed to be the key to the genesis of the group as a whole.

It has been pointed out on previous pages that the tinguaites are restricted to the northern petrographic sub-province. This corresponds with the northern structural sub-province - an area in which the exposures of Madison limestone cover only about 5 percent of the total area underlain by sedimentary rocks. This contrasts with a figure of approximately 40 percent for the southern sub-province. Field evidence shows that an important step in the later stages of emplacement of the initial monzonitic intrusions within the northern sub-province, was the breaching of the Madison limestone by magmatic stoping. It is believed that limestone blocks thus stoped, sank and desilicated some magma at depth, thereby giving rise to the tinguaites according to Daly's hypothesis.

The syenites are regarded as products of contaminated magma, only partially desilicated, and irrupted at a stage before the alkalies became highly concentrated. They represent an intermediate stage in the development of the silica-deficient alkaline rocks. Many specimens, both in the field and under the microscope, appear intermediate between certain of the syenites and the gray tinguaites; the gray tinguaites in turn, are related by transitional types to the green tinguaites.

Although the transitional types indicate a genetic relation between "end members," these rocks do not necessarily fall into a chemical series. In general, hybrid rocks may be expected to show somewhat erratic departure from a well defined series. Variation in composition of magma at the time of contamination, differences in composition of foreign material, relative amounts of magma and foreign material, rate of reaction between magma and contaminant, and period of time between contamination and irruption all contribute to variations in the composition of syntectic rocks. An example of this variation is found at Scawt Hill (Tilley and Harwood, 1931, p. 447) where six major types and five sub-types of hybrid rocks occur in the vesiculated border zone of the dolerite. In the Judith Mountains, the variables inherent in the syntectic origin of alkalinerocks permit the explanation of such related yet different types as the "normal" syenites, the alkali syenites from Collar Gulch and the Red Mountain area, quartz aegirine syenite from Collar Peak, and various types of tinguaites. The partial analyses below (table 6) show that even among the closely related tinguaites there is a considerable range in chemical composition.

TABLE 6. --Variation in composition of tinguaites shown by partial analyses

| | Gray tinguaite (number 7) | Gray tinguaite (number 6) | Green tinguaite (number 9) |
|---|---|---|---|
| $K_2O$ | 7.50 | 8.72 | 7.68 |
| $Na_2O$ | 5.08 | 3.18 | 6.73 |
| $Fe_2O_3$ | 2.40 | 4.02 | 3.03 |
| $FeO$ | 2.07 | 1.84 | 1.38 |
| $MgO$ | 0.60 | 1.96 | 0.58 |
| $CaO$ | 3.16 | 3.14 | 1.94 |

## Evaluation of Contrasting Modes of Origin

The association of alkaline and calc-alkaline rocks in the Judith Mountains negates, for the origin of the tinguaites, those theories based on two separate and unrelated parental magmas. From the remaining theories there emerge two principal theses: (1) An origin based on fractional crystallization, and (2) A syntectic origin. Bowen, the chief protagonist of the first theory, derives alkaline magmas by special conditions of fractionation of a basaltic magma. Daly, the author of the syntectic theory, achieves the same result by the assimilation of carbonate rock. The genesis of the Judith Mountain tinguaites may be examined with respect to these two modes of origin.

Bowen's Hypotheses, -

Reactive resorption of biotite and hornblende:

The micas, excepting secondary sericite, are rare constituents of any of the Judith Mountain rocks. If the assumption is made that biotite is missing because of the gravitational settling required by the theory, then why is hornblende, an earlier mineral phase, so abundant?

Separation of biotite and early-formed quartz from liquid rich in $NaAlSiO_4$:

The objections noted above apply equally to this theory.

Pseudoleucite reaction:

It has already been noted that this theory seems adequate to account for rocks of phonolitic composition. But it seems doubtful that the prescribed course of differentiation has been followed with sufficient frequency to explain all such rocks. Furthermore, this theory does not satisfactorily explain the peculiar concentration of alkaline rocks within certain areas. The petrographic province of central Montana (Pirsson, 1905) and (Larsen, 1940) contains both alkaline and calc-alkaline rocks, but it is the persistent occurrence of alkaline rocks in many of the scattered mountain groups that sets the province apart as a unit.

The igneous rocks of the Judith Mountains must be considered in relation to similar rocks found elsewhere in the province. If it is assumed that the pseudoleucite reaction is responsible for the development of the nepheline bearing rocks, what are the special factors that have controlled this intricate process of differentiation in not one, but in all of the separate yet related occurrences? The difficulty of finding appropriate controlling factors is apparent, and for this reason, the pseudoleucite reaction theory is rejected for the rocks in question. Certain aspects of the syntectic theory are discussed in this connection on page 183.

Daly's Hyopthesis. --There is no specific evidence in the Judith Mountains against limestone syntexis. This may be due to: (1) The syntectic theory is expressed only in general terms and therefore has a certain degree of freedom which is lacking in Bowen's precisely defined mechanisms, or (2) The tinguaites are the result of limestone syntexis.

What evidence is present in the Judith Mountains to support the concept of a syntectic origin of the tinguaites? The development of lime silicates along limestone-igneous contacts has long been cited as evidence favoring the syntectic origin of alkaline rocks. This evidence is lacking in the Judith Mountains. The limestone at most quartz monzonite contacts is bleached and partially recrystallized, but the wholesale replacement of the limestone by heavy lime silicates has been observed at only a few localities. But the tinguaites bear no relation to the quartz monzonite-limestone contacts. They have been intruded from below and cut quartz monzonite and sediment alike (pl. 45).

The lack of reaction along the contacts is not surprising; rather it is to be expected. The abundance of intratelluric phenocrysts reveals that, not only was the magma not endowed with any superheat, but also that the temperature had fallen sufficiently to precipitate perhaps one quarter to one third of the total volume of the magma as crystalline material at the time of intrusion to its present position. The source of the tinguaite magma was below, -- there also must be the site of reaction. This is, of course, a very convenient place for reaction to occur, but the writer finds it far easier to sink large blocks of limestone into a zone of hotter and perhaps more basic magma than to do the same with crystals of biotite and hornblende as required by Bowen's theory of reactive resorption. Bowen in general rejects limestone syntexis, but admits (1928, p. 222) that, "The addition of limestone to basaltic magma may perhaps give rise to liquid capable of precipitating melilite in some cases and from such a liquid it is possible that some alkaline rocks may form by further differentiation".

The strongest evidence for a syntectic origin of the tinguaites is the coincidence of the petrographic and structural sub-provinces. The alkaline rocks are confined to the northern sub-province, in which the mechanism of emplacement was such that large segments of the Madison limestone were removed by magmatic stoping. Limestone was thus available for reaction with some magma at depth. In the northern part of the mountains, the rocks irrupted subsequent to the stoping of the limestone are predominantly those types poor in silica, rich in the alkalies and rich in the volatiles. In the southern sub-province where the Madison limestone was not thus removed, the rocks which follow in sequence the initial quartz monzonites are not syenite, alkali syenite, and tinguaite, but the highly siliceous rhyolites of the calc-alkaline series.

The writer was once admonished to have opinions and not convictions. Admittedly, the evidence in support of a syntectic origin is permissive. But to ascribe the striking coincidence of structural and petrographic sub-provinces to chance is to ignore the field evidence--evidence so compelling that the writer cannot withhold the opinion that the tinguaites of the Judith Mountains are the result of limestone syntexis.

## Alkali Granite Porphyry of Judith Peak

Evidence has been presented (p. 167) indicating that the alkali granite porphyry of Judith Peak is related to both the calc-alkaline series and the hybrid rocks. There seem to be no general prejudices against accepting a genetic relation between an alkali granite and some calc-alkaline parent magma. Indeed, unless the concept of two primary magmas is restored - one yielding only alkaline rocks, and the other calc-alkaline rocks - there is no alternative. But the suggestion of a relation between highly siliceous alkaline rocks and feldspathoid-bearing types may be met with some resistance. However, the concept is not a new one, and the occurrence of both types among alkaline suites of many areas seem to be more than accidental. Bowen (1915, pp. 57-58) stated - "In passing from the normal biotite granites to the nephelite syenites and related rocks, an important stage has been passed over, viz., the stage of alkaline granites and syenites".

But in the Judith Mountains, the alkali granite is not intermediate in age between a biotite granite and the nepheline-bearing rocks. How then, may the high silica content of the alkali granite porphyry be reconciled with the concept that the related alkaline rocks have originated in part by the extraction of silica by reaction with limestone? The writer believes that the alkali granite represents a late siliceous differentiate of the calc-alkaline series, contaminated by alkaline fluids derived from a tinguaite magma - fluids with which the tinguaite was endowed by the action of resurgent carbon dioxide.

No direct mixing of magmas is implied. The examination of many thin sections reveals the presence of no minerals which do not properly belong in the alkali granite, i.e., no relicts of minerals found in the tinguaites, but which would not be expected in the granite, e.g., melanite, spinel, etc. Furthermore, the addition of tinguaite magma would not only enrich the rhyolite in the alkalies, but would also cause a reduction of silica, a reduction not indicated by the composition of the alkali granite.

But the proposed mechanism does require the co-existence of rhyolite magma and solutions escaping from a tinguaite magma chamber. On preceding pages it has been emphasized that in the northern sub-province, rocks irrupted following the initial quartz monzonite intrusions were successively richer in the alkalies and poorer in silica. This is generally true for those rocks which the writer believes originated by limestone syntexis. But these do not include all rocks. Some of the post-monzonitic rocks are calc-alkaline and siliceous.

The complexity of resevoir conditions which existed beneath the mountains is attested to by the intricate pattern of different textural and compositional facies within the composite stocks, and mineralogical evidence suggests actual mixing of some of the calc-alkaline magmas. Although co-existence of rhyolite and tinguaite magma within the same area thus seems quite possible, there are reasons for believing that the contaminating solutions were expelled at a stage when the crystallization of the tinguaite magma was well advanced: (1) The alkali granite is younger than the tinguaites, and (2) The alkali granite is rich in soda whereas potash is the dominant alkali of the tinguaites.

The soda:potash ratios in the sequence, gray tinguaite (early) - green tinguaite (late) - alkali granite (latest) are shown in table 7, below.

TABLE 7.--Soda:potash ratios of tinguaites and alkali granite

| Gray tinguaite | Green tinguaite | Alkali granite |
|---|---|---|
| 0.51* | 0.87 | 1.06 |

*average of two.

The ratios show a definite increase in soda relative to potash in the later rocks.

The sequence of soda following potash has been observed by Grubenman and Niggli (1924) who state that where both alkalies have been introduced in contact metamorphism it is common to find potash older than soda. The same sequence is demonstrated in some of the complex pegmatites where soda-bearing solutions have formed replacement units of cleavelandite or sugary albite in the earlier products of aqueo-igneous crystallization. Pecora (1942) has noted the same soda-potash trend in a potash rich syenite and its soda-rich, nepheline-bearing pegmatite derivative in the Bearpaw Mountains, Montana. Gilluly (1932-1933) has shown conclusively the importance of late solutions rich in soda, in the formation of albite granite near Sparta, Oregon.

Soda following potash is a reversal of the normal sequence of crystallization, and Bowen (1932, p. 123) attributes this to a fractional distillation rather than fractional crystallization. Volatiles, whether juvenile or resurgent, thus appear to be effective, not only in concentrating the alkalies, but also in separating them into an earlier potash rich phase, followed by a soda rich phase. Such a separation is suggested in the Judith Mountains by the late sodic solutions that produced the analcite and natrolite in the green tinguaites, and by the soda:potash ratios shown in table 7. The solutions that contaminated the rhyolite probably belong to a stage of high volatile concentration when soda predominated over potash.

The exact form of the alkalies in solution is not known. Shand (1930, p. 417) gives equations (assuming resurgent volatiles) indicating the presence of $Na_2SiO_3$, $Na_2CO_3$, and $NaAlSiO_4$ and equivalent potassium compounds. Bowen (1915, pp. 45-46) gives equations (based on juvenile volatiles) which yield $Na_2CO_3$, $NaAlSiO_4$ and NaOH, and the corresponding potassium compounds. The solutions would thus appear to be undersaturated in silica with respect to the feldspar molecules, but the resultant dilution of silica in the rhyolite would be much less than that produced by actual mixing of magmas. Furthermore, some of the alkali compounds are highly corrosive in contact with silica, and passage of these solutions through any quartz bearing rock would tend to enrich the solutions in $SiO_2$.

In summary, the alkali granite follows the tinguaites in the irruptive sequence, it was intruded close to the center of one of the tinguaite dike swarms, and the alkali ratio of the alkali granite agrees with the changing composition of thetinguaite magma.

The addition of solutions to the rhyolite magma necessary to affect the required increase in the alkalies would reduce the viscosity of the magma. The alkali granite contains only 0.32 percent $H_2O+$ (probably from the allophane) and no hydrous minerals that were original constituents of the rock. But the abundance of volatiles in the magma is clearly shown by the granitization of the sandstone and shale inclusions and by the silicification of the peripheral zone of the fine-grained facies of the alkali granite and adjacent rocks -- silicification believed due in part to fluids squeezed out of the alkali granite porphyry by filter pressing.

The high volatile content of the magma might be expected to lower the temperature of crystallization. Evidence indicating a high concentration of volatile constituents and a resultant depression of the temperature of crystallization has already been noted in the simultaneous precipitation of the two alkali feldspars (p. 161). In this connection it is interesting to note that the high-low quartz inversion of the phenocrysts from the Judith Peak granite porphyry indicates a temperature of formation characteristic of quartz in granite - well below that of most rhyolites (Keith and Tuttle, 1952). They (1952, p. 203) attribute this to the presence of trace elements, concentrated in the volatiles, which enter into the quartz structure. One final point is the possibility that the reduced viscosity of the alkali granite magma might help explain the gigantism of the quartz phenocrysts.

## CONCLUSIONS

From Canada to Mexico, the area east of the Rocky Mountain front is marked by an irregular belt of scattered igneous centers in which the incidence of alkaline rocks is far above that of an equivalent volume of rocks in the orogenic belt to the west. Related but separate areas are found west of the Rocky Mountain front in parts of the Wyoming Basin and the Colorado Plateau.

Larsen (1940) has discussed those rocks which lie within the northern end of this belt - the petrographic province of central Montana. He believes that basalt was the primary magma for the entire province. The parent magma of each sub-province is represented by the exposed basic rocks, either basalt, orthoclase basalt, shonkinite or similar mafic rocks. The "alkalic basalts" are explained as products of slow differentiation at great depth with the separation of calcic plagioclase, hypersthene, and some olivine. Larsen believes that a long period without deformation would favor the slow deep-seated differentiation necessary to yield the basic alkaline rocks. The less basic, and generally later, rocks are thought to be the result of rapid fractionation of the various basic magmas - modified in most cases by the assimilation of granitic material. The amount of assimilated material is greatest in those sub-provinces with the most siliceous rocks.

Holmes (1945) has noted the transformation of inclusions of granite to leucitic material in some of the basic lavas of southwest Uganda, and assimilation of granitic material has been suggested by Williams (1936) in the Colorado Plateau to explain the high potash content of rocks in the Navajo sub-province, as compared with the high soda content of rocks in the adjacent Hopi sub-province. Evidence is found in the abundance of granitic inclusions, partly resorbed, in the Navajo rocks and the almost complete absence of such inclusions in rocks of the Hopi sub-province. The parent magma beneath both sub-provinces is assumed to have been a nepheline basalt. The observations of Holmes and Williams suggest that selective fusion of granitic material results in an increase in potash, but not in silica.

Some control seems necessary to account for the concentration of alkaline rocks in the relatively stable Montana foreland. Harker, (1909, pp. 93-100) has postulated a world-wide division of alkaline and calc-alkaline suites on a tectonic basis. Backlund (1933) correlates alkaline rocks with a peridotite parental magma generated beneath stable areas, as contrasted with basaltic magma underlying epiorogenic areas, and granitic magma beneath orogenic belts. The writer does not agree with these generalizations, but feels that tectonic events have been important in the generation of alkaline rocks in central Montana.

On an earlier page Bowen's theory based on the pseudoleucite reaction was rejected on the grounds that it failed to explain the distribution of rocks noted above. Limestone syntexis has been advanced as the preferred theory to explain the alkaline rocks of the Judith Mountains. This theory must meet the same requirements as those demanded of Bowen's theory, i.e., it must account for the concentration of alkaline rocks in the central Montana region. The writer proposes the following explanation.

In the orogenic belt to the west the development of syntectics would be inhibited by the disturbance and destruction of magma reservoirs by repeated tectonic movements. In the foreland belt, long continued periods of crustal stability would permit uninterrupted contamination and favor the development of syntectics.

In the Judith Mountains, structural evidence indicates that the Madison limestone was the source of carbonate material which is thought to have reacted with the magma to yield the alkaline rocks. But the Madison limestone was not necessarily the dominant contaminating agent in the other mountain groups of central Montana. Carbonate material is present throughout the sedimentary sequence of the region,--especially in the Ellis group, the Heath formation, the Devonian, the Cambrian, and in some areas, the pre-Cambrian Beltian rocks.

The structural and petrographic relations which so strongly suggest a syntectic origin for the alkaline rocks of the Judith Mountains may be completely obscured in the related mountain groups - especially in those where the principal sources of reactive rock are deeply buried, or where extrusives have covered much of the surface. The writer does not believe that any one theory on the origin of alkaline rocks is adequate for all occurrences. However, the evidence so well displayed in the Judith Mountains may provide a solution to the vexing problem of the origin of the alkaline rocks so abundant in the "platform" areas of the Rocky Mountain region.

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