General Geology and Petrology of the Precambrian Crystalline Rocks, Park and Jefferson Counties, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 608-B

General Geology and Petrology of the Precambrian Crystalline Rocks, Park and Jefferson Counties, Colorado

By C. C. HAWLEY *and* R. A. WOBUS

GEOLOGY AND ORE DEPOSITS OF THE SOUTHERN TARRYALL REGION, PARK AND JEFFERSON COUNTIES, COLORADO

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Metamorphic rocks in the Tarryall region were intruded by Precambrian igneous rocks in three distinct episodes 1.7, 1.46, and 1.04 billion years ago. Late phases of the final intrusion, the Pikes Peak Granite, were accompanied by beryllium-bearing greisens

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CONVERSION TO METRIC SYSTEM

In this report the main units of measurement are inches, feet, miles, and square miles. These units may be converted to the metric system by multiplying by the following factors:

English unit *To convert*	*Multiply by*	*Metric unit* *To obtain*
Inches	2.54	Centimetres (cm)
Feet	0.3048	Metres (m)
Miles	1.609	Kilometres (km)
Square miles	2.59	Square kilometres (km^2)

GEOLOGY AND ORE DEPOSITS OF THE SOUTHERN TARRYALL REGION, PARK AND JEFFERSON COUNTIES, COLORADO

GENERAL GEOLOGY AND PETROLOGY OF THE PRECAMBRIAN CRYSTALLINE ROCKS, PARK AND JEFFERSON COUNTIES,COLORADC

By C. C. HAWLEY and R. A. WOBUS

ABSTRACT

The southern Tarryall region in the southwestern part of the Colorado Front Range is underlain by dominantly metasedimentary and igneous rocks of Precambrian age. The youngest of these rocks are related to the Pikes Peak Granite, and are the parents and dominant hosts of greisen mineral deposits described in Chapter A of this professional paper.

A sequence of layered metamorphic rocks, which forms the matrix for Precambrian intrusive rocks, consists of locally sillimanitic biotite gneiss, sillimanite-cordierite quartz gneiss, calc-silicate gneiss, and amphibolite. These rocks formed as a result of the metamorphism of clastic sedimentary rocks containing subordinate interlayered limy beds. The primary metamorphic assemblage of potassium feldspar and sillimanite in the biotite gneiss, along with calcic plagioclase and hornblende in amphibolite, indicates that the layered gneiss series is of almandine amphibolite facies of regional metamorphism. These assemblages plus laboratory data suggest maximum p–T conditions of approximately 6 kb and 700°C, with water available to reactions and a system locally open to CO_2.

Approximately at the time of regional metamorphism—circa 1.7 b.y. (billion years) ago (Precambrian X)—the rocks were folded over northeasterly trending axes and were invaded by magma of average granodioritic composition. The first generation of intrusive rocks is tentatively correlated with the Boulder Creek Granodiorite; quartz-diorite gneiss, granodiorite gneiss, and quartz monzonite gneiss comprise the main Boulder Creek(?) rock types. Although locally crosscutting, the orthogneiss plutons show structures and long segments of their contacts that are conformable with the older layered rocks. Late in Boulder Creek(?) time or as a separate event mafic magmas were emplaced, producing hornblendites, diorites, and gabbros, now slightly metamorphosed.

Some 250 million years after emplacement of the Boulder Creek(?), or near 1.46 b.y. ago (Precambrian Y), the area was invaded by magmas of dominant quartz monzonitic composition which are correlated, tentatively, with the Silver Plume Quartz Monzonite. Although varied texturally, the main Silver Plume(?) masses are similar in composition and are crudely oval shaped plutons that deformed, recrystallized and locally retrograded the layered metamorphic hosts. A locally named unit, the quartz monzonite of Elevenmile Canyon, is probably related to the Silver Plume period of plutonism.

The next event recorded in the rocks began approximately 400 million years after emplacement of the Silver Plume(?) Quartz Monzonite. This event, essentially plutonic and dated near 1.04 b.y. ago, was dominated by the emplacement of the Pikes Peak Granite and the locally important Redskin Granite. The Pikes Peak Granite of the region includes a small batholith termed the Tarryall Mountains batholith as well as a small part of the main Pikes Peak batholith. In both batholiths, the rocks are biotitic, coarse-grained, nearly massive, and characterized by fluorine approaching 0.5 weight percent. Local facies in the Tarryall Mountains batholith are enriched enough in rare metals like tin, beryllium, lithium, and rubidium to be called tin granites, as is the Redskin Granite. The Redskin contrasts with the Pikes Peak in its fine- to medium-grained texture, higher muscovite content, and slightly more sodic composition, but it resembles the Pikes Peak in its massive, sharply crosscutting plutons, and in its radiometric age, trace metal and fluorine content. Biotites from both Redskin and Pikes Peak Granites are extremely iron-rich and, though similar to pegmatite biotites, are enriched in trivalent iron or alumina; they are most similar to biotites from other greisen-bearing granite bodies.

The porphyritic and granite-aplite facies of the Redskin Granite are the hosts of most beryllium-bearing greisen deposits. It is proposed that the greisens were formed from fluorine-rich aqueous fluids which separated, possibly continuously, from late fluorine- and water-rich melts. Essentially they are the culmination of a trend toward volatile enrichment traceable through the Pikes Peak and Redskin Granites. This enrichment is monitored by the increased soda, muscovite, and discrete plagioclase content of the younger rocks of the series.

Locally overlying the Redskin Granite and all older rocks are rocks and deposits of Tertiary and Quaternary age. Andesitic volcanics at the southwest edge of the area and scattered welded rhyolitic tuffs in the southeastern and south-central parts of the region are part of the Thirtynine Mile Andesite and Wall Mountain Tuff.

Structures in the old layered rocks were formed mainly in two episodes of deformation. The first episode, near the time of maximum regional metamorphism and Boulder Creek(?) emplacement, resulted in the broad open northeast-plunging Tarryall anticline and Round Mountain syncline. The second period of deformation was local and is related in time and space to Silver Plume(?) emplacement. Faulting, primarily on steep northwest-striking sets, began before Silver Plume time, was intermittent through Pikes Peak time, and likely continued in the post-Precambrian. A dominant orthogonal joint system oriented vertically and horizontally suggests that most post-Pikes Peak movement in the area was vertical.

The history of the region through Paleozoic and Mesozoic time can only be deduced relative to nearby areas, but volcanism and lake bed formation (Oligocene) and at least minor faulting occurred in middle to late(?) Tertiary time in and near the region.

INTRODUCTION

Attention was focused on the southern Tarryall region, Colorado, by the discovery of beryllium ore on the Badger Flats in 1955 and the subsequent exploitation of the ore at the Boomer mine. The region is also noteworthy because of an unusually complete and varied suite of Precambrian rocks which includes the three main Precambrian granitic units of the Front Range—Boulder Creek(?), Silver Plume(?), and Pikes Peak. These rocks are in juxtaposition in the region; they clearly show crosscutting relations and differences in petrologic character related to the level of their emplacement. The granitic rocks were intruded into an older layered gneiss terrane corresponding lithologically to the Idaho Springs Formation of the central Front Range.

This report deals mainly with the general geology of the Precambrian rocks; as such it complements chapter A (Hawley, 1969) which described the beryllium deposits. The igneous rocks are especially stressed in this chapter; for example, an attempt is made to trace the evolution of the Pikes Peak granitic rocks from granodiorite through alkalic granite to the residual hydrothermal solutions which formed the beryllium deposits of the region.

LOCATION AND GEOGRAPHY

As defined here, the southern Tarryall region includes the southern part of the Tarryall Creek drainage, the Tarryall Mountains, and Badger Flats, and most of the Puma Hills. The area studied either by reconnaissance or by detailed methods is irregular, but lies within the boundaries of lat 38°52′30″ and 39°22′30″ N. and long 105°15′ and 105°37′30″ W. (fig. 1).

Part of the region is easily accessible from paved or graded gravel roads. U.S. Highway 24 crosses the southern part of the area and main graded roads which lead northward from it join at Tarryall and connect with U.S. Highway 285 at Jefferson. Other graded gravel roads lead west and southwest from Lake George. The northeastern part of the area, which includes the Tarryall Mountains, is accessible only by trail.

The region is one of physiographic contrast. The broad, sparsely timbered Badger Flats gives way abruptly to the timbered Puma Hills to the southwest and to the rugged Tarryall Mountains to the northeast. West of the Puma Hills is the broad, nearly treeless, intermontane basin of South Park at an average altitude of about 9,000 feet. The highest point in the region is Bison Peak (12,431 ft) at the northwest edge of the McCurdy Mountain quadrangle; the lowest is slightly less than 8,000 feet. Although the highest peaks of the Tarryall Mountains barely reach timberline, their massive outcrops of pinnacled and exfoliated granite have an aspect shared by few other Colorado ranges.

The region is drained by the South Platte River which flows northeasterly from Elevenmile Canyon Reservoir in South Park through the rugged Elevenmile Canyon and turns north near the town of Lake George. Tarryall Creek, a main tributary, flows southeastward to the western boundary of the Tarryall Mountains, turns abruptly to the east at the southern end of the range and flows easterly through a narrow canyon to its junction with the South Platte. The other main tributary stream has two names; its northern portion is known as Lost Creek, its southern part as Goose Creek. The creek cuts across the Pikes Peak Granite, and parts of the stream flow through boulder fields of the granite where no water can be seen at the surface. The stream south of the southernmost boulder field is Goose Creek; to the north it is Lost Creek.

Wildlife is not abundant but a variety of species find suitable environments because of the several contrasting physiographic regions. Herds of Rocky Mountain Big Horn sheep roam within the Tarryall Mountains. The Badger Flats area has small herds of antelope and deer; elk and black bear, as well as badger, beaver, bobcat, and coyote have been met in the field. The mountain bison formerly ranged to the top of the Tarryall and Kenosha Mountains, but the only evidence seen of these great beasts was a badly weathered skull near the top of McCurdy Mountain in the Tarryalls.

Ranching is a main industry of the region, and a few prosperous ranches lie along the valley of Tarryall Creek. Most of the other small ranches have been abandoned for many years, although they formerly produced cattle, potatoes, and small crops of grain. Lumbering and mining supplement the incomes of some families, and the U.S. Forest Service station at Lake George employs local residents on a seasonal basis. The tourist industry is important and will surely become more so. A portion of the Tarryall Mountains has been designated as a scenic area by the Forest Service, and pack trails are being built or rehabilitated to improve access to the area.

The name Tarryall, which has been applied to two villages, a mountain range, and a creek, has an interesting history. Placer prospectors decided to stop or "tarry-all" along a small stream in South Park on July 19, 1859, and shortly thereafter struck rich gold-bearing gravel (Stringham, 1943). They called the stream the Tarryall, a name given shortly afterwards to a small settlement at the placer diggings. Inasmuch as the original discoverers had claimed all the most productive ground, latecomers called the place "Grab-all." The greed of the first prospectors rankled several people so much that a new camp nearby—hopefully of contrasting virtue—was called Fairplay.

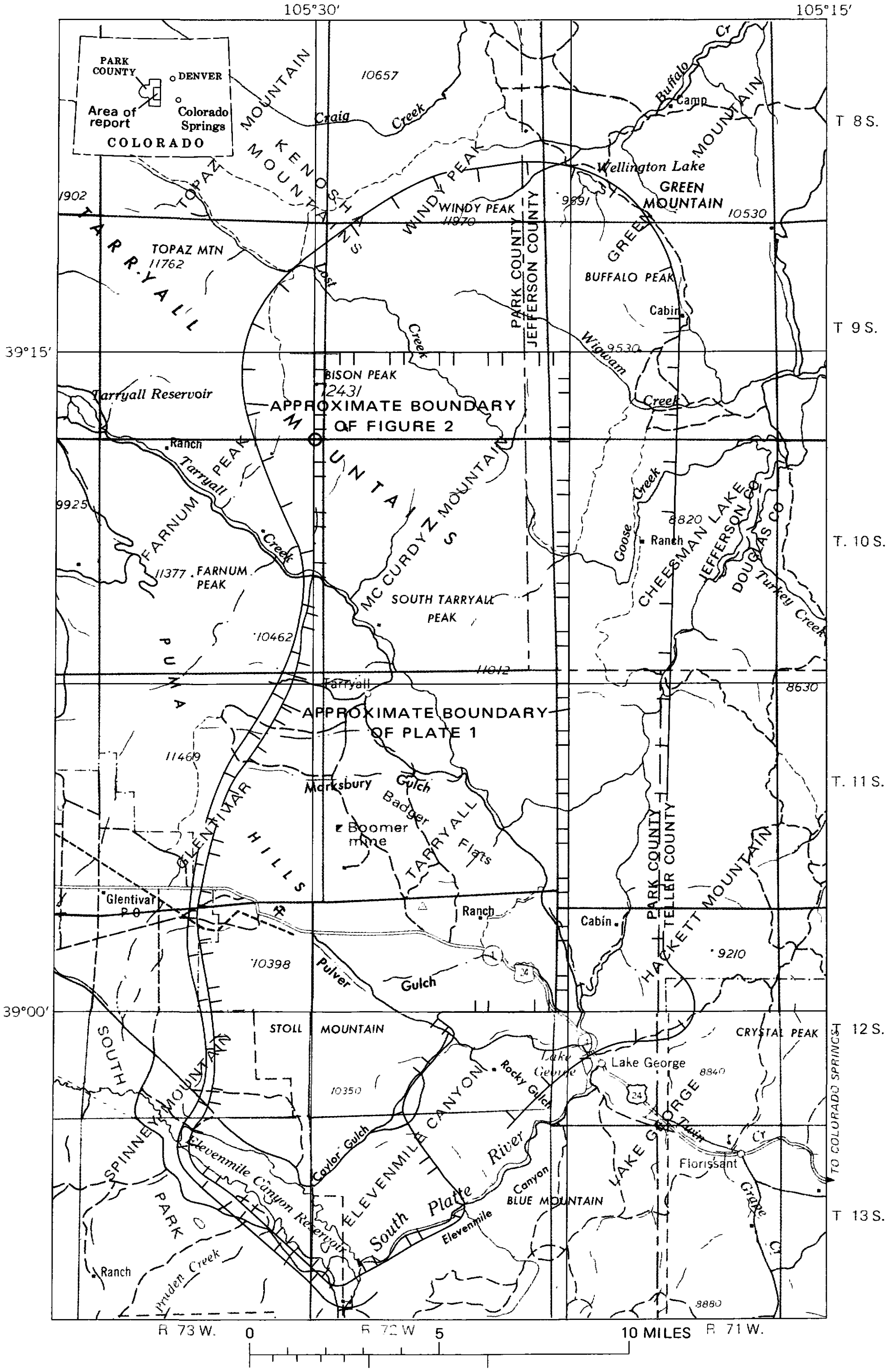


FIGURE 1.—Index map of the southern Tarryall region. From U.S. Geological Survey Denver and Pueblo 1:250,000-scale topographic quadrangles, 1953–63 and 1954–62.

The village that is now called Tarryall was first called Puma or Puma City. This latter name had been preempted, however, by another settlement (Wolle, 1949), and the name Tarryall was adopted after the original settlement named Tarryall, about 50 miles to the northwest, was abandoned. Puma City was never an important mining center, although gold- and silver-bearing deposits were discovered in the 1890's and there was a small mining boom about 1897.

GEOLOGIC INVESTIGATIONS

This investigation.—This report is based primarily on geologic studies by Hawley in 1959–66 and Wobus in 1964–67, but we have obtained much valuable information from the reports of other investigators that are cited below and elsewhere in the text.

The kind and detail of geologic mapping done by the authors varied. The geologic mapping in most of the Tarryall quadrangle and the southern part of the McCurdy Mountain quadrangle was done in detail (1:20,000 or larger scale) in order to study mineral occurrences and to locate mine workings (Hawley, 1969). Mapping in the southwestern part of the Tarryall quadrangle, and in the Elevenmile Canyon, Spinney Mountain, and Glentivar quadrangles—the region of the Puma Hills—was done at 1:24,000 scale (Wobus, 1966). The northern part of the McCurdy Mountain quadrangle was mapped at 1:62,500 scale because it is inaccessible and because this scale was adequate to portray its broad granitic units. Reconnaissance mapping was done at 1:125,000 scale in marginal areas.

The mineralogic or modal composition of rocks was established by point counting of thin sections and stained slabs. Measurements of fine-grained rocks, including all metasedimentary rocks, were on single thin sections; many are visual estimates. Most measurements of medium- or coarse-grained rocks are averages of point counts from two thin sections or combinations of thin sections and stained slabs. The samples of tables 2, 3, and others were chosen to represent the range of composition found in the rock units. Optical methods were used to estimate the anorthite content of the plagioclase. Regular normal zoning in composition is shown as 37 $\rightarrow$ 26 (percent anorthite content), as in table 6.

Chemical analyses for the project were made in the Denver laboratories of the U.S. Geological Survey. The standard quantitative rock analyses were made under the supervision of Lee C. Peck; semiquantitative spectrographic analyses were made under the supervision of A. T. Myers, by N. M. Conklin, J. C. Hamilton and R. G. Havens.

Two whole rock rubidium-strontium age determinations reported here were made by Carl E. Hedge for the project; earlier potassium-argon and rubidium-strontium analyses made by C. E. Hedge, H. H. Thomas, Richard Marvin, and Frank Walthall were published in a report defining the Redskin Granite (Hawley and others, 1966).

Other investigations.—Before 1958, the geology of the southern Tarryall region was known only from reconnaissance studies, and the only geologic map of the entire area was the Colorado geologic map (U.S. Geological Survey, 1935). Since 1958, detailed investigations have been made by several geologists, including Hutchinson, Kraus, Stewart, Chapin, and Epis.

R. M. Hutchinson of the Colorado School of Mines has mapped a large part of the area north and east of the southern Tarryall region, and one report covers the geology of part of the McCurdy Mountain quadrangle (Hutchinson, 1960a). Other geologists associated with Colorado School of Mines have also worked in or near the region; Gotthard Kraus (written commun., 1960) mapped part of the Elevenmile Canyon area in the southeast part of the region, and D. D. Stewart (1964) studied a syenitic intrusive exposed north of Lake George and just east of the area mapped in detail in this study. In the southwestern part of the region, Hutchinson (1960b) included a large-scale geologic sketch map of the Wilkerson Pass area and a series of approximate modes of metasedimentary rocks on the south side of Badger Mountain in a road log for Guide to the Geology of Colorado (p. 157–159). C. E. Chapin and R. C. Epis (1964; Epis and Chapin, 1974) studied the Thirtynine Mile Andesite (Tertiary), which covers the Precambrian rocks at the southwestern edge of the Puma Hills. The Elkhorn thrust just west of the region in eastern South Park was studied by D. L. Sawatzky (1964).

ACKNOWLEDGMENTS

The fieldwork and most of the laboratory studies by Hawley were made for the U.S. Geological Survey. The petrographic study of the Redskin Granite and the preparation of a thesis on the Lake George beryllium area were done partly at the University of Colorado under a National Science Foundation Graduate Fellowship. The mapping of the Puma Hills was done by Wobus as the basis for a Ph. D. dissertation at Stanford University; financial support, gratefully acknowledged, was provided by the National Science Foundation and the Shell Grant for Fundamental Research at Stanford.

Both authors had the opportunity of discussing geologic aspects of the area in the field and office with Dr. R. M. Hutchinson, Colorado School of Mines. Drs. R. R. Compton, Stanford University, and R. M. Honea, then of the University of Colorado, made brief, helpful visits to the projects in the field. Mr. Ruperto Laniz, Stanford University, and R. B. Taylor and Jerry Tucker, aided in staining techniques and photography of hand specimens and thin sections. D. E. Lee aided in making mineral separations. We are especially indebted to W. N. Sharp who was associated with Hawley on the project from 1959 until 1962 and mapped part of the Redskin stock and its mineral occurrences. Later, Hawley was assisted by R. H. Helming in the fall of 1962, and W. H. Raymond and Michael Feldman for short periods in 1963 and 1964, respectively. Carlos Reynaldi of the Argentine Atomic Energy Commission and Leon Groves assisted in the mapping of the Tarryall Mountains batholith in August 1965.

Many residents of the area aided us in our investigations. Mr. H. H. Moses and sons, Mr. Jack Smith, and Mr. Roger A. Sanborn furnished bases of operation. Others that helped include D. H. Peaker and Harlan Foresyth, U.S. Beryllium Corp., and Jerome McLain, George Cox, and Lawson D. Summer. Ranchers in the area were most cooperative in allowing access to private land.

GENERAL GEOLOGY

The southern Tarryall region is underlain by rocks of Precambrian age which are locally covered by a veneer of rocks or sediments of Tertiary and Quaternary age. Most of the Precambrian rocks can be assigned to one of five main units—layered gneiss, Boulder Creek(?) Granodiorite, Silver Plume(?) Quartz Monzonite, Pikes Peak Granite, and Redskin Granite. The south-central and southwestern parts of the area are underlain by an older igneous-metamorphic complex that consists mainly of the layered gneiss, Boulder Creek(?) Granodiorite and Silver Plume(?) Quartz Monzonite (fig. 2). The eastern and northern parts of the area are underlain by nearly massive upper Precambrian Pikes Peak and Redskin Granites.

The oldest rocks are those of the layered gneiss. These rocks were folded and strongly metamorphosed at about the time of emplacement of the Boulder Creek(?) Granodiorite and were deformed again by forcible emplacement of the Silver Plume(?) Quartz Monzonite. The Pikes Peak and Redskin Granites are much younger and cut sharply across virtually all other rock units of Precambrian age.

Bands of different composition in the layered gneiss, phacolithic intrusions, and changes in foliation define large northerly plunging folds in the layered gneiss, more evident after allowance has been made for the distortional effects of the Silver Plume(?) bodies. Generally cross-cutting the fold structures are major faults of the area which trend north-northwest to north, as represented by the Badger Flats fault, and about west-northwest to northwest, as represented by the Webber Park and Pulver Gulch faults. Both fault sets formed in Precambrian time but have had more than one period of movement.

The veneer of Tertiary and Quaternary rocks and deposits, which locally covers the Precambrian, consists of boulder deposits, welded tuff, andesite and rhyolitic tuff of the Thirtynine Mile Andesite, gravel deposits, colluvium, and alluvium. Although not exposed in the southern Tarryall region, sedimentary rocks of Paleozoic and Mesozoic age, as well as Tertiary sedimentary and volcanic rocks, occur in the structurally complex intermontane basin of South Park, immediately west of the mapped area. The Elkhorn thrust (Sawatzky, 1964), a major Laramide fault at the eastern edge of South Park, has brought the Precambrian crystalline rocks of the Puma Hills westward over the Cretaceous and lower Tertiary sedimentary rocks of the park, just west of the southern Tarryall region.

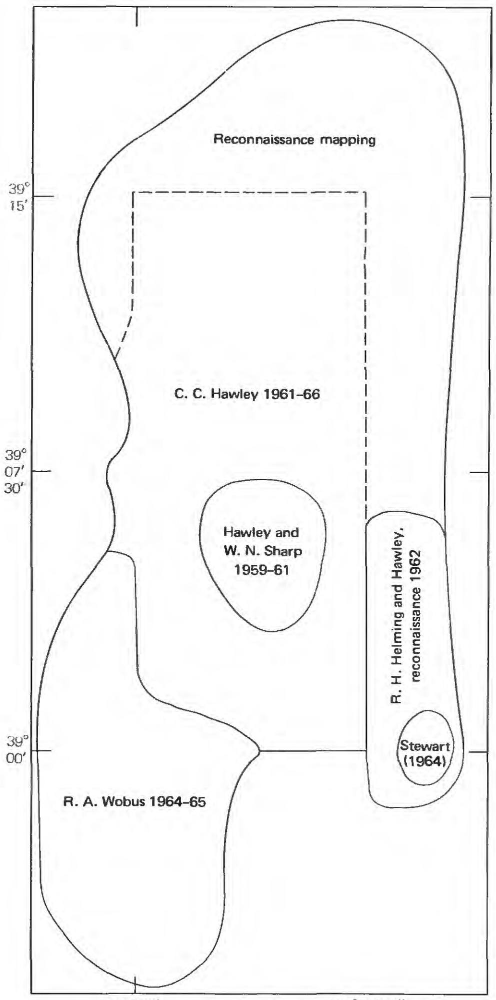
PRECAMBRIAN ROCKS AND THEIR NOMENCLATURE

A formal stratigraphic nomenclature for the Precambrian rocks of the Front Range presents many problems because of the unfossiliferous nature of the metasedimentary rocks and the widespread variation in the metaigneous and igneous rocks. Three main approaches have been made to the problems of naming and correlation: (1) to name and describe the rock units lithologically without recourse to formational names, (2) to assign local formation names, and (3) to use very general formational names over wide areas. None of these is wholly satisfactory. The first fails to emphasize the order that has, in fact, been found by many workers; the second leads to a multiplicity of names; and the third fails to recognize important differences among the rocks and inevitably leads to miscorrelation. The approach used here (table 1) is to apply formational names of widespread rock types if correlations are certain or probable(?) and also to add local names for other distinctive rock types. In addition, the layered gneiss, correlated with the Idaho Springs Formation in U.S. Geological Survey Professional Paper 608–A (Hawley, 1969), is subdivided here into lithologic facies as permitted by the scale of the mapping.

Most of the metaigneous and igneous rocks of the area fall into three distinct geologic groups found throughout the Front Range and are grouped according to age, common mode of occurrence, composition, mineralogy, and structure. The general relations of the three igneous rock groups have been described succinctly by Tweto (1966):

"The oldest group, exemplified by Boulder Creek Granite, is granodioritic, gneissic and syntectonic * * *. The second group, exemplified by Silver Plume Granite, is quartz monzonitic to granitic, only locally foliated, and late syntectonic to post-tectonic; granites in it are not all synchronous and are widespread in the Front Range * * *. The youngest group, exemplified by Pikes Peak Granite, is granitic, massive, and post-tectonic * * *."

The Boulder Creek(?) Granodiorite and the Silver Plume(?) Quartz Monzonite of the southern Tarryall region have the requisite characteristics and are correlated indirectly. The Pikes Peak and related rocks of the region



INDEX SHOWING MAPPING CREDIT

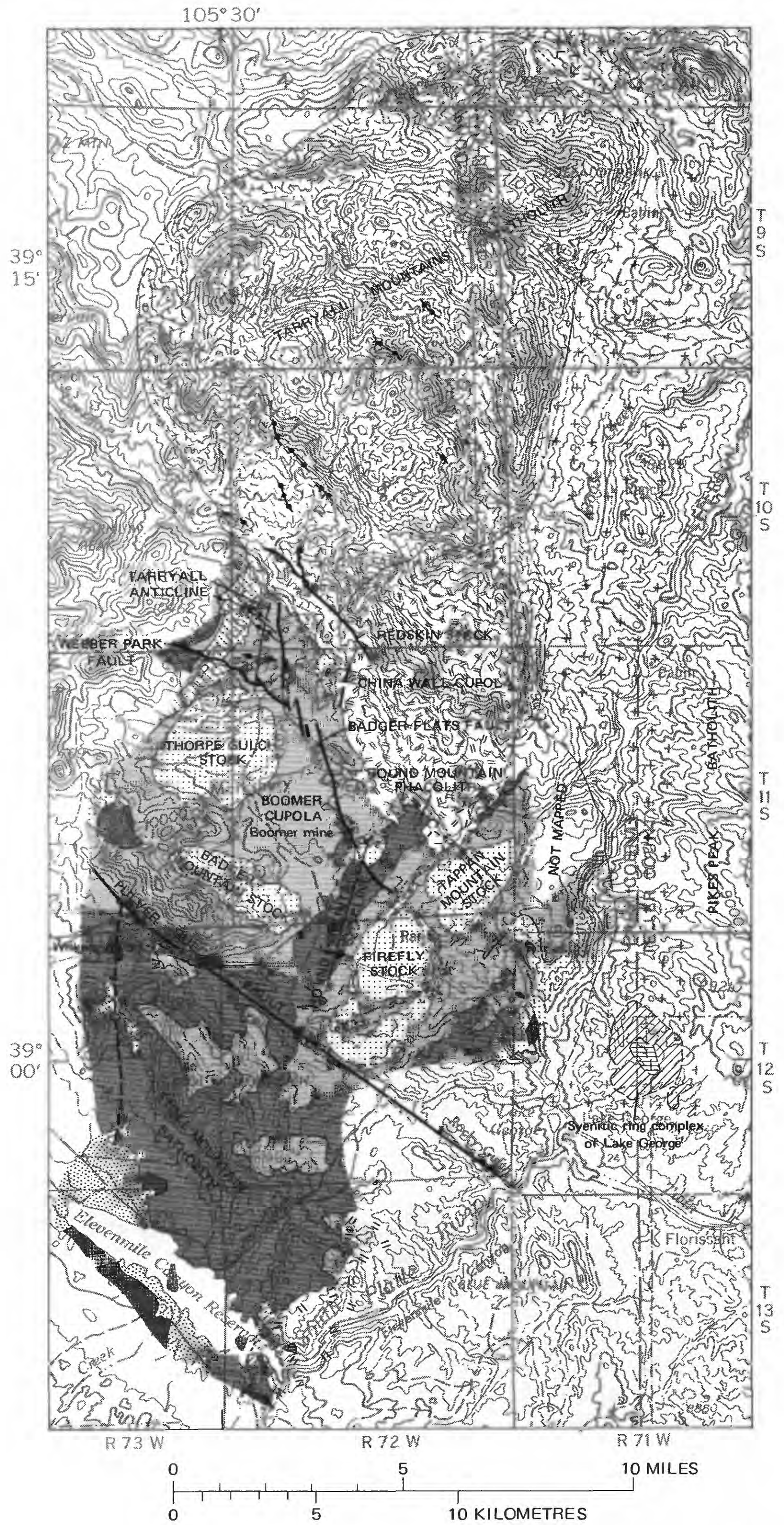
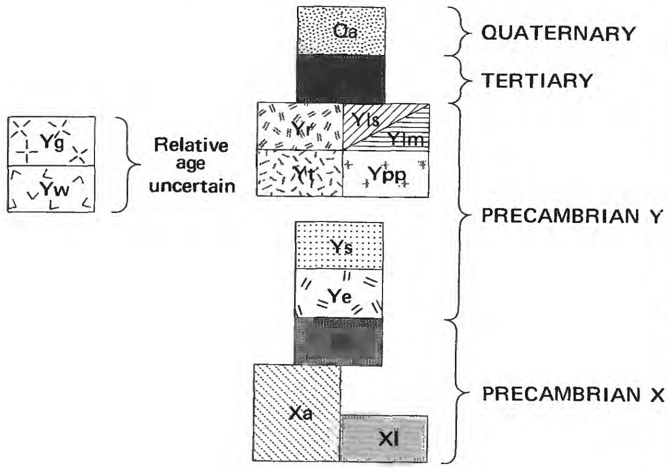


FIGURE 2 (above and facing page).—Generalized geologic map of the southern Tarryall region. Base from U.S. Geological Survey Denver and Pueblo 1:250,000-scale topographic quadrangles, 1953–63 and 1954–62.

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

Qa	Quaternary alluvium
Tv	Tertiary volcanics
	Precambrian Y
Yr	Redskin Granite
	Ring complex of Lake George
Yls	Syenite
Ylm	Syenomonzonite
	Pikes Peak Granite
Yt	Granite of Tarryall Mountains batholith
Ypp	Granite of Pikes Peak batholith
Yg	Gabbro and quartz monzonite
Yw	Granodiorite of Wellington Lake
Ys	Silver Plume(?) Quartz Monzonite
Ye	Quartz monzonite of Elevenmile Canyon
	Precambrian X
Xb	Boulder Creek(?) Granodiorite
Xa	Amphibolite
Xl	Layered gneiss

Contact — Dashed where inferred; dotted where concealed

Fault — Dashed where inferred

Vein

are posttectonic and have been dated radiometrically as Pikes Peak; they are also so close to the type locality as to leave little doubt of correlation.

LAYERED GNEISS

The oldest rocks of the region are interlayered biotite-bearing gneisses and associated rocks of presumed metasedimentary origin and amphibolite of uncertain origin (fig. 2). These rocks form the framework of the complex of metamorphic and igneous rocks of the southwestern part of the region. These oldest rocks are lithologically similar to the Idaho Springs Formation of the central Front Range (Ball, 1906).

The layered gneiss sequence is made up mainly of sillimanitic biotite-muscovite gneiss (locally migmatitic) and fine-grained biotite gneiss; minor units are sillimanite-cordierite quartz gneiss, calc-silicate gneiss, and amphibolite (pl. 1). The two main lithologic types are arranged in an apparent stratigraphic order in which a fine-grained biotite gneiss layer lies between or forms a lens in sillimanitic biotite-muscovite gneiss and migmatite. The sillimanite-cordierite quartz gneiss forms a well-defined marker horizon in the main sillimanite-bearing unit, and thin, discontinuous calc-silicate layers are present at many places. A prominent amphibolite layer occurs near the contact of fine-grained biotite gneiss and the upper sillimanitic layer; other amphibolites form elongate lenses, particularly in fine-grained biotite gneiss and in association with calc-silicate gneiss.

The foliation and banding in the gneisses is generally parallel to compositional layering; hence it is believed that the foliation is nearly parallel to the original bedding of former sedimentary units. In migmatitic parts of the layered gneiss unit, however, the rocks have been greatly recrystallized, so that the correspondence between bedding and foliation is likely to be crude.

SILLIMANITIC BIOTITE-MUSCOVITE GNEISS AND MIGMATITE

The sillimanitic biotite-muscovite gneiss and migmatite is a heterogeneous unit which crops out in the western, southern, and southeastern parts of the southern Tarryall region. Rocks comprising this unit range in composition from sillimanite-poor, biotite-quartz-plagioclase gneiss (similar to fine-grained biotite gneiss to be described later) to highly sillimanitic biotite-muscovite gneiss. Rock of granitic composition is present in most outcrops, giving these gneisses a migmatitic appearance. All of these components are intermixed on a scale ranging from less than an inch to many hundreds of feet, and contacts between the various types are commonly gradational. The particularly sillimanitic rocks are distinguished from the biotite-quartz-plagioclase gneisses on the map only in the Puma Hills (figs. 3, 4).

The granitic component of the migmatitic gneisses occurs in irregular patches, pods, and conformable layers, as well as in dilational dikes and at the crests of minor folds. In general, the amount of granitic material is greater in the more highly sillimanitic gneisses, but the distribution of the granitic component bears no relation to the distribution of the large igneous plutons. In the most sillimanitic rocks, thin, crinkled, dark-colored bands rich in sillimanite and biotite are irregularly interlayered with massive granitic-looking material. Excellent exposures on a ridge just south of Pulver Gulch road (near the aban-

TABLE 1.—*Suggested correlation of Precambrian rocks in the southern Tarryall region, central Front Range, and at Cripple Creek*

Age	Southern Tarryall region	Georgetown quadrangle (Ball, 1906, 1908)	Front Range mineral belt (Lovering and Goddard, 1950)	Central City district (Sims and Gable, 1964)	Cripple Creek (Graton, 1906)
PRECAMBRIAN Y	Redskin Granite--4 main facies-		Windy Point Granite-------------		Spring Creek Granite.
	Gabbro and quartz monzonite----				Olivine syenite and related rock.
	Pikes Peak Granite--3 main facies in Tarryall Mountains batholith.		Pikes Peak Granite-------------		Massive Pikes Peak Granite.
	Granodiorite of Wellington Lake				
	Silver Plume(?) Quartz Monzonite	Silver Plume Granite---------	Silver Plume Granite-----------	Biotite-muscovite granite--	Cripple Creek Granite.
	Quartz monzonite of Elevenmile Canyon.				
PRECAMBRIAN X	Mafic and metaigneous rocks				
	Boulder Creek(?) Granodiorite (includes quartz diorite gneiss, granodiorite gneiss, and quartz monzonite gneiss).	Quartz monzonite (adamellite). Possibly also gneissoid granite and Rosalie Granite.	Boulder Creek Granite and quartz monzonite.	Granodiorite and associated rocks. Possibly microcline-bearing gneiss.	Womack Gneiss and gneissic Pikes Peak Granite.
	Lithologic units; order may not reflect age:				
	Layered gneiss----------------	Idaho Springs Formation-------	Idaho Springs Formation---------	Metamorphosed layered rocks	Schist.
	Calc-silicate gneiss				
	Fine-grained biotite gneiss-	Biotite schist-------------		Biotite-quartz-plagioclase gneiss.	
	Sillimanite-cordierite quartz gneiss.	Quartz gneiss and lime-silicate rocks.		Calc-silicate gneiss and related rocks.	
	Sillimanitic biotite-muscovite gneiss and migmatite.	Biotite-sillimanite schist--		Sillimanitic biotite-quartz gneiss.	
	Amphibolite------------------	Hornblende gneiss-----------	Swandyke Hornblende Gneiss------	Amphibolite	

doned school in sec. 21, T. 12 S., R. 72 W.) show distinctly bounded granitic layers ½–1 inch thick, alternating with and conformable to tightly folded biotite-sillimanite layers (fig. 5). The same outcrops also contain vaguely bounded irregular patches of massive granitic rock in which biotite-sillimanite segregations appear to float.

In hand specimen, the sillimanitic biotite-muscovite gneiss is dark-gray to black, fine- to medium-grained, and moderately to strongly foliated. Biotite is dominant, but both sillimanite and muscovite are commonly visible. Sillimanite forms thin films, aggregates of fine-grained acicular crystals, and rods, nodules, and single euhedral crystals as much as 3 cm (centimeters) long which are generally well alined (fig. 6). Muscovite is coarse grained and irregular in form.

Viewed microscopically, sillimanite characteristically occurs in matted aggregates or clusters of very fine grained subparallel needles, and as trains of segmented needles that follow the form of minor folds in the gneiss. Most needles are less than 1 mm (millimeter) in length, and the short length and obvious segmentation of many grains indicate that crystals were commonly broken during deformation. Sillimanite needles arranged in tiny folds are locally enclosed in nonfolded muscovite poikiloblasts up to 1 cm across. Plagioclase, generally andesine, is present in most samples (table 2). Sample localities are shown on figure 7. Microcline is locally present; it fills minor fractures in quartz and plagioclase or forms poikiloblasts, and it appears to have formed late. Quartz generally is in anhedral polycrystalline grains with pronounced undulatory extinction; some is in granoblastic pods. The biotite is strongly pleochroic from tan to dark brown and contains zircon and apatite inclusions. Cordierite was noted in one sample.

SILLIMANITE-CORDIERITE QUARTZ GNEISS

The sillimanite-cordierite quartz gneiss is a distinctive marker unit as much as 1,500 feet thick in the sillimanitic biotite-muscovite gneiss on the southeast flank of the Round Mountain syncline (pl. 1). Quartz diorite orthogneiss and some quartz monzonitic gneiss of Boulder Creek(?) age are in contact with the sillimanite-cordierite quartz gneiss, and it is inferred that the emplacement of Boulder Creek(?) Granodiorite of the Round Mountain phacolithic body was partly guided by the northwestern contact of the sillimanite-cordierite-bearing layer. The sillimanite-cordierite gneiss is cut by the Redskin stock but can be traced for about 3½ miles southwest of the stock and for 1½ miles to the northeast.

The sillimanite-cordierite quartz gneiss is gray to dark-gray fine-grained very hard and dense rock consisting mainly of quartz and sillimanite. The sillimanite forms laminae anastomosing through the rock, and, where an outcrop surface coincides with a sillimanitic lamina, the rock is silvery white. The rock is generally darker and denser than the fine-grained biotite gneiss and is more homogeneous, darker, and less migmatitic than typical sillimanitic biotite-muscovite gneiss and migmatite. Locally, as near the gabbro exposed near Tarryall Creek in secs. 23 and 26, T. 11 S., R. 72 W., the rock is strongly magnetic.

In thin section the rock consists of quartz (35–50 percent), sillimanite (10–15 percent), cordierite (5–20 percent), sodic andesine (5–15 percent), potassium feldspar (5–10 percent), smaller amounts of biotite, muscovite and magnetite, and accessory apatite and zircon. Foliation and schistosity are defined principally by sillimanite laminae and secondarily by the orientation of quartz and biotite.

TABLE 2.—*Modal composition (volume percent) of sillimanitic biotite-muscovite gneiss and fine-grained biotite gneiss*

[Sample localities shown on fig. 7–; N.D., not determined; Tr, trace. Leaders (...) indicate no data. Modes are visual estimates of single thin sections]

	Sillimanitic biotite-muscovite gneiss						Fine-grained biotite gneiss				
Sample No. (fig. 7)	1	2	3	4	5	6	7	8	9	10	11
Field No.	281-1	281-2	54	344	120	100	128	276	27	BA-14	T2-35
Quartz	17	28	45	49	65	35	35	47	75	44	54
Plagioclase	--	8	21	--	--	52	50	29	7	46	27
Potassium feldspar	--	33	--	--	--	10	4	2	10	--	--
Biotite	25	16	10	25	15	3	3	20	3	10	17
Muscovite	7	10	22	5	8	--	--	--	3	Tr	--
Sillimanite	50	5	1	20	7	--	--	--	--	--	--
Hornblende	1	--	--	--	--	--	7	--	--	--	--
Zircon	Tr	Tr	Tr	--	1	--	.5	.5	--	Tr	Tr
Opaque minerals	--	--	1	1	4	--	--	1	--	Tr	2
Sphene	--	Tr	--	--	--	--	Tr	.5	Tr	--	--
Apatite	--	Tr	--	Tr	--	--	.5	Tr	Tr	Tr	Tr
Garnet	--	--	--	--	--	--	--	Tr	--	--	--
Composition of plagioclase[1]	N.D.	30-35	45	N.D.	N.D.	30	32	45	50-60	N.D.	30-35

[1]Percent An.

Sample descriptions

1. Tightly folded sillimanite-rich segregation in migmatite.
2. Sillimanitic biotite-quartz-microcline gneiss with coarse muscovite clots.
3. Well-foliated gneiss from contact with Boulder Creek(?) quartz diorite gneiss.
4. Tightly folded sillimanitic gneiss from contact with Boulder Creek(?) granodiorite gneiss.
5. Gneiss with coarse muscovite plates from shallow prospect hole.
6. Pinkish gneiss with prominent medium-sized quartz grains.
7. Isoclinally folded hornblendic gneiss.
8. Thinly banded gneiss with reaction rims around accessory magnetite grains.
9. Quartz-rich gneiss interlayered with calc-silicate and amphibolite.

10-11. Weakly foliated gneiss, "salt-and-pepper" appearance of quartz, feldspar, and biotite grains.

The quartz grains, which average about 1 mm across, show little evidence of strain.

Sillimanite, in addition to forming laminae, also is found as scattered crystals; it is both cut by and included in cordierite, and forms small crystals oriented along microperthite lamellae in potassium feldspar. These relations suggest a fairly long period of sillimanite growth. Muscovite poikiloblastically encloses deformed sillimanite and is interpreted as a younger mineral.

The surface weathering of the rock is shown by minor alteration of the feldspars to sericite and clay minerals, and of cordierite to sericite and chlorite.

FINE-GRAINED BIOTITE GNEISS

A fine-grained biotite-quartz-plagioclase gneiss unit is as much as 15,000 feet across near the crest of the Tarryall anticline but appears to pinch out to the west (pl. 1). This rock type is similar to one that forms interlayers inches or feet in thickness in the heterogeneous sillimanitic biotite-muscovite gneiss and migmatite unit.

Megascopically the fine-grained biotite gneiss is a relatively homogeneous rock. It has a weak foliation, due to the alinement of small biotite flakes, but it has a well-defined mineral lineation that is very apparent on weathered surfaces parallel or nearly parallel to the schistosity. On close inspection, the gneiss is seen to have the salt-and-pepper aspect that is very typical of biotite-quartz-plagioclase rocks of the Idaho Springs Formation (Ball, 1908, p. 40). Locally the rock grades into a very light colored quartz gneiss.

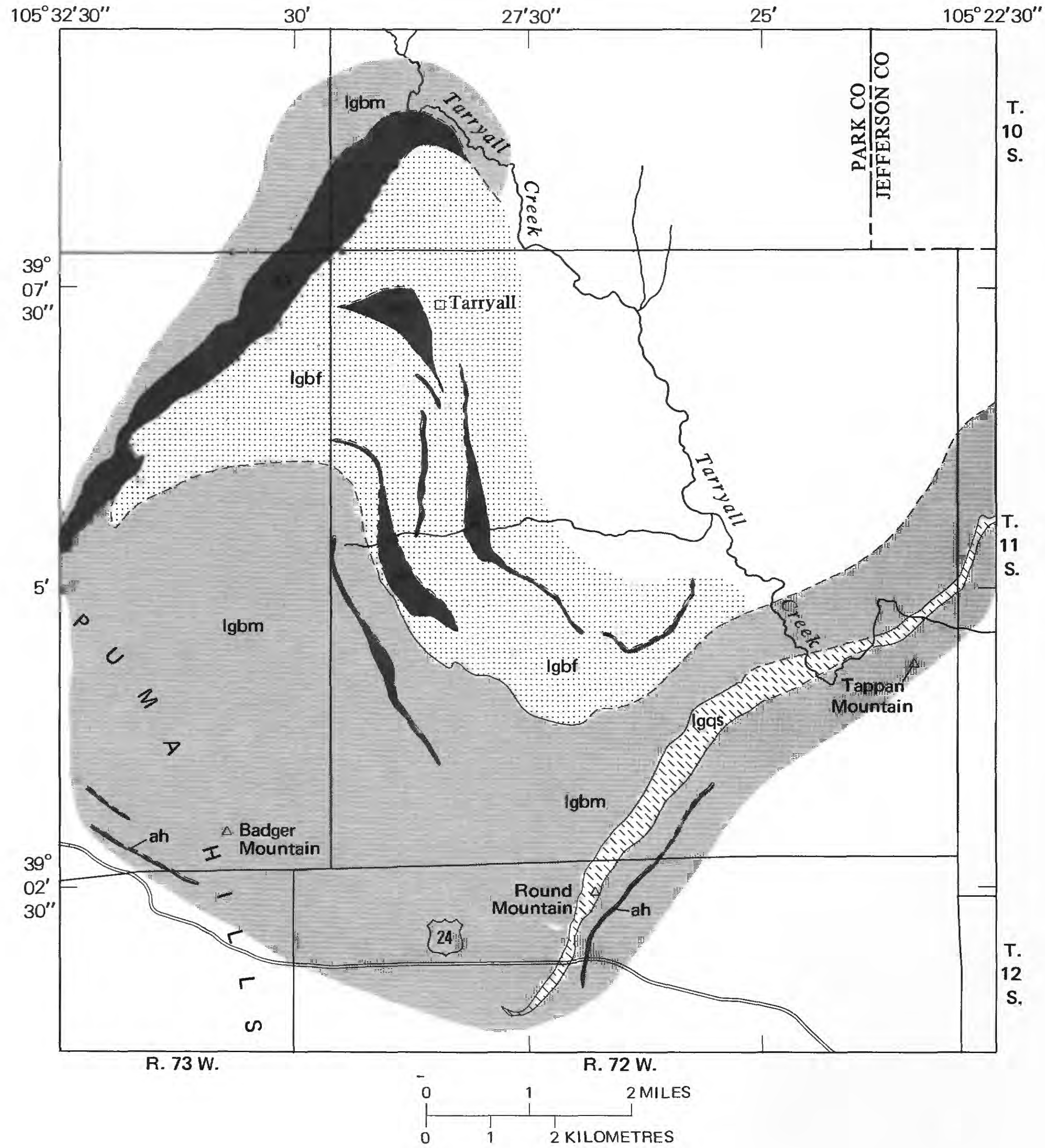
The fine-grained biotite gneiss is a granoblastic rock which consists mainly of quartz, plagioclase, potassic feldspar, and biotite (table 2). Locally the general granoblastic texture is modified by the presence of elongate pods rich in quartz or plagioclase which appear to have forced aside foliation defined by biotite flakes. Outside of the pods quartz shows undulatory extinction, and in the more quartzose types has a sutured appearance. The plagioclase is generally albite-twinned andesine, partly sericitized, and is partly poikiloblastic. Potassium feldspar (microcline) is less abundant than plagioclase in relatively quartz-poor varieties. The dark brown biotite of the rock contains zircons with pleochroic halos. Muscovite is present locally, but sillimanite is very sparse and was not seen in hand specimens. Hornblende and magnetite were seen in a few sections; magnetite commonly occurs surrounded by a reaction rim nearly free of mafic minerals.

CALC-SILICATE GNEISS

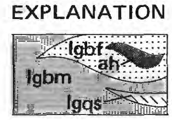
Calc-silicate gneiss is a widely distributed but minor rock unit in the layered gneiss. Calc-silicate rock occurs in discontinuous lenses which range from inches to hundreds of feet in thickness in the sillimanitic biotite-muscovite gneiss and in the fine grained biotite gneiss. The best exposures of calc-silicate gneiss are on the southern and eastern slopes of Badger Mountain, on Round Mountain, and along the southern and eastern margins of the Firefly stock (pl. 1), all of which are included in the Tarryall Springs scheelite district of Tweto (1960).

Besides the occurrence of one or more calcium- or magnesium-bearing minerals, a main characteristic of the calc-silicate rock is its mineralogic and textural variability. The calc-silicate rocks range from fine to coarse grained, and as described by Tweto (1960, p. 1410):

"Some calc-silicate rocks are almost monomineralic and some contain a large variety of minerals. Some are dark; some are light; some are finely banded, and some are un-



EXPLANATION



lgbf, fine-grained biotite gneiss
lgqs, sillimanitic biotite-quartz gneiss
lgbm, sillimanitic biotite-muscovite gneiss and migmatite
ah, amphibolite; locally includes calc-silicate gneiss and quartzite

Mapped contact

Projected or otherwise inferred contact

FIGURE 3.—Generalized map of the layered gneiss prior to intrusion of granitic rocks, Puma Hills. Base from figure 2, this report.

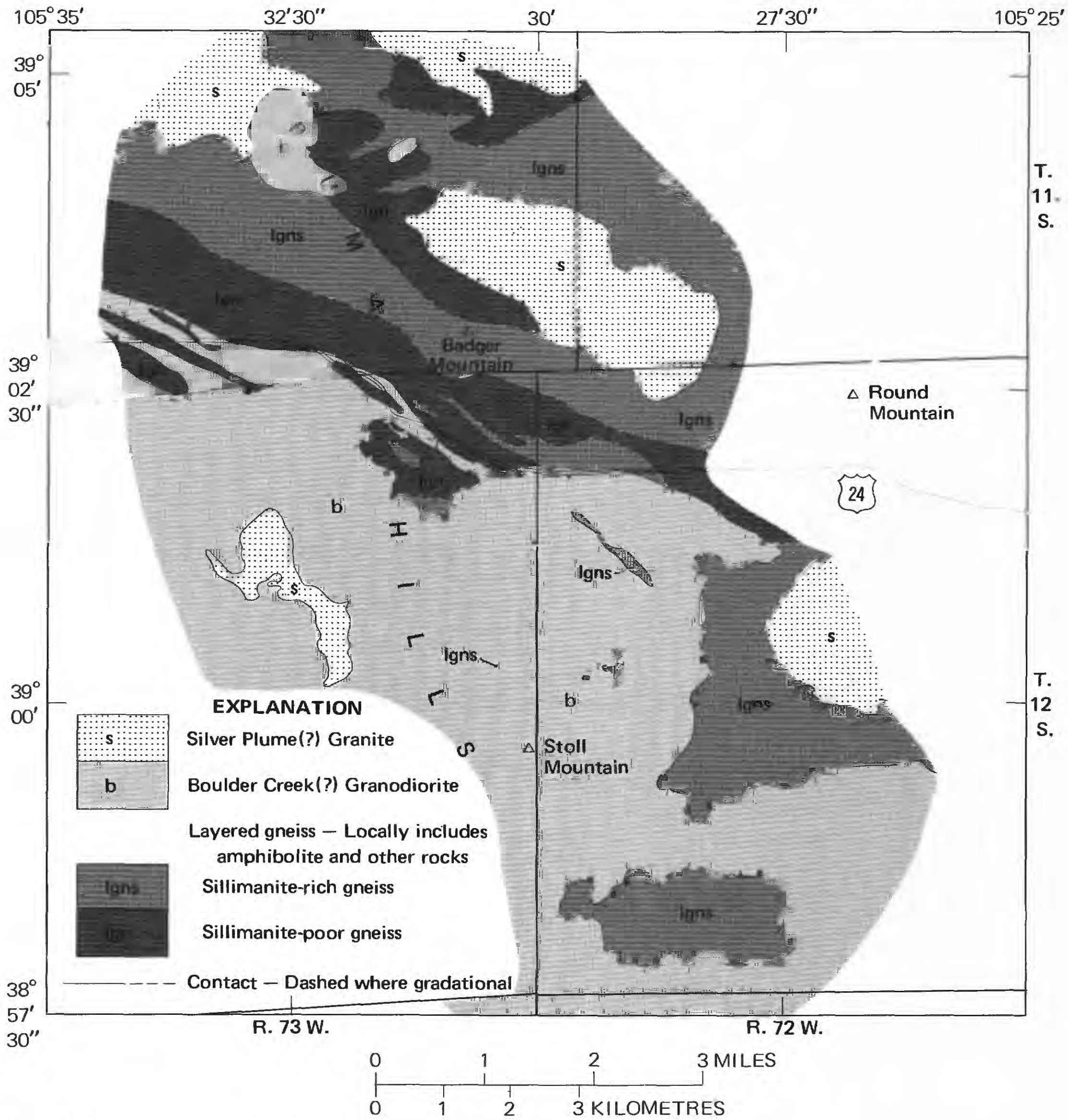


FIGURE 4.—Generalized map showing distribution of sillimanite-rich rocks in sillimanitic biotite-muscovite gneiss, Puma Hills. Geology by R. A. Wobus, 1964–65. Base from figure 2, this report.

banded. Composition changes rapidly across the strike***." Locally the calc-silicate rocks grade into garnet- or epidote-bearing tactite.

Characteristic minerals of the calc-silicate rocks, including tactites, are grossularite-andradite, epidote-clinozoisite, idocrase, diopside, labradorite, hornblende-actinolite, scapolite, and calcite. Wollastonite was observed in the central part of sec. 32, T. 12 S., R. 72 W., where it occurs in a thin (30-ft) calc-silicate lens in sillimanitic biotite-muscovite gneiss. Wollastonite was reported by Tweto (1960, p. 1418) who considered it to be an important primary mineral in calc-silicate rocks of the Tarryall Springs scheelite district. Some rocks also contain small amounts of scheelite, molybdenite, chalcopyrite, and zinc-bearing minerals. Common mineral assemblages are: (1) horneblende-diopside-quartz-labradorite, (2) quartz-garnet-epidote-(scheelite), (3) calcite-diopside, (4) hornblende (actinolite)-diopside-epidote-labradorite-quartz, and (5) wollastonite-quartz-calcite. Modal compositions of some specimens are reported in table 3.

Although the calc-silicate gneisses are varied, they share certain features. In the fine-grained rocks studied in thin section, most minerals are anhedral; in the coarse-grained varieties garnet, idocrase, and epidote are subhedral to euhedral. Garnet (grossularite-andradite) forms poikiloblasts which enclose other calc-silicate minerals and quartz. The epidote minerals vary from faintly to strongly pleochroic and enclose or embay garnet, diopside, calcic plagioclase, and hornblende. Calcite fills small vugs in the

FIGURE 5.—Migmatitic sillimanitic biotite-muscovite gneiss, Pulver Gulch.

coarse-grained varieties. Minerals of the hornblende-actinolite series comprise more than 25 percent of some of the rocks. These minerals are faintly to strongly pleochroic from tan to light brown to dark green or blue green. Magnesian olivine highly altered to serpentine was noted in a few rocks.

Diopside is in prismatic grains surrounded by calcite or is intergrown with hornblende or quartz. Quartz is common, and locally the calc-silicate rocks grade into pale-green diopsidic quartzites. Quartz in quartz-rich pods and veinlets has a sutured fabric and the grains show undulatory extinction.

AMPHIBOLITE

Amphibolite is widely distributed as layers, lenses, pods and rods in the layered gneiss and has contacts concordant

FIGURE 6.—Alined sillimanite crystals in sillimanitic biotite-muscovite gneiss, Badger Mountain.

TABLE 3.—*Modal composition (volume percent) of calc-silicate gneiss and related rocks*

[Sample localities shown in fig. 7; Tr, trace, Leaders (...) indicate no data]

Sample No. (fig. 7)	12	13	14	15	16	17	18
Field No.	58	161	241	271-2	275	105	350
Quartz	--	--	18	4	1	--	--
Diopside	3	--	--	15	--	31	--
Epidote-clinozoisite	--	--	7	12	37	3	40
Hornblende	30	--	Tr	--	60	5	20
Grossularite-andradite	--	--	5	25	--	--	--
Vesuvianite	--	--	--	8	--	--	--
Olivine	23	40	--	--	--	--	--
Wollastonite	--	--	--	Tr	--	--	--
Scapolite	5	--	--	--	--	--	--
Plagioclase	--	--	70	--	--	60	37
Anthophyllite	15	--	--	--	--	--	--
Calcite	--	55	--	35	--	--	--
Chlorite	19	--	--	--	--	--	--
Other	5	5	--	1	2	--	3
Composition of plagioclase[1]	--	--	47	--	--	50-55	75-80

[1]Percent An.

Sample descriptions

12. Massive, dark-green, fine-grained calc-silicate rock from prospect shaft. Also contains 1 percent spinel, 4 percent opaque minerals and trace of apatite.
13. Highly altered, massive, medium-grained calc-silicate from Great Western mine, Wilkerson Pass. Contains 3 percent muscovite, 2 percent opaque minerals.
14. Mottled, fine-grained calc-silicate gneiss cut by Boulder Creek(?) Granodiorite.
15. Medium-grained calc-silicate gneiss from prospect pit; nearby layers contain abundant wollastonite. Contains 1 percent microcline.
16. Moderately foliated epidote-actinolite gneiss. Contains 2 percent sphene, trace opaque minerals.
17. Layered diopside-labradorite calc-silicate gneiss. Contains 1 percent sphene.
18. Fine-grained, massive rock with epidote-filled fractures. Contains 3 percent opaque minerals and traces of apatite and spinel.

with the foliation of adjacent biotite gneiss. In contrast other rocks of amphibolitic composition occur sparsely in small crosscutting masses; these amphibolites are described with the mafic metaigneous rocks.

The largest conformable mass of amphibolite is a layer as much as 3,500 feet thick which crops out west and north of Tarryall . The mass can be traced from the Tarryall Mountains batholith about 5 miles in a southwesterly direction where it is cut off by a pluton of Silver Plume(?) Quartz Monzonite. The layer separates fine-grained biotite gneiss from sillimanitic biotite-muscovite gneiss of the layered gneiss (pl. 1; figs. 3, 4). Other prominent layers of amphibolite crop out east and south of Tarryall and are

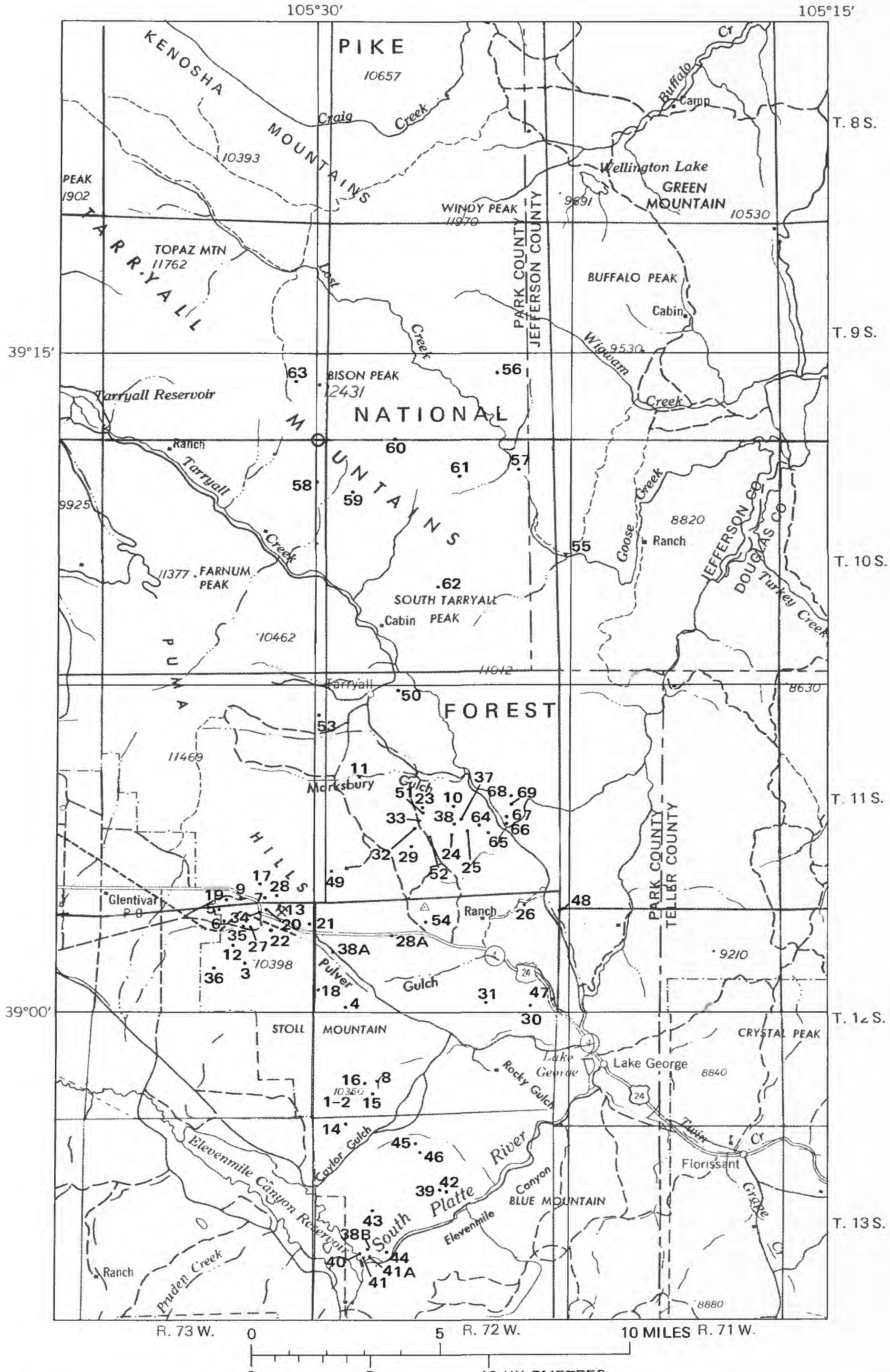


FIGURE 7.—Sample locality map. Base from U.S. Geological Survey Denver and Pueblo 1:250,000-scale topographic quadrangles, 1953–63 and 1954–62.

locally included in Silver Plume(?) Quartz Monzonite. Amphibolite also is in podlike bodies which range from a few inches across to an irregular mass about 3,800 feet long exposed west of Tarryall. Indentation of biotite gneiss into the large amphibolite pod exposed west of Tarryall (NW¼, sec. 6, T. 11 S., R. 72 W.) suggests a very large scale boudinage similar to that of the common small-scale amphibolite layers and less competent biotite gneiss that form boudins in low-pressure areas.

In hand specimen, the typical amphibolite is a black or mottled black and white, fine- to medium-grained gneiss consisting principally of hornblende and calcic plagioclase (table 4). Foliation is caused by the segregation of light- and dark-colored minerals into layers or clots. Alinement of hornblende crystals within the layers also locally defines a lineation. The foliation of this rock and the conformable habit of its occurrence distinguish it from more massive and crosscutting amphibolitic metadiorite.

Petrographic study reveals that most mineral grains of the amphibolite are anhedral, with the exception of subhedral prisms of hornblende and of granoblastic aggregates of plagioclase and quartz. Individual grains of hornblende are usually small (1–2 mm long), but hornblende clusters up to 1½ cm in diameter are present in a few samples. Some thin sections show tight folds in which unbroken hornblende laths occur in granoblastic quartz and plagioclase.

The hornblende of these rocks is of two types—a nearly colorless variety, presumably with a low iron content (faintly pleochroic from colorless to pale yellow or light green), and a more deeply colored type which is strongly pleochroic from pale yellow or green to dark green or blue green. The two varieties were observed together in only one specimen, where the faintly pleochroic type appeared to be the younger. Alteration products of hornblende in these rocks are epidote-clinozoisite and chlorite.

Plagioclase ranges in composition from labradorite to bytownite, and some shows faint normal zoning. Most plagioclase shows some degree of alteration to saussurite.

A magnesian rock determined microscopically to consist mainly of cordierite and anthophyllite has been assigned to the amphibolite unit. The only known occurrence of the rock is on a southwest-trending spur of Badger Mountain, in the south part of sec. 35, T. 11 S., R. 73 W. A thin section of the magnesian gneiss contains faintly pleochroic anthophyllite ($2V = +65°$) in acicular to prismatic grains. Untwinned cordierite in the rock is highly poikiloblastic and very little altered; pleochroic halos around zircon inclusions in the cordierite help to distinguish it from feldspar and quartz (fig. 8).

Like the calc-silicate rocks, amphibolite has locally been converted by metasomatic reactions into tactite composed essentially of garnet, quartz, and diopside; some of the mixed rocks resulting from partial alteration of this kind were probably mapped as calc-silicate. The importance of this type of alteration of amphibolite is uncertain, but it is present on a hand specimen scale at a prospect near Marksbury Gulch (fig. 9).

DERIVATION OF THE LAYERED GNEISS AND AMPHIBOLITE UNITS

The layered gneisses of the southern Tarryall region are believed to be the high-grade regional metamorphic equivalents of a thick succession of sedimentary rocks. Variations in present lithology, in general, represent compositional variations within the original sediments. Silimanitic gneisses were derived from argillaceous sediments, and the interlayered fine-grained biotite gneisses were most likely impure sandstones. Calc-silicate gneiss was formed by regional metamorphism of impure calcareous rocks (siliceous dolomites and limestones). Metasomatism was also a factor in the development of calc-silicate gneiss, especially of tactitelike varieties and rocks containing scapolite and sulfides.

The origin of the amphibolitic rocks is uncertain. The generally conformable nature of the amphibolite bodies is compatible with a sedimentary origin, but this mode of occurrence would also be characteristic of basalt flows or sills. Some amphibolite, such as that forming small pods and lenses in biotite paragneiss, is almost certainly a metamorphosed calcareous or dolomitic sediment. The shape and distribution of larger amphibolite pods, as well as of the irregular body west of Tarryall, are probably the result of boudinage.

Recrystallization and small-scale metamorphic differentiation in the layered gneisses have obliterated all primary sedimentary structures that may have been present; these processes have, at the same time, produced the mineral segregations, lineation, and foliation of the gneisses. These generally subsolidus processes were also responsible for such observed features as reaction rims around magnetite grains, granoblastic pods of quartz and plagioclase, sillimanite rods and nodules, and the coarse texture of some of the rocks.

Another modification of some of the layered gneisses, particularly within the sillimanitic biotite-muscovite gneiss, has been the formation of migmatites. The origin of migmatites by the partial melting (anatexis) of metasedimentary gneisses best explains the field relations of the migmatitic rocks of the southern Tarryall region. The granitic veinlets and pods of the migmatites segregated as a melt, leaving a crystalline residuum of more refractory minerals (such as biotite, sillimanite, and hornblende) enriched in iron, magnesium, calcium, and aluminum. The granitic segregations are generally parallel to the foliation defined by the mafic residua, but highly contorted and swirled migmatites suggest that anatexis took place concurrently with deformation. Apparently, the

TABLE 4.—*Modal composition (volume percent) of amphibolite and related rocks*

[Sample localities shown in fig. 7; Tr, trace; N.D., not determined; leaders (...) indicate no data]

Sample No. (fig. 7)	19	20	21	22	23
Field No.	97	131	433	32	1-14
Hornblende	55	--	40	30	67
Plagioclase	35	9	50	43	32
Anthophyllite	--	45	--	--	--
Epidote	--	--	--	18	--
Cordierite	--	20	--	--	--
Chlorite	5	Tr	--	--	--
Sericite	--	--	10	--	--
Opaque minerals	4	1	Tr	7	Tr
Apatite	Tr	Tr	--	--	--
Sphene	--	--	--	2	1
Zircon	--	Tr	--	--	--
Spinel	1	--	--	--	--
Quartz	--	25	--	--	Tr
Rutile	--	--	Tr	--	--
Composition of plagioclase[1]	85	60-25	70	75-80	N.D.

[1]Percent An.

Sample descriptions

19. Medium-grained banded amphibolite.
20. Cordierite-anthophyllite gneiss from thin layer adjacent to quartz-rich gneiss.
21. Disharmonically folded medium-grained amphibolite.
22. Medium-grained massive amphibolite associated with calc-silicate gneiss.
23. Fine-grained gneissic hornblendic amphibolite; foliation defined by hornblende- and plagioclase-rich layers.

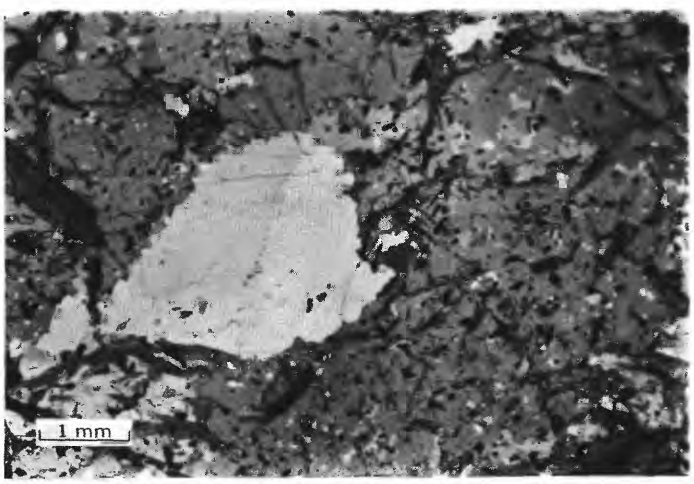


FIGURE 8.—Poikiloblastic cordierite and nearly inclusion-free quartz in cordierite-anthophyllite amphibolite. Crossed nicols.

anatectic melt was also squeezed into adjacent gneisses, forming discordant veinlets and dilative dikes, and into the crests of flowage folds.

Experimental work by Winkler and his coworkers has shown that the partial melting of quartzo-feldspathic gneisses in the presence of water is "inevitable" in terranes of high-grade regional metamorphism (Winkler, 1965, p. 199). Temperatures as low as 650°–700°C will initiate melting if water is available. The presence of water during the regional metamorphism of sedimentary rocks is assumed; some water is present in the original sediments, filling pores and adsorbed on grains, and additional water is produced by dehydration reactions during metamorphism. The temperature at which melting begins and the composition of the initial melt depend on the Ab-An ratio of the metasedimentary gneisses (Winkler, 1965)

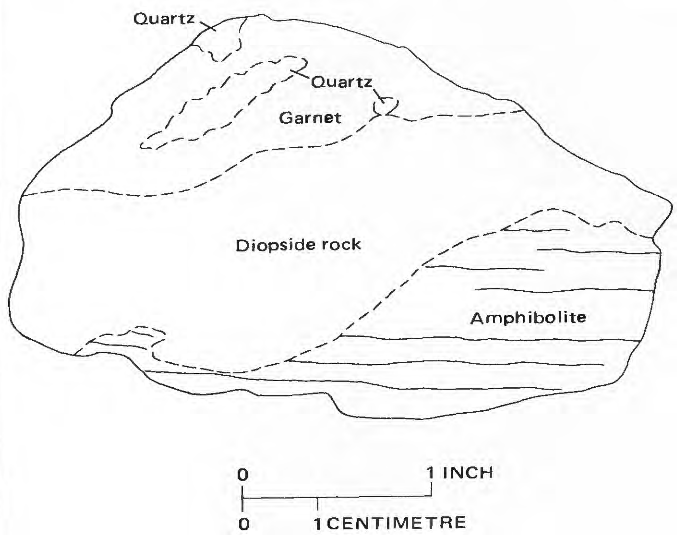


FIGURE 9.—Sketch showing gradation of hornblende-plagioclase amphibolite into garnet-quartz tactite; lines show trace of foliation. Sample from prospect south of Marksburg Gulch in the SW¼SE¼ sec. 18, T. 11 S., R. 72 W.

and on the water pressure of the system (Tuttle and Bowen, 1958; Luth and others, 1964).

The uneven distribution of migmatites through the layered gneiss sequence probably relates to initial variations in mineralogy and to different amounts of water within the gneisses. The fact that the sillimanitic gneisses are more migmatitic than are the sillimanite-free varieties suggests that partial melting may have been controlled by water produced by the reaction:

muscovite + quartz ⇆ sillimanite + K-feldspar + H_2O

Even where conditions preclude the melting of large amounts of quartzo-feldspathic material to form migmatites, some melting probably occurred on a very minor scale, as suggested by the frequent petrographic observations of "late quartz" and "late microcline" surrounding or cutting across all other mineral phases in a gneiss.

METAMORPHIC REACTIONS AND CONDITIONS OF METAMORPHISM

The layered gneisses contain mineral assemblages indicative of the sillimanite-potassic feldspar grade (upper almandine amphibolite facies) of regional metamorphism. The individual mineral assemblages of these high-grade gneisses vary with the composition of the original rock.

In the sillimanitic biotite-muscovite gneiss, the widespread occurrence of sillimanite and the presence of microcline indicate that the equilibrium temperature for the reaction:

muscovite + quartz ⇆ sillimanite + K-feldspar + H_2O

was exceeded during the metamorphism of pelitic rocks. On the basis of experimental work, Winkler (1965, p. 57) suggested that this reaction proceeds to the right at a temperature of about 640°C and a water pressure of 2,000 bars, the equilibrium temperature increasing with rising pressures. Temperatures of regional metamorphism greater than 600°C correspond to crustal depths of at least 20 km (kilometers) if an average geothermal gradient of 30°C per km is assumed. At such depths, load pressures in excess of 5 kb (kilobars) would be expected and the fluid pressure might be expected to approach the load pressure (Turner, 1968, p. 60).

An upper limit for the fluid pressure during the metamorphism of the layered gneisses can be estimated from the presence of cordierite and the absence of garnet in some of the gneisses. Experimental work by Hirschberg (reported in Winkler, 1965, p. 160) revealed that manganese-free almandine is stable in lieu of cordierite at pressures greater than 6–7 kb at 650°C, a temperature almost certainly attained during the metamorphism of the layered gneisses, considering the abundance of sillimanite.

The occurrence of primary wollastonite in regionally metamorphosed calc-silicate gneiss can also be used to interpret the conditions of metamorphism (Harker and Tuttle, 1955; Weeks, 1956; Greenwood, 1962). In the map area, wollastonite occurs in a thin (30-foot) calc-silicate lens in sillimanitic gneiss. It is associated with both quartz and calcite, but the calcite forms large grains enclosing wollastonite and appears to be retrograde. The presence of wollastonite in gneisses metamorphosed at high pressures and at temperatures between 600° and 700° suggests that the local calc-silicate system must have been at least partially open to the escape of CO_2 produced by the reaction:

$$\text{calcite} + \text{quartz} \leftrightharpoons \text{wollastonite} + CO_2.$$

Thus the mole fraction CO_2/H_2O must have been between 0.2 and 0.5 (fig. 10), meaning that some CO_2 was able to leave the system. Considering the small size of the calc-silicate body in relation to the great volume of the surrounding gneisses, it is likely that CO_2 mixed with H_2O from the gneisses, thereby reducing the partial pressure of CO_2 in the fluid phase and allowing the above reaction to proceed to the right under conditions of regional metamorphism.

In summary, the following conclusions have been reached regarding the conditions of the main period of regional metamorphism: (1) the highest temperatures attained were in the region 650°–700°C, (2) pressures of about 5–6 kb were reached, (3) metamorphism occurred at a minimum depth of about 20 km, and (4) local calc-silicate systems were partially open to the escape of CO_2 produced by the metamorphic reactions.

Superposed on the regional metamorphic features are mineralogic changes produced by retrograde metamorphism. Retrograde muscovite after sillimanite is wide-

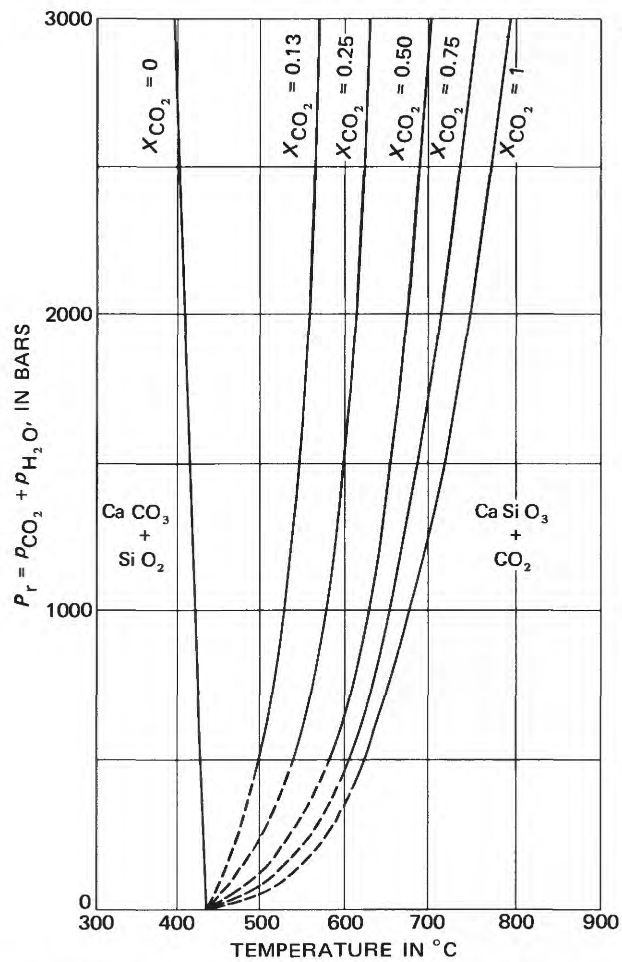


FIGURE 10.—Equilibrium curves for the formation of wollastonite from calcite and quartz for various constant compositions of the fluid phase (mole fractions CO_2/H_2O). From Winkler (1965), based on experimental data from Greenwood (1962) and Harker and Tuttle (1955).

spread, calcite replaces wollastonite, plagioclase has been locally converted to saussurite, and secondary epidote-clinozoisite and chlorite were recognized in many samples. In addition, local hydrothermal metamorphism was responsible for the local development of tactitelike mineral assemblages in calc-silicate rocks and amphibolite.

INTRUSIVE ROCKS

The southern Tarryall region has a large and varied suite of igneous rocks. Most of these are related to one of three main intrusive series, the Boulder Creek(?) Granodiorite, the Silver Plume(?) Quartz Monzonite, and the Pikes Peak Granite.

The Boulder Creek(?) rocks are oldest and have a well-developed gneissic foliation. They occur in partly conformable and partly disconformable bodies; their internal structure, however, is generally conformable to that of the enclosing paragneiss. Silver Plume(?) Quartz Monzonite tends to occur in discrete crosscutting stocks and in dikes and sills. Foliation, where present, is defined by flow-oriented feldspar crystals, and it parallels the contacts of the plutons. The youngest intrusives, the Pikes Peak and Redskin Granites, form sharply crosscutting stocks and batholiths which have very poorly developed internal structure.

BOULDER CREEK(?) GRANODIORITE

Gneissic rocks tentatively correlated with the Boulder Creek Granodiorite of the north-central Front Range range from biotite quartz diorite to granite in composition. The orthogneiss occurs in two main plutons—the Stoll Mountain batholith and the Round Mountain phacolith—in the southern and central parts of the region; it also forms a partly concordant body west of Tarryall and small, mostly concordant bodies in the southeastern part of the region (pl. 1; fig. 2). The distribution of the Boulder Creek-like rocks in terms of the present land surface just prior to emplacement of Silver Plume rocks is shown in figure 11.

The lithology of the orthogneiss varies widely, but three main types can be distinguished: (1) quartz diorite gneiss, (2) granodiorite gneiss, and (3) quartz monzonite gneiss. The three rock types are shown to be variants of one main granitic series because of their intimate association in the larger plutons, their similarity in structure and degree of metamorphism, and because of the types of plutons formed. Contacts between the orthogneiss and layered metasedimentary gneisses are sharp and generally concordant; biotite paragneiss inclusions are common especially in the quartz diorite gneiss, and the quartz dioritic type itself locally forms inclusions in quartz monzonite gneiss. The average composition of the orthogneiss varieties is approximately granodiorite. The range of composition, in terms of quartz, plagioclase, and potassium feldspar is shown graphically in figure 12.

QUARTZ DIORITE GNEISS

The quartz diorite gneiss of the Boulder Creek(?) intrusives forms plutons as much as 1 square mile in area, and along with the granodiorite gneiss or quartz monzonite gneiss it comprises parts of larger Boulder Creek(?) plutons. At several places the quartz diorite gneiss occurs at the contact between quartz monzonite gneiss and biotite paragneiss, suggesting that it is a border phase of the Boulder Creek rocks. In the Round Mountain phacolith, for example, the quartz diorite forms the trough and southeast flank of the pluton, lying between the layered paragneisses and quartz monzonite gneiss. Contacts between the quartz diorite gneiss and quartz monzonite gneiss are well exposed at several places along the south side of the Round Mountain phacolith, as well as in the Stoll Mountain batholith at the U.S. Forest Service overlook at Wilkerson Pass.

Typical quartz diorite gneiss is a medium-grained, mottled black and white rock which ranges from nearly equigranular to seriate porphyritic and from almost massive to strongly gneissic. Foliation is defined either by vaguely bounded inclusions of the biotite paragneiss or by cataclastic banding. Viewed microscopically the gneiss is xenomorphic granular to cataclastic in texture. The grain size is commonly uneven with the average size between 1 and 2 mm, but with plagioclase grains as large as 5 mm. Coarse pods of quartz and plagioclase—between 5 and 7 mm across—are granoblastic and are surrounded by biotite flakes that appear to have been forced aside by the pods. Cataclastic textures are common, as shown by bent plagioclase twin lamellae, broken grains of quartz and plagioclase, and polycrystalline quartz with undulatory extinction. Although the quartz diorite gneiss is less strongly foliated than the quartz monzonite gneiss, cataclastic textures are commonly better developed in the quartz diorite. This seems to indicate that the more mafic quartz diorite gneiss responded to deformation more by mechanical granulation than by recrystallization.

The quartz diorite gneiss is composed essentially of plagioclase, quartz, and biotite (tables 5, 6). The plagioclase is dominantly calcic andesine to sodic labradorite. It is faintly zoned with both normal and oscillatory types; cores of crystals are generally labradorite or calcic andesine, and some rims are sodic andesine. Some of the larger plagioclase crystals are composite, and some grains have albite twinning which cuts across zoning. Biotite is strongly pleochroic from tan to dark brown. Apatite (locally visible megascopically) and opaque iron oxides are the main accessory minerals, although zircon is generally present and sphene and fluorite occur locally. The accessory minerals commonly occur with the biotite.

GRANODIORITE GNEISS

Granodiorite gneiss forms part of the Stoll Mountain batholith, small bodies to the east of Stoll Mountain, and a partly conformable body south and west of the Boomer mine on Badger Flats (pl. 1). The granodiorite gneiss is less extensive than the slightly less mafic quartz monzonite or the quartz diorite gneiss facies of the Boulder Creek(?).

The granodiorite gneiss is tan to gray, medium-grained rock with well-developed foliation caused by the segregation of biotite-rich and quartz-feldspar layers. It is even grained and is slightly finer grained than the average quartz diorite gneiss or quartz monzonite gneiss. In hand specimen it strongly resembles the microcline gneiss of the central Front Range (Sims and Gable, 1964, p. C10–C13).

As seen microscopically, the rock has equigranular texture. Cataclasis is indicated, in general, by fractures partly healed with muscovite and locally by small folds that are broken. The composition, as determined from thin sections (tables 5, 6) ranges from quartz diorite to quartz monzonite. Quartz, commonly containing a few rutile

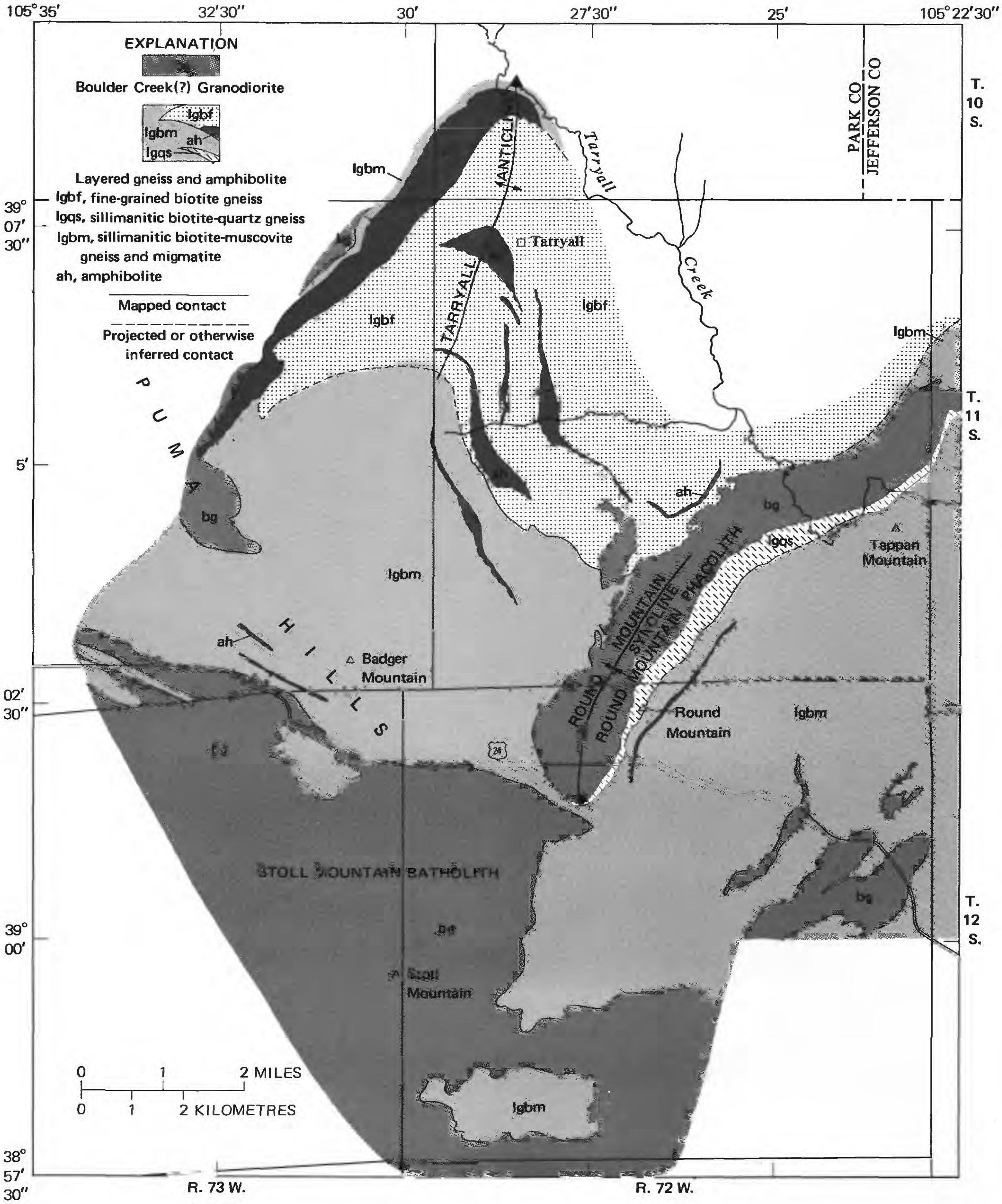


FIGURE 11.—Generalized map of the Boulder Creek(?) Granodiorite, amphibolite, and layered gneiss prior to intrusion of the Silver Plume(?) Quartz Monzonite, southern Tarryall region. Base from figure 2, this report.

TABLE 5.—*Modal (volume percent) composition of Boulder Creek(?) Granodiorite*

[Sample localities shown in fig. 7. N.D., not determined. Tr, trace. Leaders (...) indicate no data]

	Quartz diorite gneiss					Granodiorite gneiss					Quartz monzonite gneiss				
Sample No. (fig. 7)	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Field No.	BA-342	BA-900	T4-131	17	156	BA-79	T4-302	T4-445	BA-230	II-7	6	18	85	ML-4-1	BA-4561
Laboratory No.	---	---	---	--	---	---	---	---	---	---	--	--	--	H3237	---
Quartz	22	24	27	40	32	24	23	21	31	24	40	46	34	31.5	32.5
Plagioclase: Oligoclase-andesine	38	59	33	30	45	66	50	41	47	42	21	12	18	41	53.5
Potassic feldspar	0	0	1	0	0	.5	.5	6	11	21	36	35	35	16.5	9.5
Biotite	38	15	31	29	18	9	24	24	9	13	3	5	10	11	3.5
Muscovite	--	--	--	--	--	.5	1	.5	2	Tr	--	1	2	Tr	1
Apatite	1	.5	1.5	--	Tr	Tr	.5	2.5	Tr	--	Tr	1	1	--	--
Sphene	--	--	Tr	--	--	--	.5	2	--	--	--	--	--	--	--
Zircon	Tr	Tr	Tr	--	Tr	--	--	--	--	--	Tr	Tr	--	Tr	Tr
Opaque minerals	1	1.5	5.5	--	Tr	Tr	.5	2	Tr	Tr	Tr	--	--	Tr	Tr
Clinozoisite (C) and fluorite (F)	--	--	1F	--	--	--	--	1C	--	--	--	--	--	--	--
Range of composition of major zoned plagioclase[1]	40	39-43	44-55	40	40-45	N.D.	36-45	36	N.D.	N.D.	25	25-30	35	N.D.	N.D.

[1]Percent An.

Sample descriptions

Quartz diorite gneiss:

24-26. Coarse-grained gneiss, strongly foliated.

27. Medium-grained gneiss from zone between layered gneiss and Boulder Creek(?) granitic gneiss.

28. Slightly porphyritic gneiss from concordant layer in migmatitic layered gneiss.

Granodiorite gneiss:

29. Medium-grained, pale-gray well-foliated gneiss.

30-31. Medium-grained, medium-gray well-foliated gneiss.

32-33. Medium-grained, pale-gray well-foliated gneiss.

Quartz monzonite gneiss:

34. Medium-grained gneiss, weakly foliated, from aqueduct trench.

35. Coarse-grained gneiss, strongly foliated, from prospect pit.

36. Coarse-grained gneiss with microcline augen; contains partly assimilated inclusions of biotite gneiss.

37. Coarse-grained gneiss with microcline augen.

38. Coarse-grained rock, poorly developed foliation.

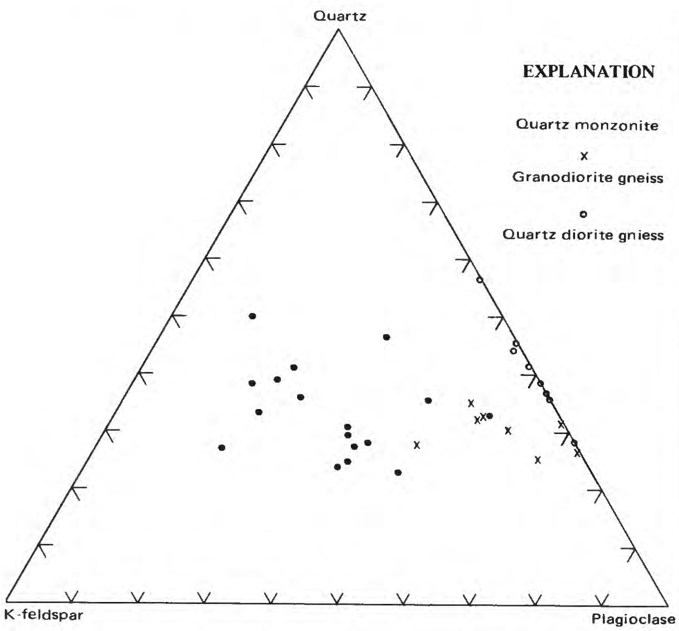


FIGURE 12.—Modal composition (quartz-plagioclase-potassium feldspar) of the Boulder Creek(?) Granodiorite. Rock types were classified in the field.

needles, makes up about 20 to 30 percent of the rock. Plagioclase varies from about 40 to 60 percent and is mainly sodic andesine, although in quartz dioritic varieties it may be as calcic as An_{45}. Biotite, which is the dominant mafic mineral, forms well alined tabular plates. As in the quartz diorite gneiss, the main accessories are apatite and opaque minerals, with minor amounts of sphene, clinozoisite(?), and zircon.

Variation in color index observable in the field and variation in the rock composition as determined microscopically suggest that some of the sill-like bodies of granodiorite gneiss are differentiated. The southern portion of the body near the Boomer mine is near quartz diorite in composition while that to the north is granodiorite to quartz monzonite.

QUARTZ MONZONITE GNEISS

The dominant unit of the Boulder Creek(?) rocks, here called quartz monzonite gneiss, forms a body of batholithic dimensions called the Stoll Mountain batholith, which crops out in the southern part of the region and continues to the east, south, and west beyond the map boundaries. The batholith continues at least to the eastern end of Elevenmile Canyon (Wobus, 1966) and apparently the same rock, once called Pikes Peak Granite (Stark and others, 1949), forms the core of South Dome 5 miles west of Elevenmile Canyon Reservoir. It also is exposed in an area of about 9 square miles east of the Agate Creek drainage in South Park, approximately 15 miles west of the reservoir.

Quartz monzonite gneiss also forms most of the asymmetric Round Mountain phacolith. Prior to the intrusion of younger igneous rocks, this phacolithic mass was at least 5 miles long and one-half mile wide (fig. 11). Several smaller bodies occur southeast of the Round Mountain syncline and one apparently extensive body is partly exposed west of the Tarryall Mountains batholith in the northern part of the area.

TABLE 6.—*Chemical and normative (weight percent) composition of Boulder Creek(?) Granodiorite*

[Chemical analysts: Ellen S. Daniels, G. O. Riddle, and Paula M. Buschman. Sample localities shown in fig. 7. N.D., not determined]

	Quartz monzonite gneiss		
Sample No. (fig. 7)--	37	38A	38B
Field No.-------------	ML-4-1	E627	E628
Laboratory No.--------	H3237	D101310	D101312
Chemical composition			
SiO_2	75.20	67.91	71.50
Al_2O_3	12.98	15.24	14.56
Fe_2O_3	.50	1.54	1.04
FeO	1.39	2.74	1.39
MgO	.30	1.06	.53
CaO	1.20	3.44	1.95
Na_2O	3.07	2.66	2.93
K_2O	4.19	3.79	5.13
H_2O+	.30	.37	.34
H_2O-	.17	.04	.02
TiO_2	.22	.73	.39
P_2O_5	.04	.17	.11
MnO	.07	.07	.06
CO_2	.01	.02	.05
Cl	.01	0	.02
F	.11	.12	.09
Subtotal---------	99.76	99.91	100.11
Less O---------	.05	.05	.04
Total------------	99.71	99.86	100.07
Normative composition			
q	37.96	28.70	30.15
or	24.76	22.40	30.32
ab	25.90	22.43	26.65
an	4.84	15.01	8.02
c	1.64	1.28	1.28
en	.75	2.64	1.32
fs	1.91	2.68	1.16
fr	.22	.23	.18
ap	.10	.40	.26
fluorine	0	0	0
il	.42	1.39	.74
mt	.73	2.23	1.51
other	.04	.06	.14

Sample descriptions

37. Coarse-grained gneiss with microcline augen.

38A. Coarse-grained gneiss, weakly foliated, with irregular microcline augen as much as 1 inch long, from roadcut.

38B. Coarse-grained gneiss, strongly foliated, with pink microcline-rich layers, from cliffs above Reservoir Campground.

The best exposed contact of the Stoll Mountain batholith with older paragneisses roughly parallels U.S. Highway 24 across Wilkerson Pass. This contact is concordant to the foliation of the metasedimentary rocks on a broad scale but is discordant in detail. Concordant lenses (several feet thick) of medium-grained and pegmatitic quartz monzonite gneiss alternate with biotite-quartz-plagioclase paragneiss and amphibolite in roadcuts along the north side of U.S. Highway 24 near the summit of the pass. Small pendants of metasedimentary gneiss and quartz diorite gneiss occur in quartz monzonite gneiss within 2 miles south of the contact and are irregular or elongate parallel to it. The foliation of the inclusions is parallel to that of the quartz monzonite gneiss; the contacts of the pendants with the quartz monzonite are sharp and locally discordant.

Other gneiss contacts with pendants of metasedimentary gneiss to the south are more obviously intrusive. Apophyses of younger gneiss penetrate the older rocks, generally along foliation planes. An easily accessible outcrop showing this relationship is found in the north-central part of sec. 12, T. 13 S., R. 73 W., about 200 feet west of the well in the North Shore campground at Elevenmile Canyon Reservoir. At this outcrop an inclusion (too small to map) of biotite gneiss is intruded by quartz monzonite gneiss, and quartz-feldspar pods have developed in the biotite gneiss within a few inches of the quartz-monzonite apophyses (fig. 13). Such contact relations as these, and the sharp and locally discordant boundaries between quartz monzonite gneiss and inclusions, attest to the intrusion emplacement of the quartz monzonite.

The quartz monzonite gneiss consists of three main textural varieties which intergrade. One type is a pink, medium-grained, well-foliated gneiss; the second and most widespread is a pink, medium- to coarse-grained augengneiss; and the third is fine-grained gneiss, very light colored and not as obviously foliated. The foliation in the first two types is due mostly to the separation of the light and dark minerals into layers; a strong biotite lineation is also typical of these two types.

The medium- to coarse-grained augen type itself varies from a rock in which feldspar crystals are nearly euhedral (fig. 14*A*) to one in which they are strongly deformed (fig. 14*B*). In the augengneiss, the strongest component of the foliation, the biotite, is wrapped around the potassium feldspar augen. The augen are composed mainly of potassium feldspar and commonly are 2–5 cm long. In some places augen are vaguely defined polycrystalline aggregates of potassium feldspar; in others they are subhedral Carlsbad-twinned single crystals with minor inclusions of plagioclase and biotite. Close inspection of stained slabs of single crystal augen shows a faint concentric zonal arrangement of the included plagioclase and biotite.

Microscopically the quartz monzonite gneiss is xenomorphic porphyritic in the augen type to xenomor-

FIGURE 13.—Apophyses of quartz monzonite gneiss (Boulder Creek?) in fine-grained biotite gneiss of the layered gneiss.

phic granular in the other two types. Foliation is defined by alined biotite plates and, in some sections, by subparallel orientation of quartz and feldspar grains. Three feldspars are visible microscopically—major potassium feldspar and oligoclase-andesine, and minor albite-oligoclase. The dominant plagioclase is calcic oligoclase to sodic andesine which has albite and carlsbad twinning; it is locally normally zoned with cores about 5–10 percent more calcic than the rims. Composition planes of carlsbad twins locally disrupt zoning. The potassium feldspar is mainly grid-twinned microcline. Some orthoclase(?) is found near Badger and O'Brien Gulches, and as it occurs close to an intrusive mass of gabbro and granite, it is interpreted as the result of partial disordering of the potassium feldspar by heat from the yonger intrusives. Albite-oligoclase constitutes as much as 8 percent of the rock and occurs in the potassium feldspar grains or as partial rims around the potassium feldspar and the more calcic plagioclase.

Microcline appears from its textural relations to represent at least three generations. The oldest microcline is enclosed and partially replaced by larger grains of microcline, including augen, with a different orientation of grid twinning. These same large grains also enclose and partially replace smaller oligoclase-andesine grains along twin planes, so that the albite twinning of the plagioclase gradually merges with the grid twinning of the microcline. The youngest generation of microcline, particularly evident within the microcline augen, forms grains that fill tiny cracks in the augen: here the microcline occurs with elongate grains of quartz which appear virtually unstrained when compared with quartz that has strong undulatory extinction in the groundmass.

A study of four thin sections of individual microcline augen confirmed that these large grains are carlsbad-twinned single crystals. Each side of the twin contains

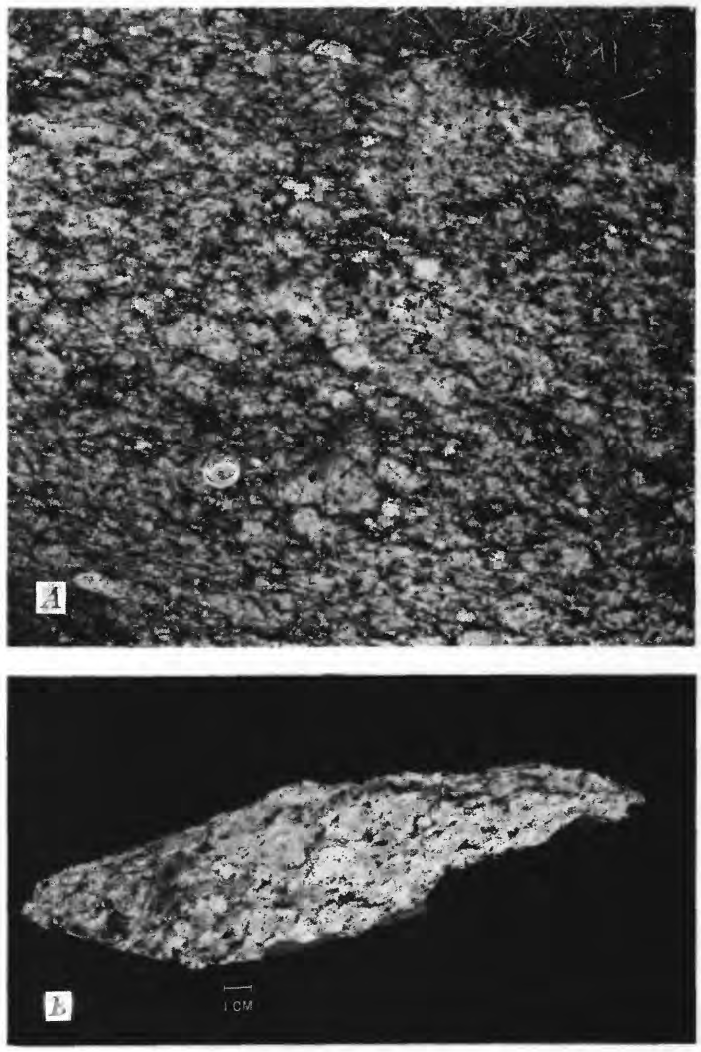


FIGURE 14.—Quartz monzonite gneiss, Boulder Creek(?) Granodiorite. *A*, Rock with dominantly tabular feldspar. *B*, Rock with deformed feldspar.

numerous crystallographically alined stringers and blebs of albite-oligoclase which cut the microcline grid twinning; the orientation of these stringers is different on opposite sides of the composition plane.

Myrmekitic intergrowths of quartz and plagioclase are present in all thin sections of quartz monzonite gneiss in amounts up to several percent. The form of the intergrowth varies from isolated blebs of quartz to dendritic or vermicular varieties, though much of this variation is probably caused by the orientation of the thin sections. Myrmekite generally occurs at grain boundaries between plagioclase and microcline, although a few examples of myrmekitic textures in microcline in contact with other microcline or quartz grains were observed. Myrmekite also replaces plagioclase inclusions in microcline augen, but only those plagioclase grains near the rims of the augen are so replaced.

Biotite is a major constituent of the quartz monzonite gneiss, forming medium to coarse clusters of grains that surround augen. The biotite is strongly pleochroic from tan to dark brown and is altered to chlorite in some samples. The common accessory minerals—zircon, apatite, magnetite, and some sphene—are commonly associated with biotite.

The composition of the unit varies from granodiorite to granite and averages quartz monzonite (table 5; fig. 12); it thus slightly overlaps the composition of the granodiorite gneiss. Chemical analyses of three specimens also indicate a wide variation in composition (table 6).

One whole-rock Rb-Sr age determination was made of a sample of augengneiss from a roadcut about 200 feet south of the Caylor Gulch Road near the center of sec. 7, T. 13 S., R. 72 W. An age of 1.62 b.y. was indicated, though this must be considered a minimum age due to weathering of the sample (C. E. Hedge, written commun., 1966). No mappable intrusive body of younger rock is near the sample locality, but the granitic gneiss at this locality, as in most exposures, is cut by small, sharply bounded dikes (several inches to several feet thick) of leucocratic quartz monzonite. The effect of these dikes on the isotopic ratios, and hence on this age determination, cannot be evaluated.

MAFIC METAIGNEOUS ROCKS

Small bodies of mafic and ultramafic rocks occur in widely scattered parts of the southern Tarryall region. An igneous origin is assumed, as remnants of intersertal textures have survived metamorphic recrystallization and as the rock bodies locally crosscut the foliation of the enclosing gneisses. Three varieties—metadiorite, metagabbro, and biotite hornblendite—are mapped (pl. 1).

Bodies of slightly metamorphosed mafic and ultramafic rocks are found near the southern map boundary (sec. 12, T. 13 S., R. 73 W.) and in sec. 12, T. 12 S., R. 72 W. A small body of pyroxenite, exposed in sec. 20, T. 11 S., R. 72 W., has been mined for decorative crushed rock. Contacts between the mafic rocks and adjacent rock types are, in general, poorly exposed, but dikes of metadiorite cut the Boulder Creek(?) Quartz Diorite in sec. 14, T. 12S., R. 72 W., and biotite hornblendite is locally cut by pegmatite of probable Silver Plume age. Metadiorite is altered to calc-silicate rock just west of Warlings Ranch (sec. 6, T. 12 S., R. 71 W.), a type of alteration elsewhere inferred to be related to Silver Plume plutonism. Some of the mafic and ultramafic igneous rocks are therefore assumed to be younger than the Boulder Creek(?) rocks and older than the Silver Plume(?). Possibly the mafic rocks are late phases of the Boulder Creek plutonic episode. The same age sequence—dominant granodiorite (Boulder Creek) succeeded by metadiorite and quartz diorite—is found in the central Front Range (Harrison and Wells, 1959, p. 15).

Mafic and ultramafic rocks of this unit are dark green or black, medium grained, and massive to weakly foliated. They are composed predominantly of hornblende (hornblendite and biotite hornblendite), plagioclase and hornblende (metadiorite), or plagioclase and augite (metagabbro).

As seen in thin section the mafic and ultramafic rocks are medium grained and hypidiomorphic granular. Nonoriented, subhedral plagioclase laths 1–3 mm long locally enclose smaller grains of augite in a medium-grained intergranular texture. The mafic minerals also occur in 3–4 mm clusters of several grains. Plagioclase is twinned according to albite, pericline, and carlsbad laws and shows normal zoning within the range labradorite-calcic andesine. Hornblende is strongly pleochroic from tan to dark green and has $2V$ ranging from $-70°$ to an anomalous $+35°$. It is extensively altered to epidote, chlorite, and biotite. Augite is a low calcium variety ($2V = +25°$) and is partly altered to hornblende and chlorite. Quartz, locally present in minor amounts, is clearly late and replaces all minerals, forming vermicular intergrowths with plagioclase and biotite in one section. Opaque minerals, especially magnetite, are abundant.

QUARTZ MONZONITE OF ELEVENMILE CANYON

A porphyritic quartz monzonite is well exposed over about 5 square miles in the southern part of the map area, especially in the cliffs in the western part of Elevenmile Canyon. Reconnaissance shows that this rock type continues eastward to the mouth of the canyon, where it is cut by the Pikes Peak Granite (Wobus, 1966). The quartz monzonite throughout its extent contains numerous large inclusions of gneissic Boulder Creek(?) Granodiorite. It is cut in most outcrops by dikes of leucogranite to leucocratic quartz monzonite, tentatively correlated with the Silver Plume, or by dikes of granite pegmatite. The quartz monzonite of Elevenmile Canyon cuts across the foliation of the quartz monzonite gneiss of Boulder Creek(?) age in cliffs north of Reservoir Campground in Elevenmile Canyon and forms dikes that cut the gneiss at other locations.

Three varieties of the quartz monzonite of Elevenmile Canyon have been recognized, although they could not be separated in mapping at the present scale. The most abundant type is a massive to weakly foliated, medium- to coarse-grained, porphyritic pink quartz monzonite with anhedral to subhedral microcline phenocrysts 1–1½ cm long in a biotite-rich groundmass. A younger facies, which intrudes the rock just described, is a lighter pink medium-grained massive quartz monzonite with tabular microcline phenocrysts 4–8 mm long. The third variety is darker pink to gray, medium grained, and of granodiorite composition; it appears to be a border facies and was found only at the northwestern extremity of the quartz monzonite near the head of Springer Gulch. Modal analyses of samples of each type are given in table 7 and are plotted in figure 15.

TABLE 7.—*Modal composition (volume percent) of quartz monzonite of Elevenmile Canyon*

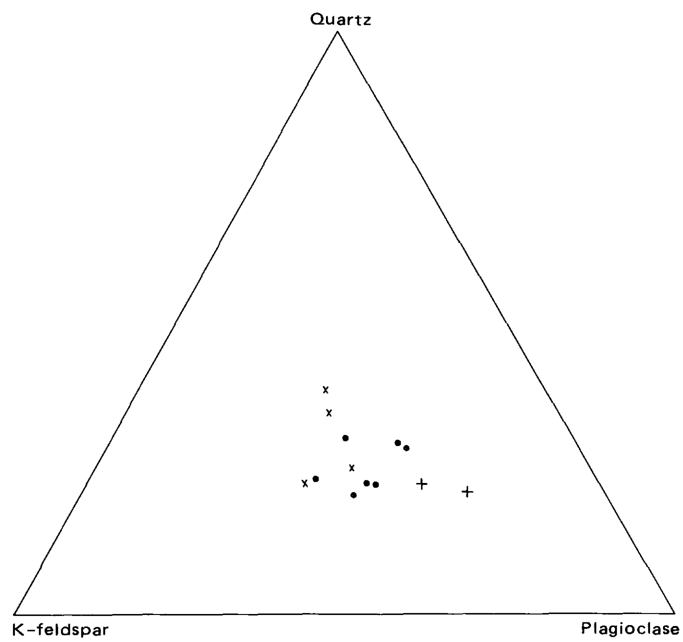
[Sample localities shown in fig. 7; Tr, trace; leaders (...) indicate no data]

	Coarse-grained porphyritic facies				Medium-grained facies			Border facies	
Sample No. (fig. 7)--	39	40	41	41a	42	43	44	45	46
Field No.-------------	561	619	634	629	561-2	586	601	559	580
Quartz----------------	19	22	18	30	31	23	31	18	15
Plagioclase-----------	37	33	30	33	29	35	23	41	42
Potassic feldspar-----	29	21	38	30	33	33	27	22	15
Biotite---------------	--	--	12	5	--	7	--	--	24
Muscovite-------------	--	--	--	--	--	Tr	--	--	1
Opaque minerals-------	--	--	Tr	1	--	2	--	--	1
Sphene----------------	--	--	1	Tr	--	Tr	--	--	2
Apatite---------------	--	--	Tr	1	--	Tr	--	--	Tr
Zircon----------------	--	--	1	Tr	--	Tr	--	--	Tr
Epidote---------------	--	--	--	--	--	Tr	--	--	1
Total dark minerals[1]--	15	24	--	--	7	--	19	19	--
Composition of plagioclase[2]--------	--	--	37-26	28	--	38	--	--	30

[1]Visual estimate from stained slab.
[2]Percent An.

Sample descriptions

39. Weakly foliated; medium- to coarse-grained quartz monzonite with pink microcline phenocrysts as much as 1.5 cm long.
40. Coarse-grained biotite quartz monzonite from outcrop cut by dikes of Silver Plume(?) Quartz Monzonite.
41. Weakly foliated, medium- to coarse-grained quartz monzonite with pink microcline phenocrysts.
41a. Medium- to coarse-grained porphyritic quartz monzonite.
42. Pink, medium-grained, nonporphyritic quartz monzonite.
43. Weakly foliated, medium-grained quartz monzonite with nonalined microcline phenocrysts 0.6-1.2 cm long.
44. Pink moderately lineated, medium-grained quartz monzonite with tabular microcline phenocrysts.
45. Massive, medium-grained granodiorite from contact zone between quartz monzonite and quartz monzonite gneiss.
46. Weakly foliated, medium-grained granodiorite from contact zone.



EXPLANATION

- • Coarse-grained porphyritic facies
- x Medium-grained facies
- + Border facies

FIGURE 15.—Modal composition (quartz-plagioclase-potassium feldspar) of the quartz monzonite of Elevenmile Canyon.

Thin sections show that the typical quartz monzonite of Elevenmile Canyon is xenomorphic and porphyritic, containing microcline phenocrysts as much as 1½ cm long set in a groundmass of grains averaging one-fourth mm in diameter. Most microcline phenocrysts are carlsbad twinned and some enclose small plagioclase grains. Plagioclase is faintly zoned (normal zoning) from intermediate andesine to calcic oligoclase; it generally shows albite or combination albite-carlsbad twinning. Polycrystalline quartz grains have undulatory extinction, and some appear crushed. Myrmekite similar to that described in quartz monzonite gneiss of Boulder Creek(?) Granodiorite occurs in plagioclase and at plagioclase-microcline grain boundaries. Biotite, pleochroic from tan to dark brown, is associated with the accessory minerals, which are predominantly sphene, apatite, zircon, and epidote.

Whole rock isotopic (Rb-Sr) dating of a sample of the coarsest facies of this unit (collected from a freshly blasted outcrop about 100 feet north of the dam of Elevenmile Canyon Reservoir) indicates an absolute age of 1.46±0.15 b.y. (C. E. Hedge, written commun., 1966). This is only slightly older than the 1.40–1.45 b.y. age currently accepted for the Silver Plume Granite (Hedge and others, 1967), and it seems likely that the quartz monzonite of Elevenmile Canyon is an early phase of the Silver Plume plutonism.

SILVER PLUME(?) QUARTZ MONZONITE

Massive to flow-foliated plutonic igneous rocks of dominant quartz monzonitic composition are tentatively correlated with the Silver Plume Granite of the central Front Range. The Silver Plume(?) Quartz Monzonite of the southern Tarryall region occurs in stocks as large as 5 square miles in area and in a great many dikes. The stocks are mainly in the south-central part of the area, between the Redskin stock and the Stoll Mountain batholith (pl. 1; fig. 2). The contacts of the Silver Plume(?) stocks are mainly concordant, but unlike the Boulder Creek(?) Granodiorite which also has common concordant contacts, the Silver Plume(?) Quartz Monzonite strongly deformed its wall rocks. Local migmatites related to its emplacement are also characteristic of the contact zones around the Silver Plume(?) Quartz Monzonite.

Three varieties of the Silver Plume(?) were mapped according to differences in grain size and structure (pl. 1). These are called (1) fine- to medium-grained quartz monzonite, (2) fine-grained quartz monzonite, and (3) medium- to coarse-grained quartz monzonite. The medium- to coarse-grained type forms separate plutons; the two finer grained varieties occur together in some bodies and are described together. As noted earlier, the quartz monzonite of Elevenmile Canyon is probably related to the Silver Plume(?) rocks, and many of the granite pegmatites of the region also are related to the Silver Plume.

Contacts of the Silver Plume(?) Quartz Monzonite are generally sharp and discordant in detail. Nevertheless the foliation of the host layered gneisses generally outlines the shape of the intrusive bodies because of plastic deformation associated with the emplacement of the quartz monzonite. This relationship is particularly well shown near the township line separating T. 11 S. and T. 12 S. in the Tarryall quadrangle, where the biotite paragneiss of the layered gneiss is in a synclinal fold between two Silver Plume(?) plutons. Intrusive emplacement of the quartz monzonite also is indicated by numerous inclusions and by sill-like apophyses of quartz monzonite which penetrate into the host gneisses parallel to their foliation.

Outcrops of the Silver Plume(?) are typically rounded, show well-developed vertical conjugate joint systems, and are commonly pitted on exposed surfaces. The quartz monzonite on weathering disintegrates into a fine-grained white sand, easily distinguishable from colluvium derived from other rock units.

That the Silver Plume(?) was derived from a fairly wet magma is indicated by occurrence of both biotite and muscovite as varietal minerals, by associated migmatization and retrogressive development of coarse muscovite in its wall rocks, by abundance of pegmatites and by associated mineralization. The association of tungsten-bearing tactite deposits with the Silver Plume(?) is particularly noticeable in the northeastern part of T. 12 S., R. 72 W.

MEDIUM- TO COARSE-GRAINED QUARTZ MONZONITE

This variety of the Silver Plume(?) is confined to the southeastern part of the Tarryall quadrangle, where it forms a partly discordant body with many concordant apophyses (pl. 1). This occurrence is part of a pluton, incompletely shown on the generalized map (fig. 2), which parallels the South Platte River and is cut off by the Pikes Peak batholith to the northeast.

This quartz monzonite is a pale-reddish brown, markedly porphyritic rock whose grain size ranges from 3-7 mm. Two feldspars are visible in hand specimen, a white irregularly shaped plagioclase and a reddish-brown tabular potassium feldspar. The potassium feldspar crystals give the rock a porphyritic aspect, and they are alined in a weakly developed flow foliation. As seen microscopically the rock is hypidiomorphic granular and consists of sparsely perthitic microcline, calcic oligoclase, quartz, subordinate biotite and muscovite, and accessory apatite, monazite(?), zircon, and opaque oxides (table 8). Myrmekite is common and occurs along plagioclase-microcline grain boundaries, adjacent to microcline crystals, and apparently as discrete grains. Like other phases of the Silver Plume period of plutonism, the medium- to coarse-grained type is a quartz monzonite but is slightly less quartzose than the other varieties in the region (fig. 16).

TABLE 8.—*Modal composition (volume percent) of Silver Plume(?) Quartz Monzonite*

[Sample localities shown in fig. 7. N.D., not determined; Tr, trace; leaders (...) indicate no data]

	Medium- to coarse-grained facies		Fine- to medium-grained facies				Fine-grained facies	
Sample No. (fig. 7)--	47	48	49	50	51	52	53	54
Field No.-------------	T4-58	T4-95	TR-20	BA-936	27-10	BA-249	T2-121	T3-101
Quartz----------------	22.5	21.5	26	31	33	36	30	35
Plagioclase-----------	35.5	33.5	30	25	26	20.5	27	29
Potassium feldspar----	31	33.5	32	38.5	31	33	34	27
Biotite---------------	7	4.5	8	4	9	4.0	6	5
Muscovite-------------	2	5.0	3	.5	1	[1]6.5	3	3
Sillimanite-----------	0	0	0	1.2	0	[1]---	---	---
Zircon----------------	Tr	Tr	Tr	Tr	Tr	---	---	---
Opaque minerals-------	1.5	1.5	Tr	---	---	Tr	---	1
Apatite---------------	.5	Tr	---	---	---	Tr	---	---
Monazite(?)-----------	Tr	.5	---	---	---	---	---	---
Unknown radioactive mineral------------	---	---	---	Tr	---	---	---	---
Fluorite--------------	---	---	---	---	---	Tr	---	---
Composition of plagioclase[2]--------	30-26	N.D.	N.D.	N.D.	N.D.	N.D.	18-4	14-7

[1]Includes fine-grained sillimanite.
[2]Percent An.

Sample descriptions

47-48. Biotitic, pale-pinkish-gray, seriate porphyritic quartz monzonite with noticeable tabular crystals of potassium feldspar.
49. Pale-gray to yellowish-white, seriate porphyritic quartz monzonite from prospect pit of uranium-bearing vein.
50-51. Pale-gray seriate porphyritic biotite quartz monzonite.
52. Muscovite-biotite quartz monzonite.
53-54. Pale-gray, well-foliated biotite-muscovite quartz monzonite; occurs with pegmatitic interlayers.

FINE- TO MEDIUM-GRAINED AND FINE-GRAINED QUARTZ MONZONITES

Nearly massive to moderately foliated fine- to medium-grained and fine-grained quartz monzonites, also tentatively correlated with the Silver Plume Quartz Monzonite of the central Front Range, form four stocks each more than 2 square miles in area, several other bodies of about one-half square mile each, and many dikes. The four larger plutons are the Tappan Mountain, Firefly, Badger Mountain, and Thorpe Gulch stocks (pl. 1); all are circular to crudely oval in shape. The Firefly and Tappan Mountain stocks probably merge at depth (pl. 1, section *A-A'*). The Thorpe Gulch, Tappan Mountain, and Firefly stocks are composite in character, consisting partly of nearly massive, leucocratic, fine- to medium-grained quartz monzonite and partly of the fine-grained quartz monzonite that is locally moderately foliated. The fine-grained facies forms the outer zones of the plutons, as at Tappan Mountain, and the discontinuous marginal zones, as at Thorpe Gulch; it also occurs in long concordant apophyses of the plutons, where it has a well-developed flow foliation. These two relatively fine grained varieties of the Silver Plume(?) apparently intergrade, particularly in the Firefly stock, but the more massive fine- to medium-grained type cuts the foliated fine-grained quartz monzonite in secs. 35 and 36, T. 11 S., R. 72 W., in the Tappan Mountain stock.

The fine- to medium-grained quartz monzonite ranges from very pale brown or red to almost white in color and from massive to weakly foliated; the foliation is defined

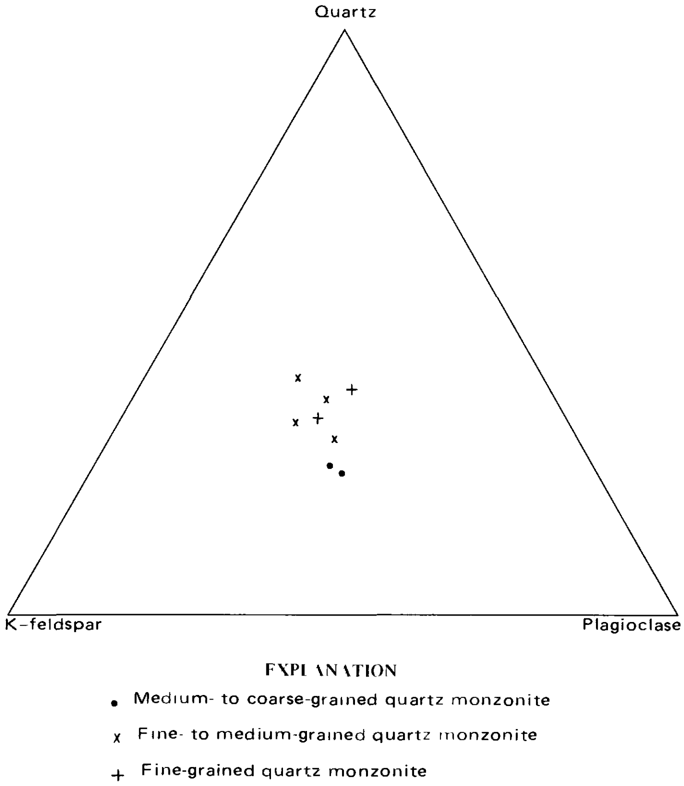


FIGURE 16.—Modal composition (quartz-plagioclase-potassium feldspar) of the Silver Plume(?) Quartz Monzonite.

principally by tabular crystals of potassium-feldspar. Both biotite and muscovite are present and are commonly visible in hand specimen. Locally the rock is pegmatitic and is cut by or grades into sparsely miarolitic coarse-grained granite or pegmatite. The fine-grained quartz monzonite is also light colored but locally is moderately well foliated. Concordant pegmatite is very characteristic of the foliated fine-grained quartz monzonite, as can be seen in outcrops near U.S. Highway 24 in the NE¼ sec. 9, T. 12 S., R. 72 W.

Viewed microscopically, the fine- to medium-grained quartz monzonite is hypidiomorphic granular and contains a few subhedral microcline grains as long as 7 mm. Microcline is grid twinned and commonly carlsbad twinned; some of the crystals are partly rimmed by sodic plagioclase. Most of the plagioclase in this rock is polysynthetically twinned calcic oligoclase; some is faintly zoned and partially altered to sericite. Where the plagioclase is in contact with microcline, it may be partially replaced by myrmekite or may have a thin rim of low-index, untwinned plagioclase similar to that just described. Ragged muscovite grains are partly altered to a fine-grained highly birefringent mineral (sericite?). Biotite, generally more abundant than muscovite, is pleochroic from tan to dark brown (dark green in one section) and is typically associated with the accessory minerals.

GRANITE PEGMATITE OF PRE-PIKES PEAK AGE

Although granite pegmatite of several generations and possibly of diverse origin occurs in the southern Tarryall region, a common variety occurs in and near bodies of the Silver Plume(?) Quartz Monzonite. Pegmatite bodies of this generation are concordant pods or layers or discordant dikes as much as several tens of feet thick; many were to small to map.

In general, pegmatites of Silver Plume(?) age are composed of massive coarse-grained milky quartz, pink perthitic microcline, and white plagioclase of albite-oligoclase composition. Biotite and muscovite occur in plates as much as several inches across; locally muscovite rims the biotite plates. Magnetite, tourmaline (variety schorl), garnet, and beryl are sparse constitutents of the pegmatite.

Pegmatites related to the Silver Plume(?) Quartz Monzonite have been mined on a small scale for quartz and feldspar, and some have been prospected for beryl. Beryl-bearing pegmatites are widely distributed, but are seemingly more abundant in the northwestern part of the region.

PIKES PEAK GRANITE AND ASSOCIATED ROCKS

Pikes Peak Granite and associated rocks underlie a major part of the southern Tarryall region, especially the part east and north of the igneous-metamorphic complex composed of the rocks just described. In contrast to the generally conformable and foliated Boulder Creek(?) and Silver Plume(?) bodies, the Pikes Peak and derivative rocks form massive sharp-walled plutons. One of these, the major Pikes Peak batholith, at least 1,200 square miles in area, is exposed mainly to the east of the region but extends into it in a small area near Goose Creek. A smaller batholith of Pikes Peak Granite—the Tarryall Mountains mass—is entirely within the region and underlies a 95-square-mile area (fig. 17).

Other igneous rocks such as the Redskin Granite, an unnamed gabbro and related quartz monzonite, and the granodiorite of Wellington Lake (fig. 2) are closely associated with the Pikes Peak in the Tarryall region. Like the Pikes Peak they are posttectonic epizonal bodies. Association, common geologic characteristics, chemical trends, and in some cases radioactive age determinations show that these rocks belong to a magma series related to the Pikes Peak Granite. Other members of the series include the syenite of Lake George (Stewart, 1964), the Mount Rosa Granite, a peralkaline granite (Gross and Heinrich, 1965), and the olivine syenite and related rocks of the Cripple Creek district (Graton, 1906). The magma series is thus represented by rocks ranging from gabbro to granite and syenite in composition and includes both peralkaline

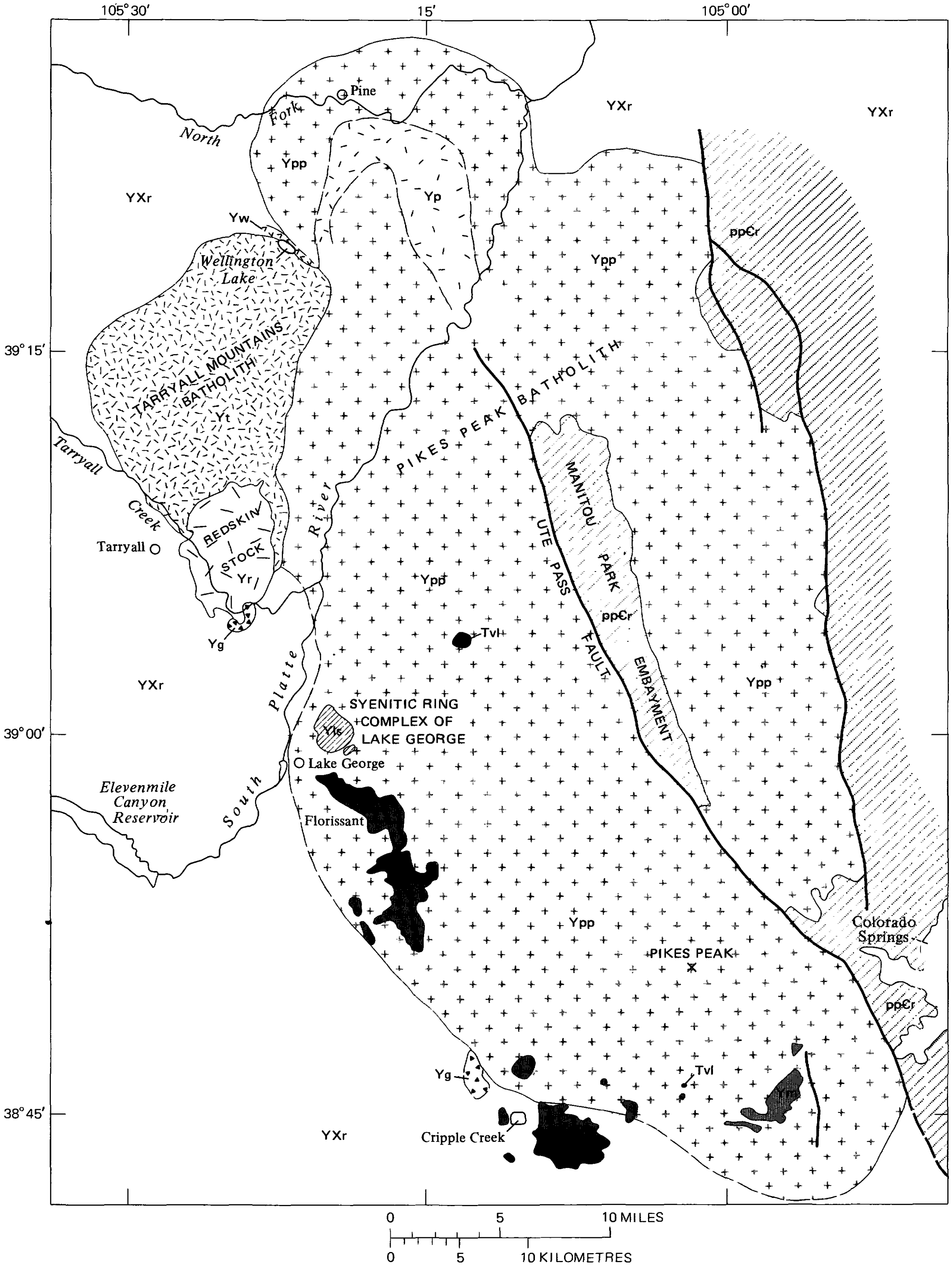
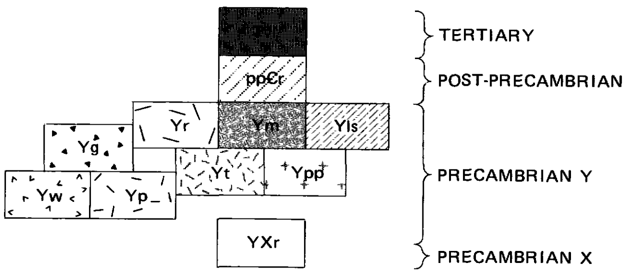


FIGURE 17 (above and facing page).—Generalized geologic map of the Tarryall Mountains and Pikes Peak batholiths. Geology by C. C. Hawley and W. N. Sharp, 1959-66, Hutchinson (1960a), Lindgren and Ransome (1906), Gross and Heinrich (1965), and Stewart (1964).

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

Tvl	TERTIARY VOLCANIC ROCKS AND LACUSTRINE SEDIMENTS
ppЄr	POST-PRECAMBRIAN ROCKS
	PRECAMBRIAN Y
Yr	Redskin Granite
Ym	Mount Rosa Granite
Yls	Syenitic ring complex of Lake George
Yg	Mafic extrusive rocks — Includes olivine syenite and olivine gabbro of Cripple Creek
	Pikes Peak Granite and associated rocks
Yt	Granite of Tarryall Mountains batholith
Ypp	Granite and quartz monzonite of Pikes Peak batholith
Yw	Granodiorite of Wellington Lake
Yp	Granodiorite of Pine area
YXr	PRECAMBRIAN Y AND X ROCKS

——— Contact — Dashed where approximately located

——— Fault — Dashed where approximately located

(Mount Rosa) and peraluminous alkali (Redskin) granite derivatives.

The rocks emphasized in this report are the Pikes Peak Granite in the Tarryall Mountains batholith and the Redskin Granite. Minor rock types of the region discussed briefly, and not necessarily in order of age, are quartz monzonite of the Pikes Peak batholith, the granodiorite of Wellington Lake and the composite gabbro and quartz monzonite body exposed just south of the Redskin stock.

OCCURRENCE OF THE PIKES PEAK GRANITE

The Pikes Peak Granite is chiefly in two batholithic masses. The smaller Tarryall Mountains batholith is a pluton, pear-shaped in plan, whose southern part has been obliterated by the intrusion of the Redskin stock (fig. 17). The main Pikes Peak batholith is roughly oval and has a lobate northern contact. The Pikes Peak batholith has an area of about 1,200 square miles, including the downwarped and faulted sedimentary rocks of the Deckers embayment, but it is certainly larger than this because its eastern edge has been truncated by erosion or has been downfaulted at the eastern edge of the Front Range.

The Tarryall Mountains and Pikes Peak batholiths are in contact for about 12 miles along a generally north-south trend. Segments of the contact several miles long are nearly straight. Although the contact is poorly exposed, large-scale zonal relations indicate that neither batholith sharply crosscuts the other. Numerous inclusions of older Precambrian rocks in the Tarryall Mountains batholith near its contact with the Pikes Peak batholith suggest that a wallrock screen may have separated the two before the batholiths were eroded to their present levels. Although the apparently mutual boundary type of contact is not diagnostic of age, a slightly more alkalic composition of the granite in the Tarryall Mountains batholith suggests that it could be more differentiated and hence slightly younger than granite in the Pikes Peak batholith.

The contact of the Pikes Peak Granite in both batholiths with older Precambrian layered gneisses is generally sharp. In the few places where the actual contact may be seen it is knife edged and there are no noticeable contact effects.

AGE AND CORRELATION

Radioactive age determinations reported by Aldrich, Wetherill, Davis, and Tilton (1958), Hutchinson (1960a, c), and Giffin and Kulp (1960) indicate that the Pikes Peak Granite is about 1–1.1 b.y. old; Hedge, Peterman, and Braddock (1967, p. 551) give a best estimate of Pikes Peak cooling based on an Rb-Sr age of 1.04 b.y. In the past the Pikes Peak Granite has been tentatively correlated with the Sherman Granite of northern Colorado and southern Wyoming and with the coarse-grained strongly foliated red granite exposed near Trout Creek Pass, Colo., 35 miles southwest of the Tarryall region. Detailed mapping and radiometric studies of both Sherman Granite (David Eggler, oral commun., 1966) and augen gneiss of Trout Creek (Hutchinson and Hedge, 1967, p. 25, 27) show that both the Sherman and Trout Creek rocks are much older than the Pikes Peak. The gneissic granite exposed from an area south of Cripple Creek to near Canon City (45 miles south of the Tarryall Mountains) has also been mapped as Pikes Peak, but it is a much older rock, of Boulder Creek age. In Colorado, so far as is now known, the Pikes Peak Granite is the only large granitic mass that belongs to a period of plutonism which occurred about 1 b.y. ago.

Two granites that intruded at about this time in other parts of the Western United States share several characteristics with the Pikes Peak. According to Zartman (1963, p. 266–267) the granites of the Llano Series of Texas are about 1,030±30 m.y. (1.03+0.03 b.y.) old. They are pink granites, and it is possible to find hand specimens that are indistinguishable from the Pikes Peak. The granite is also similar to the Pikes Peak in bulk and trace element composition. Like the Pikes Peak, the Llano granites are fluorine bearing and have rapakivi phases (Hutchinson, 1960d). Although less well dated, the rapakivi granite of Gold Butte, Nev., may be approximately 1.06 b.y. old based on work by M. A. Lanphere and G. T. Wasserburg, as reported by Volborth (1962, p. 828). The analyzed samples of rapakivi granite at Gold Butte are more calcic than dominant facies of the Pikes Peak, but, like the Pikes Peak, contain greater than usual amounts of fluorine and lanthanide rare earths. According to Volborth (1962, p. 827), more siliceous facies of the granite at Gold Butte probably exist.

MEGASCOPIC DESCRIPTION

The Pikes Peak Granite is generally very pale gray to pale red in color, and from a distance most of its outcrops have a reddish hue. The granite ranges from medium to very coarse grained; most commonly it is a massive rock characterized by biotite as the most abundant varietal mineral. It is distinguished from rocks of Boulder Creek or Silver Plume age by its color, massive nature and generally coarser grain size. It is more massive and less mafic than some coarse-grained reddish-hued granites exposed at Trout Creek (35 miles to the southwest), at Canon City (45 miles to the south), and in the southern part of the Cripple Creek district.

QUARTZ MONZONITE OF THE MAIN PIKES PEAK BATHOLITH

Quartz monzonite of the main Pikes Peak batholith crops out only in the eastern part of the area, near Goose Creek in the McCurdy Mountain 7½-minute quadrangle.

The quartz monzonite is almost white to very pale red; it is less red than the granite of the Tarryall Mountains batholith. The rock is coarse grained, massive, and is jointed on a scale measured at least in tens of feet; it weathers to a grüs. Outcrop is generally poor but the quartz monzonite is well exposed in the east-trending part of the canyon of Goose Creek.

Quartz, very pale red potassium feldspar, white plagioclase (calcic oligoclase), and black biotite are distinguishable in hand specimens. The composition of one sample of quartz monzonite from Goose Creek canyon is given in table 9.

TABLE 9.—*Composition of quartz monzonite of the main Pikes Peak batholith in canyon of Goose Creek*

[Field No. M4-241; lab. No. D101308; Tr, trace]

Mineralogic composition (volume percent)	
Quartz	21
Microcline perthite	38
Plagioclase	31
Biotite	9
Fluorite	.2
Apatite	.2
Zircon	.2
Topaz	Tr
Opaque minerals	.4
Normative composition (weight percent)	
q	23.56
or	33.33
ab	30.45
an	3.63
c	1.42
en	.50
fs	3.64
mt	1.00
il	.63
ap	.12
fr	.82
other	.17
Chemical composition (weight percent)	
SiO_2	69.60
Al_2O_3	14.77
Fe_2O_3	.69
FeO	2.51
MgO	.20
CaO	1.41
Na_2O	3.66
K_2O	5.64
H_2O+	.47
H_2O-	.02
TiO_2	.33
P_2O_5	.05
MnO	.08
CO_2	.02
Cl	.07
F	.40
Subtotal	99.92
Less O	.19
Total	99.73

ROCKS OF THE TARRYALL MOUNTAINS BATHOLITH

The Tarryall Mountains batholith is a zoned pluton consisting of three main granite units — homogeneous coarse subequigranular granite, coarse porphyritic granite, and a heterogenous unit termed medium- to coarse-grained granite. The coarse subequigranular variety constitutes the main mapped rock unit of the batholith and forms a shell around the coarse porphyritic granite; in turn it is partially enveloped by the rocks of the medium- to coarse-grained mapped unit (fig. 18). Besides the dominant types, the batholith contains small dikes of pegmatite or aplite and irregular masses of fine-grained granite, locally porphyritic. The southern part of the batholith has been truncated by the Redskin stock (fig. 18). The main granitic units of the batholith are distinguish-

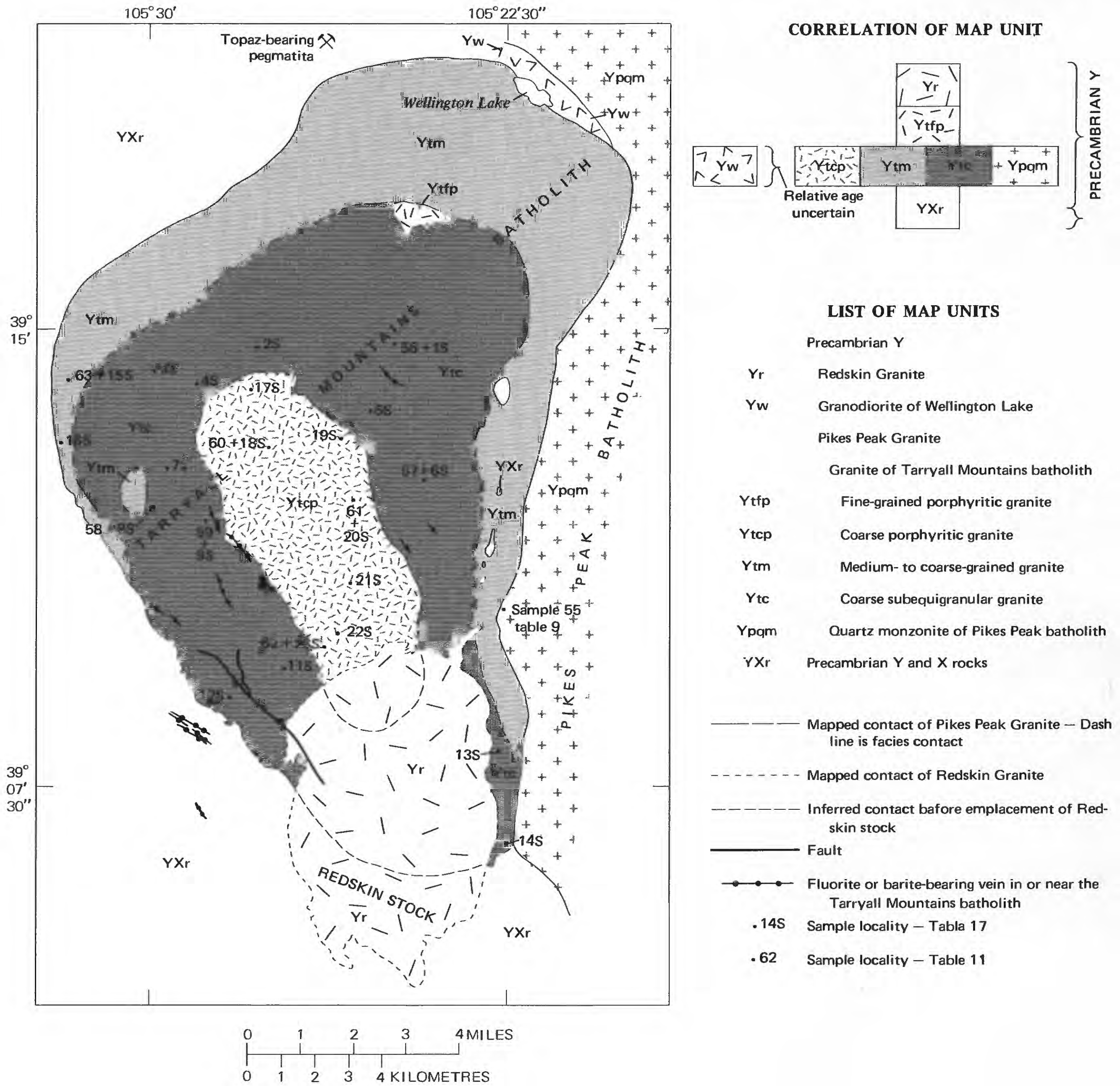


FIGURE 18.—Map of reconstructed Tarryall Mountains batholith showing distribution of facies and sample localities.

able both in the field and in thin section, although there are gradational types particularly in contact regions. In the field, the facies were separated mainly by differences in grain size and texture, as summarized below (table 10).

COARSE SUBEQUIGRANULAR GRANITE

The coarse subequigranular granite is a nearly massive rock that weathers to a grüs. It is jointed on a scale ranging from several tens to several hundreds of feet. It forms the massive rounded cliffs of the north-trending part of Goose Creek canyon, and has furnished the boulders of the Lost Creek–Goose Creek boulder fields. Locally it has a weak foliation caused by the subparallel alinement of a small number of potassium feldspar phenocrysts that are sparse in most outcrops.

Megascopic characteristics (summarized in table 10) include mixed subrectangular and ovoid perthitic potassium feldspar phenocrysts of more than 1 cm in size in a subordinate matrix of at least medium-grained plagioclase and quartz (fig. 19) and rapakivi texture (fig. 20).

The granite averages about 50 percent microcline perthite, nearly 30 percent quartz, 15 percent sodic plagioclase, and slightly more than 5 percent biotite (fig. 21; table 11).

TABLE 10.—*Megascopic characteristics of the main facies of the Pikes Peak Granite, Tarryall Mountains batholith*

[Color of all facies is almost white to very pale red, generally weathering pale reddish orange. Color is mainly due to microcline perthite; other minerals have neutral colors— plagioclase is almost white, quartz is generally gray, and biotite is almost black]

	Coarse subequigranular facies	Coarse porphyritic facies	Medium- to coarse-grained facies
Grain size	Dominant microcline is commonly 3 cm and rarely as much as 8 cm long. Plagioclase commonly ranges from 3 mm to 1 cm in length. Quartz is generally 2-5 mm, but locally forms irregular coarse aggregates.	Average grain size is less than for coarse subequigranular type. Microcline ranges in length from about 5 mm to 5 cm; most matrix grains from 2 mm to 1 cm.	Heterogeneous unit consisting partly of medium-grained granular granite and partly of medium to coarse granite.
Texture	Subequigranular to porphyritic. Local oval microcline crystals; some mantled with oligoclase (wiborgite rapakivi).	Seriate porphyritic. Tabular microcline crystals.	Granular to porphyritic.
Visible varietal minerals	Biotite, rare muscovite	Biotite, rare muscovite	Biotite, rare muscovite.
Associated dikes	Common small aplite-pegmatite dikes. Dikes and irregular masses of fine-grained granite and fine-grained porphyritic granite. Local miarolitic pegmatite segregations.	Sparse. Local miarolitic pegmatite segregations.	Sparse.
Inclusions	Very sparse	Very sparse	Abundant large inclusions of Boulder Creek(?) and Silver Plume(?) rocks on east side of Tarryall Mountains batholith.

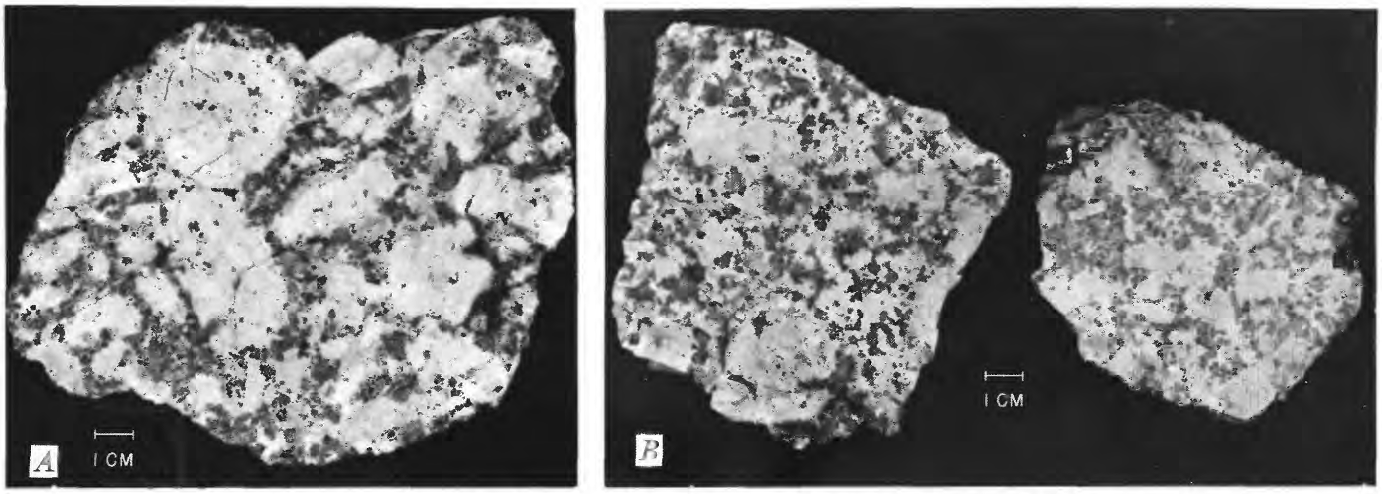


FIGURE 19.—Specimens of typical (*A*) coarse subequigranular and (*B*) coarse porphyritic Pikes Peak Granite.

The large range in modal composition shown by the field of composition partly reflects the coarse grain size of the unit. The modes were based on two standard-sized thin sections per sample, and because of the coarseness of the rock, they give only a crude approximation of the abundance of the major minerals. The inference of homogeneity of the unit is based on the similarity of many hand specimens of the rock and on the small variability in its chemical composition found in 4 samples from widely separated localities (table 11).

Microscopically the texture is xenomorphic granular. Most of the dominant microcline perthite is subhedral to anhedral, but the subordinate plagioclase, quartz, and biotite have subhedral to euhedral forms: respectively, tabular crystals, hexagonal dipyramids, and pseudohexagonal books.

The potassium-feldspar is microcline perthite in which the albite lamellae are visible in hand specimen on close inspection of the crystal surfaces. The microcline perthite crystals generally exceed 1 cm in length, are commonly as much as 3 cm long, and rarely are as much as 8 cm long. Microcline perthite shows three types of relations to descrete sodic plagioclase crystals (fig. 20). It includes small tabular plagioclase crystals, shows apparent mutual growth contacts with others, and is mantled and included in still other plagioclase. Overall these relations seem to suggest that the microcline perthite and sodic plagioclase were nearly contemporaneous in crystallization.

The discrete plagioclase grains in the granite are mainly sodic oligoclase that is commonly slightly sericitized. The biotite is a very dark variety; although no samples of the biotite from this facies were analyzed, the very low ratio of MgO to total iron in the granite (table 11) shows that the biotite must be iron-rich.

Accessory minerals seen in all thin sections of the granite are fluorite and zircon which make up, respec-

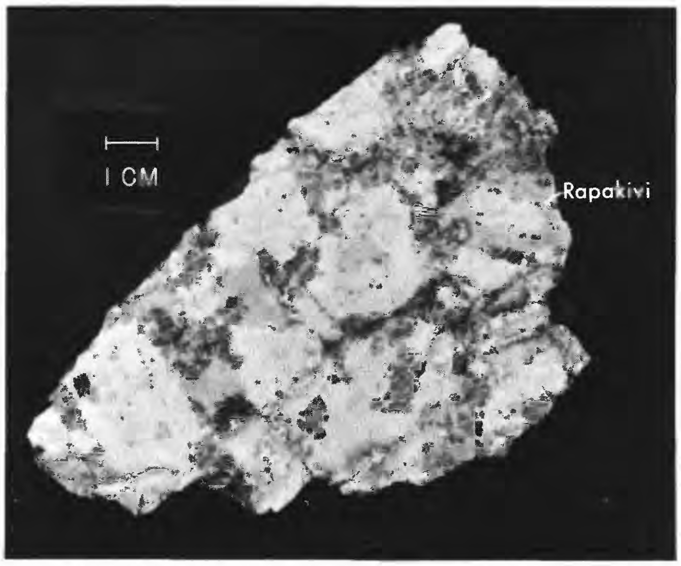


FIGURE 20.—Oligoclase-mantled microcline (rapakivi) in coarse subequigranular Pikes Peak Granite.

tively, about 0.4 and 0.1 percent of the rock. Opaque iron oxides, including magnetite, and topaz, anatase, xenotime(?) and monazite(?) also occur but in lesser quantities. The dominant mode of occurrence of the accessories, including fluorite, is as grains included in or near biotite.

Coarse Porphyritic Granite

The coarse porphyritic variety of Pikes Peak Granite forms the core of the Tarryall Mountains batholith and the topographic crest of the Tarryall Mountains. Although the crest is generally a surface of low relief, the granite locally forms tors and sharp pinnacles, some of which, like the Twin Eagles, are easily visible from the valley of Tarryall Creek. The rock is jointed on a scale measured in feet or tens of feet, rather than the tens to hundreds of feet characteristic of the coarse subequigranular type.

The coarse porphyritic granite contrasts with the coarse subequigranular type (table 10; fig. 19) in that it has a slightly smaller average grain size, a higher proportion of subrectangular potassium-feldspar, and an absence of ovoid potassium-feldspar grains. Rapakivi texture is apparently not developed in the coarse porphyritic unit.

The average modal composition, based on two thin sections from each of nine samples, is about 44 percent potassium-feldspar, 33 percent quartz, 17 percent sodic plagioclase and 5 percent biotite (fig. 21; table 11). Although only an approximation because of the coarse-grained size of the rock, the average composition is slightly more quartzose and has less potassium-feldspar than that of the enveloping coarse subequigranular granite.

As seen in hand specimen and thin section the texture of the rock is seriate porphyritic with crystal grains in hypidiomorphic granular arrangement. The potassium-feldspar crystals are as much as 5 cm long and are generally subhedral; quartz and plagioclase grains and smaller potassium-feldspar crystals form the matrix and range from about 2 mm to about 1 cm size, and are subhedral to euhedral. Quartz in particular forms aggregates of subhedral to euhedral grains. Biotite and the microscopic accessory minerals are interstitial to the quartz and feldspar, and biotite is both finer-grained and less perfectly crystallized than in the coarse-subequigranular granite.

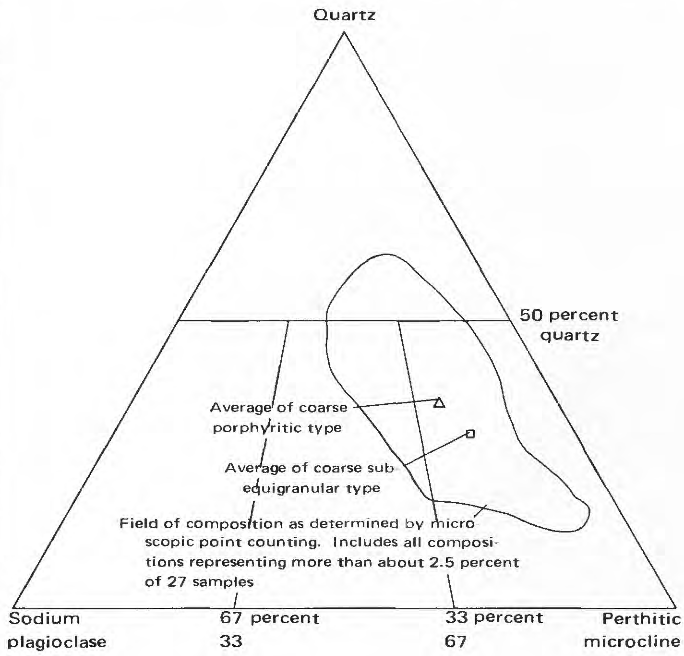


FIGURE 21.—Modal composition (quartz-microcline perthite-plagioclase) of Pikes Peak Granite in the Tarryall Mountains batholith.

The dominant feldspar is perthitic microcline, which contains from about 19 to 28 percent albite lamellae, as determined by microscopic point count. The microcline perthite includes small tabular crystals of albite-oligoclase and is in apparent mutual boundary contact with other tabular crystals of albite-oligoclase. The boundary relations between perthitic microcline and discrete sodic plagioclase are the same as in the coarse subequigranular granite, but the potassium-feldspar of the porphyritic type contains less albitic lamellae.

The accessory minerals of the coarse porphyritic unit, in approximate order of abundance, are fluorite, zircon, topaz, and opaque minerals.

Medium- to Coarse-Grained Granite

A heterogeneous unit composed principally of rocks similar to both coarse subequigranular and porphyritic varieties, a fine-grained granite with local coarse feldspar phenocrysts, and a nearly equigranular medium- to coarse-grained granite forms the discontinuous outer zone of the Tarryall Mountains batholith. Probably the unit could be subdivided in detailed mapping, but for this report it was mapped only in reconnaissance.

TABLE 11.—*Modal (volume percent) and chemical composition (weight percent) of Pikes Peak Granite, Tarryall Mountains batholith*

[Chemical analyses by Ellen S. Daniels and G. O. Riddle; Tr, trace; leaders (...) indicate no data]

	Coarse subequigranular granite							Coarse porphyritic granite						Medium- to coarse-grained granite
						Range of values in 17 modal analyses						Range of values in 9 modal analyses		
Sample No. (fig. 18)	56	57	58	59	Average			60	61	62	Average			63
Field No.	M1-50	M1-58	M2-81	TR-74	1/	High	Low	M2-36	M1-36	M3-156	2/	High	Low	FP-5
Laboratory No.	D101303	D101304	D101306	H3247				D101305	D101302	D100428				D101307
Modal composition														
Quartz	31.3	20.4	24.2	50.6	28.5	54.7	16.7	30.1	44.9	22.7	33.2	44.9	21.3	31.9
Plagioclase	17.1	23.4	9.6	21.4	14.8	25.8	6.0	15.1	15.2	14.8	16.6	25.8	8.1	16.7
Potassium-rich perthite	39.4	49.7	61.4	22.4	50.3	74.2	22.4	49.7	35.6	58.6	43.8	58.6	27.5	44.5
Biotite	10.9	5.8	4.2	4.5	5.5	10.9	2.6	4.2	2.7	2.9	5.2	10.9	.8	6.3
Muscovite	.1	Tr	Tr	.4	.2	.6	0	.4	.4	.6	.6	1.7	.3	0
Fluorite	.7	.6	.4	.6	.4	.8	.1	.5	.8	.3	.4	.8	.1	.3
Topaz	0	0	Tr	0	Tr	.1	0	0	.2	.1	.1	.2	0	0
Zircon	.2	.1	.1	Tr	.1	.3	Tr	Tr	.1	Tr	.1	.1	0	.1
Opaque minerals	.3	.1	.1	Tr	.1	.4	0	Tr	.1	Tr	Tr	.2	0	.2
Other	.1	Tr	0	Tr	Tr	.1	0	0	0	Tr	Tr	Tr	0	Tr
An content	----	----	----	13-15	----	----	----	----	----	----	----	----	----	----
Percent potassium feldspar of perthite.	67	73	66	84	76	88	66	76	80	76	78	81	72	71
Chemical composition														
SiO_2	72.96	72.30	74.35	72.39	73.00	----	----	75.79	75.86	74.38	75.34	----	----	75.14
Al_2O_3	13.44	14.02	12.82	13.20	13.37	----	----	12.57	12.38	12.79	12.58	----	----	12.29
Fe_2O_3	.56	.49	.40	.74	.55	----	----	.45	.48	.51	.48	----	----	.49
FeO	1.71	1.62	1.51	1.98	1.71	----	----	1.06	1.13	1.60	1.26	----	----	1.58
MgO	.09	.09	.07	.10	.09	----	----	.05	.06	.06	.06	----	----	.06
CaO	1.02	.99	1.00	1.20	1.05	----	----	.54	.68	.88	.70	----	----	.82
Na_2O	3.35	3.56	3.35	3.38	3.41	----	----	3.31	3.19	3.29	3.26	----	----	3.34
K_2O	5.67	6.00	5.35	5.30	5.58	----	----	5.33	5.19	5.27	5.26	----	----	5.23
H_2O+	.34	.31	.29	.34	.32	----	----	.28	.32	.39	.33	----	----	.29
H_2O-	.03	.02	.01	.09	.04	----	----	.05	.05	.06	.05	----	----	.03
TiO_2	.22	.20	.19	.26	.22	----	----	.12	.13	.17	.14	----	----	.20
P_2O_5	.02	.03	.01	.03	.02	----	----	.01	.01	.03	.02	----	----	.01
MnO	.05	.05	.04	.06	.05	----	----	.03	.03	.04	.03	----	----	.04
CO_2	.02	.01	.01	.02	.02	----	----	.01	.01	.01	.01	----	----	.01
Cl	.04	.04	.03	.05	.04	----	----	.02	.01	.03	.02	----	----	.34
F	.45	.47	.43	.49	.46	----	----	.30	.48	.67	.48	----	----	.46
Subtotal	99.97	100.20	99.87	99.63	99.93	----	----	99.92	100.01	100.18	100.02	----	----	100.33
Less O	.20	.21	.19	.22	.21	----	----	.13	.20	.26	----	----	----	.27
Total	99.71	99.99	99.68	99.41	99.72	----	----	99.79	99.81	99.92	100.02	----	----	100.06
Normative composition														
q	30.09	27.11	32.67	30.43	[3]30.08	----	----	35.36	36.64	33.95	[3]35.32	----	----	36.07
or	33.51	35.46	31.67	31.33	32.99	----	----	31.50	30.67	31.11	31.09	----	----	30.91
ab	28.05	29.83	28.13	28.20	28.55	----	----	27.86	27.01	27.84	27.57	----	----	25.75
an	1.52	1.22	1.68	2.09	1.63	----	----	.36	0	0	.12	----	----	.58
c	1.29	1.28	.93	1.21	1.18	----	----	1.25	1.51	1.68	1.48	----	----	1.41
en	.22	.22	.17	.25	.22	----	----	.13	.15	.15	.14	----	----	.15
fs	2.41	2.33	2.20	2.70	2.41	----	----	1.43	1.51	2.32	1.75	----	----	2.24
fr	.92	.96	.88	1.00	.94	----	----	.62	.91	1.16	.90	----	----	.94
ap	.05	.07	.02	.07	.05	----	----	.02	.03	.07	.04	----	----	.02
fluorine	0	0	0	0	0	----	----	0	.04	.11	.05	----	----	0
il	.42	.38	.36	.50	.42	----	----	.23	.24	.32	.26	----	----	.38
mt	.81	.71	.58	1.06	.79	----	----	.65	.69	.74	.69	----	----	.71
other	.12	.09	.07	.06	.09	----	----	.05	.04	.04	.04	----	----	.58

[1]Average of 17 samples and about 33,000 points. [2]Average of 9 samples and about 18,000 points. [3]Average of analyses given.

Besides granite, the rock unit locally contains large inclusions of Boulder Creek(?) Granodiorite, Silver Plume(?) Quartz Monzonite, and small unmapped inclusions of metasedimentary rocks. The inclusions are particularly numerous near the contact of the Pikes Peak and Tarryall Mountains batholiths in the northeast part of the McCurdy Mountain quadrangle.

An important component of the unit, nearly equigranular medium- to coarse-grained granite, strongly resembles an equigranular unit of the Redskin Granite, but is slightly coarser in grain-size.

MINOR FACIES

Pegmatite (pl. 1), aplite, fine-grained equigranular granite, and porphyritic granite form dikes and irregular shaped intrusive bodies in the Pikes Peak Granite of the Tarryall Mountains batholith and locally in older rocks near the batholith.

Pegmatites related to the Pikes Peak Granite are very sparsely distributed; most are lensoid bodies. One pegmatite approximately 4,500 feet N. 30° E. from Spruce Grove Campground had a quartz core and was mined for its quartz content. A few crystals of beryl, crudely cylindrical masses of columbite, and masses of fluorite were found there by miners Carl Quist and Bob Beal.

Aplites and layered aplite-pegmatites are numerous in an area in Hay Creek and also in upper Sand Creek. Many of the aplites occupy gently dipping fractures in the granite; they cut both coarse subequigranular and porphyritic facies. The pegmatitic zones in the dikes are locally miarolitic and contain nearly euhedral crystals of microcline, albite, fluorite, clear to smoky quartz, and rare topaz.

Fine-grained granite and a porphyritic granite with coarse microcline phenocrysts and fine-grained matrix form irregular dikelike zones which can be traced for more than 1 mile and are as much as 1,000 feet across. The dikelike masses are apparently confined to the outer zone of the batholith (not shown in fig. 2) and to the coarse subequigranular granite. Although not studied petrographically, the porphyry with fine-grained matrix resembles the Windy Point Granite of the Pikes Peak area in hand specimen, and approximately corresponds to porphyritic aplite of Hutchinson (1960a, pl. 1).

GRANODIORITE OF WELLINGTON LAKE

A lenslike body of massive granodiorite in part lies between the Pikes Peak Granite of the Tarryall Mountains batholith and older rocks near Wellington Lake. The rock, here called granodiorite of Wellington Lake, is petrographically and chemically similar to the granodiorite facies of the Pikes Peak Granite—Pikes Peak batholith—mapped by Hutchinson (1960a) near Pine, Colo. (8 miles to the north-northeast), and possibly is continuous with it (figs. 2, 17), although an unmapped area lies between the Pine and Wellington Lake occurrences.

The granodiorite is a medium-grained moderate bluish-gray rock with no apparent foliation. It consists principally of plagioclase, sparsely perthitic microcline, quartz, biotite, and hornblende. Accessory minerals in the rock are apatite, sphene, zircon, and opaque oxides. The plagioclase is andesine to oligoclase and is normally zoned. The more calcic plagioclase is moderately to strongly sericitized, and biotite and hornblende both are locally altered. Texture of the rock is xenomorphic granular. The quartz is in part fine grained and forms interstitial grains and rounded masses in the feldspars.

The granodiorite of Wellington Lake has been described previously by Hutchinson (1960a, p. 177–179, tables 1–2) and an analysis (P–9) reported by Hutchinson is compared with a new analysis (GM–1, table 12).

Although Hutchinson interpreted the granodiorite of Wellington Lake as a granitized metasedimentary rock, its sheetlike form, sharp contacts, and chemical and mineralogic character indicate that it is more likely an igneous rock.

GABBRO AND QUARTZ MONZONITE

Gabbro and associated quartz monzonite and quartz monzonite porphyry crop out near Tarryall Creek in secs. 23 and 24, T. 11 S., R. 72 W., and underlie a crudely semicircular area inferred to be the remnant of a small composite funnel-shaped pluton. Prior to the intrusion of the Redskin Granite, the body, at map altitude, is postulated to have been an oval complex about 8,000 feet long and 5,000–6,000 feet wide, consisting of an outer gabbro rim, and intermediate zone of quartz monzonite, and an asymmetric core of quartz monzonite porphyry, as shown diagrammatically in figure 22. The gabbro is in sharp contact with older metasedimentary and igneous rocks and possesses a planar flow structure from the orientation of

TABLE 12.—*Chemical and normative composition (weight percent) of granodiorite of Wellington Lake and intermediate zone granodiorite of Pikes Peak batholith*

[Chemical analysts: GM–1, Ellen S. Daniels, and G. O. Riddle; P–9, H. B. Wiik; P–5, C. O. Ingamells]

Field No.	GM-1	P-9	P-5
Chemical composition			
SiO_2	65.63	67.03	67.29
Al_2O_3	13.90	14.94	13.53
Fe_2O_3	2.46	1.36	1.77
FeO	3.53	2.79	3.30
MgO	1.09	1.20	.89
CaO	3.30	3.51	2.71
Na_2O	3.16	3.27	3.08
K_2O	4.38	4.14	4.91
H_2O+	.43	.30	.23
H_2O-	.05	.00	.04
TiO_2	1.12	.65	.90
P_2O_5	.48	.29	.50
MnO	.12	.10	.11
CO_2	.01	.00	.13
Cl	.05	.02	.03
F	.22	.15	.29
Subtotal	99.93	99.65	99.71
Less O	.10	.06	.14
Total	99.83	99.59	99.57
Normative composition			
q	22.92	22.99	25.03
or	25.88	24.46	29.02
ab	26.37	27.19	25.19
an	11.00	14.11	7.69
c	.00	.00	.50
en	2.72	2.99	2.22
fs	2.82	3.11	3.32
fr	.41	.28	.55
ap	1.14	.69	1.18
fluorine	.00	.00	.00
il	2.13	1.23	1.71
mt	3.57	1.97	2.57
other	.38	.51	.53

Sample descriptions

GM-1. Granodiorite of Wellington Lake (new analysis).

P-9. Granodiorite wedge (granitized metamorphic wallrock) from outer zone of Pikes Peak batholith. Analyses by Hutchinson (1960a).

P-5. Intermediate zone granodiorite of Pikes Peak batholith.

plagioclase tablets. Except for one part of the body (NW¼ sec. 26, T. 11 S., R. 72 W.), the planar structure dips toward the center of the body in accordance with the postulated shape of the intrusive.

Crosscutting relations show that the pluton is younger than Boulder Creek(?) and Silver Plume(?) rocks and older than the Redskin Granite. It is tentatively considered as part of the Pikes Peak because of its relatively young age, unmetamorphosed character, and location near the granite, and because of the occurrence of similar gabbroic rocks of possible Pikes Peak age in the syenitic ring complex of Lake George (fig. 2) and at Cripple Creek.

The gabbro is a coarse-grained, dark-bluish-gray to green rock that appears in hand specimen to consist of plagioclase, interstitial dark silicate minerals, and a considerable amount of a gray metallic mineral, probably ilmenite.

As seen in thin section, the texture is intersertal. In most rocks the original mafic minerals have largely been altered to an aggregate of very fine-grained biotite which corrodes the plagioclase (labradorite). In one rock (BA–515, table 13) the mafic minerals are nearly unaltered, and consist mostly of olivine, pyroxene, and an opaque mineral, with locally abundant apatite. The olivine has a $2V$ of about 79°, suggesting that it is about Fa_{34}. The pyroxene has a $2V$ of about 83°; it is biaxial negative and is probably hypersthene. Halos of biotite resembling reaction rims surround the opaque mineral, and in turn are surrounded by scattered, minute crystals of a high relief, glassy accessory, possibly corundum. The corundum(?) also is found in these rocks next to hypersthene(?).

The quartz monzonite is a bluish-gray, medium- to coarse-grained granitoid rock which locally shows a planar structure due to alinement of feldspar crystals; like the planar structure of the gabbro, it is subparallel to the outline of the body. In thin section, the rock is hypidiomorphic granular and consists principally of plagioclase (andesine), sparsely perthitic potassium feldspar, and quartz with subordinate amounts of hornblende and biotite (table 13; fig. 23). Pyroxene occurs as sparse remnants in the hornblende. The accessories are apatite, zircon, sphene, and opaque minerals.

The potassium feldspar and plagioclase tend to cluster in aggregates essentially free of other minerals. Quartz occurs in subhedral to anhedral crystals and it occurs interstitially in plagioclase-rich aggregates. Potassium feldspar locally surrounds plagioclase crystals. It is inferred that plagioclase started crystallization before potassium feldspar or quartz.

The quartz monzonite porphyry is a gray to pale pink rock with abundant bluish, cloudy quartz phenocrysts 1–2 mm across set in a groundmass that averages one-half mm or less in size. Much of the groundmass quartz is in rounded grains; the same type of quartz is included in the outer zones of alkali feldspar crystals. The rock contains more quartz and potassium feldspar than the nonporphyritic quartz monzonite (fig. 23; table 13). Accessory minerals in the porphyry are apatite, opaque minerals, zircon, and fluorite. Apatite and opaque minerals are not abundant but occur clustered with and included in the large plagioclase phenocrysts. Fluorite is mainly interstitial near biotite grains.

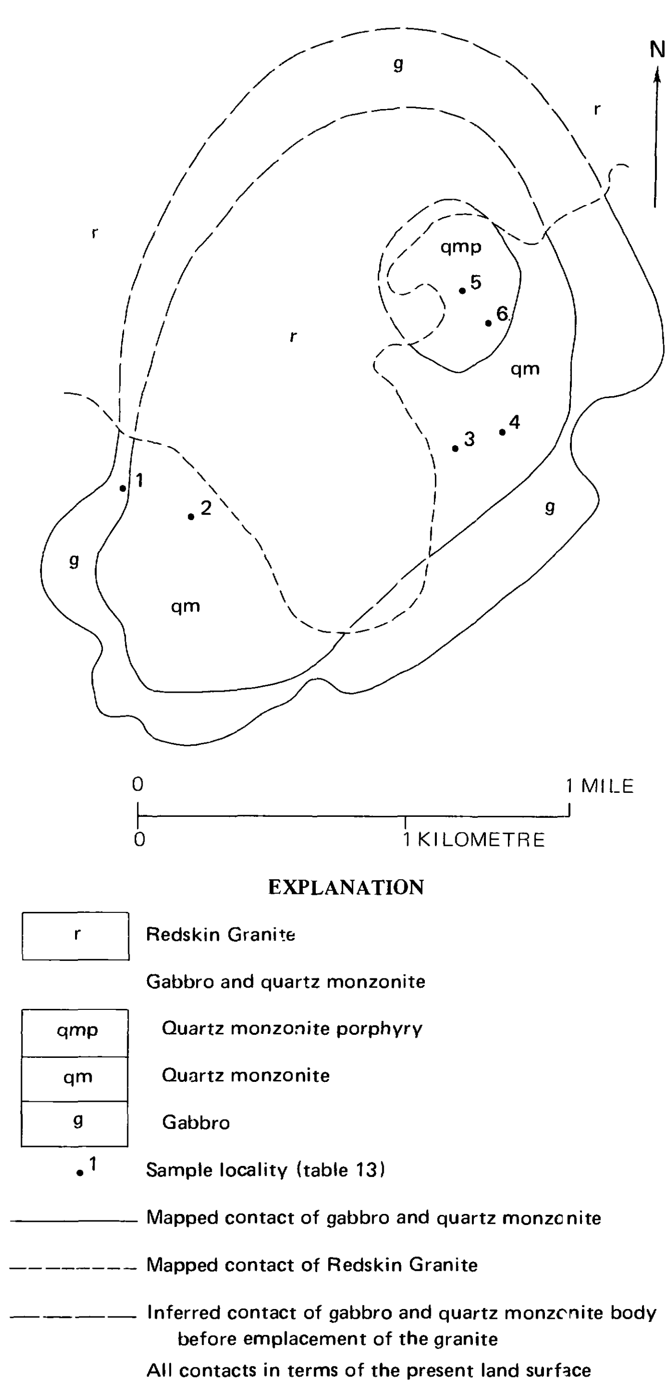


FIGURE 22.—Reconstructed gabbro and quartz monzonite body.

TABLE 13.—*Modal composition (volume percent) of gabbro, quartz monzonite, and quartz monzonite porphyry*

[Tr, trace; leaders (...) indicate no data]

Sample No. (fig. 22)	1	2	3	4	5	6
Field No. BA-	515	359	750	753	709	766
Quartz	1	18	14	21	33	36
Plagioclase	67	38.5	37.5	39	21	25
Potassium-feldspar	----	31.5	41	27	41.5	33.5
Olivine	13	----	----	----	----	----
Hypersthene(?)	3	.5	----	----	----	----
Hornblende	----	8	4	3	----	----
Biotite	5.5	2.5	2	9	3	4.5
Opaque minerals	7.5	.5	.5	1	Tr	Tr
Muscovite	----	----	----	----	1	5
Apatite	2.5	.5	.5	Tr	----	Tr
Corundum(?)	.5	----	----	----	----	----
Fluorite	----	----	----	----	.5	.5
Zircon	----	Tr	.5	Tr	Tr	Tr
Sphene	----	Tr	Tr	Tr	----	----

Sample descriptions

1. Biotitic olivine-pyroxene gabbro.
2-3. Hornblende-biotite quartz monzonite.
4. Biotite-hornblende quartz monzonite.
5-6. Biotite quartz monzonite porphyry.

REDSKIN GRANITE

The Redskin Granite underlies the east-central part of the southern Tarryall region (pl. 1; fig. 2), where it forms a stock and two small cupolas (fig. 24).

The main body of granite is an oval-shaped pluton, called the Redskin stock, which has an area of about 19 square miles and was intruded at the south edge of the Tarryall Mountains batholith of Pikes Peak Granite. West of the Redskin stock in secs. 4 and 5, T. 11 S., R. 72 W., and locally separated from it by remnants of metamorphic and older igneous rocks, is a satellitic body about one-half mile across, termed the China Wall cupola. Another small body, the Boomer pluton (cupola), is exposed near the Boomer mine in sec. 21, T. 11 S., R. 72 W., and is the host for the major beryllium deposits of the area. Thin dikes of the Redskin Granite cut the older Precambrian rocks at several places. The major concentrations of dikes are in the area near the Boomer mine and in an area just west of the Redskin stock in sec. 16, T. 11 S., R. 72 W. (pl. 1).

The contacts of the Redskin Granite with older igneous and metamorphic rocks are generally well exposed, and have been studied in several places in mine openings. The contacts are invariably sharp and in most places show no apparent contamination of the granite by wall rock or alteration of the wall rocks by the granite. Locally, however, segments of the contact are extensively greisenized.

The Redskin Granite is a red-colored granite characterized by micas rather than by hornblende or pyroxene as varietal minerals, by high fluorite or topaz content, and by the presence of zircon as the next most abundant accessory minerals. All varieties except some micrographic varieties have two feldspars, a very sodic plagioclase which forms subhedral to euhedral tabular crystals and a subhedral potassium feldspar. The potassium feldspar ranges from coarsely perthitic in the oldest variety to essentially nonperthitic in the youngest.

The beryllium-bearing greisens of the area are mainly associated with the Redskin Granite, and particularly with two facies of the granite. The granite also contains fluorite-rich veins.

AGE

Crosscutting relations show that the Redskin Granite is the youngest Precambrian igneous rock in this part of the Front Range. It cuts the Pikes Peak Granite of the Tarryall Mountains batholith, the small gabbro and quartz monzonite body exposed south of the Redskin stock, and various masses of Silver Plume(?) Quartz Monzonite and Boulder Creek(?) Granodiorite. The range in age found by Rb^{87}/Sr^{87} and K^{40}/A^{40} methods in six samples of the Redskin Granite or associated greisen was 915±50 to 1020 m.y. (Hawley and others, 1966).

ROCK DESCRIPTION AND CLASSIFICATION

The Redskin Granite is a fine- to medium-grained massive or nearly massive igneous rock that ranges from almost white to pale reddish orange or pale red in color. It resembles the Pikes Peak Granite but on an average is much finer grained, as suggested by comparison of photomicrographs made of both granites at the same magnification (fig. 25).

The Redskin Granite was divided into four main granite units or facies, termed granular, porphyritic, fine grained and granite-aplite on the basis of texture, grain size, composition and other characteristics; megascopic

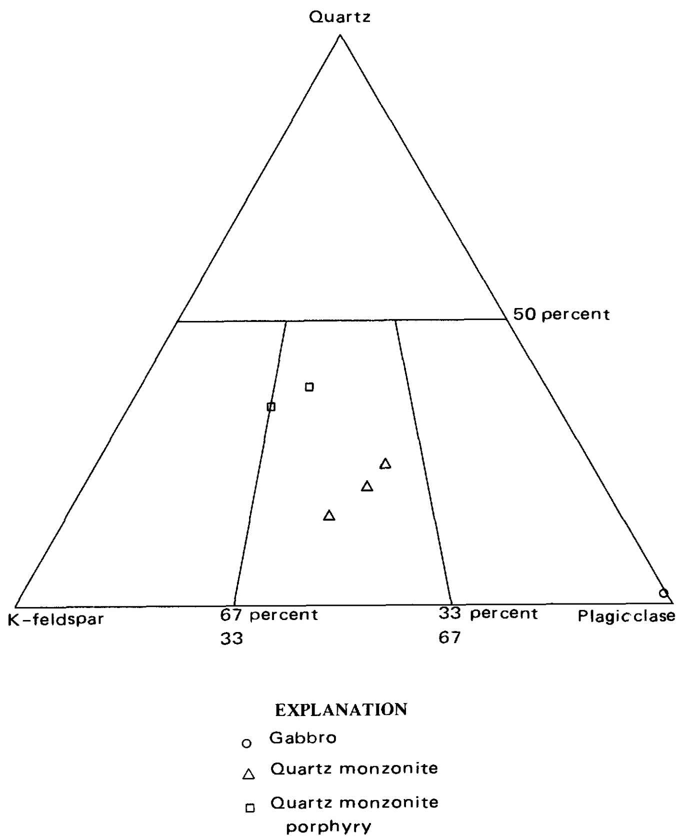


FIGURE 23.—Modal composition (quartz-plagioclase-potassium feldspar) of gabbro and associated quartz monzonite.

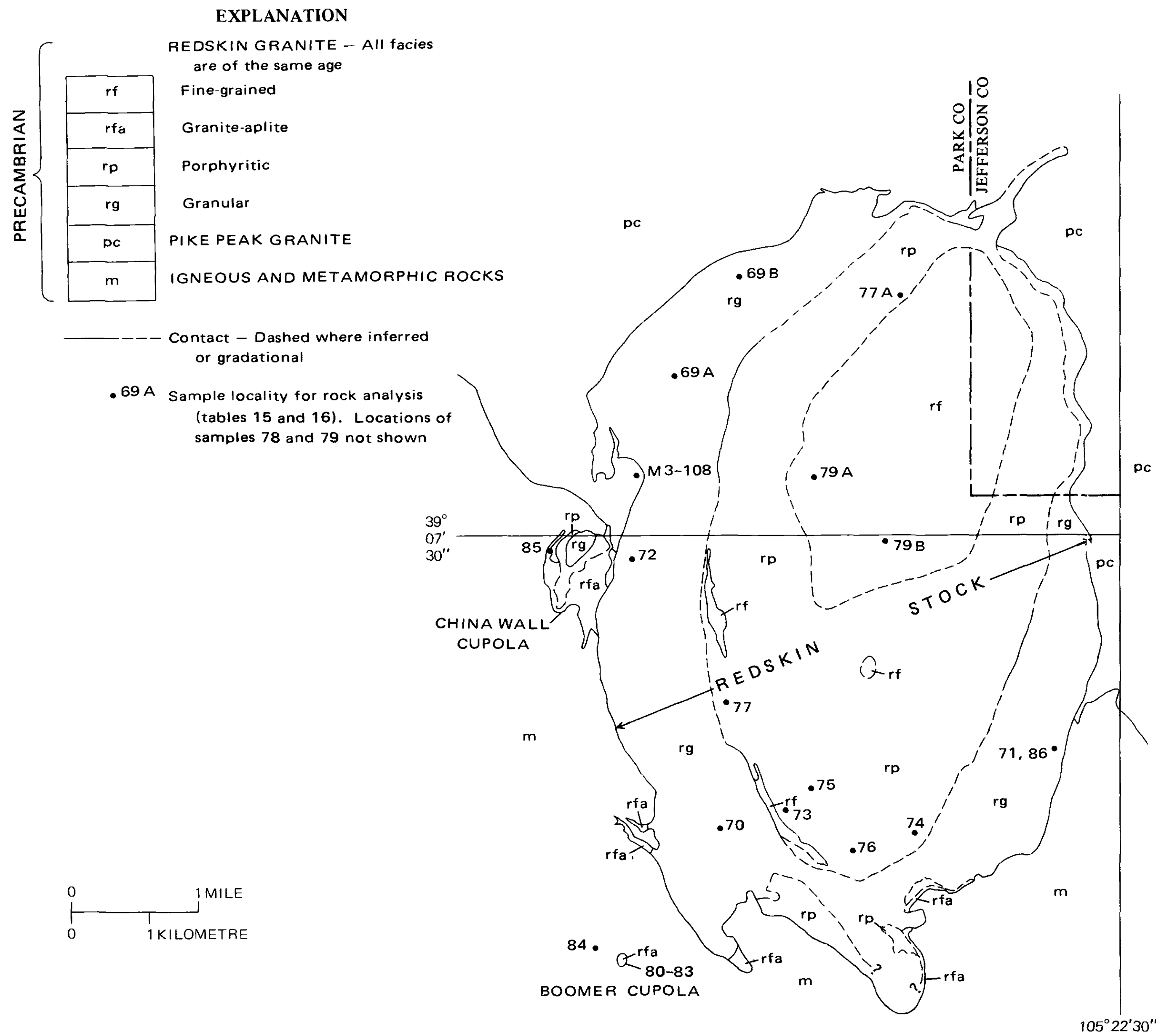


FIGURE 24.—Map showing distribution of facies of the Redskin Granite and sample localities

characteristics of the four units are given in table 14. All the varieties are generally massive, but weak foliations can locally be found in the granular and porphyritic facies. These foliations are generally subparallel to granite contacts, and are inferred to have formed by flow during granite emplacement.

Age relations among the four main facies of the Redskin Granite are only partly known, but the known or probable sequence of crystallization is

Granular granite → Granite-aplite
Granular granite → Porphyritic granite = Fine-grained granite,
→ = Local crosscutting relation,
= = Gradational relation,
Oldest (decreasing age) Youngest.

Porphyritic granite cuts granular granite at the northern end of the Redskin stock and granite-aplite dikes cut the granular granite at several places; the other relations are

TABLE 14.—*Megascopic characteristics of the main facies of the Redskin Granite*

	Granular facies	Porphyritic facies	Fine-grained facies	Granite-aplite
Color	Almost white to pale reddish orange	Pale reddish orange to pale red	Pale reddish orange to pale red	Pale red.
Grain size	Generally 3-5 mm; locally to 7-8 mm	Medium grained but average grain size appreciably less than granular type.	Generally less than 1 mm	Generally less than 1 mm.
Texture	Granitic	Seriate porphyritic	Granitic	Granitic to aplitic.
Visible varietal minerals.	Biotite	Biotite and muscovite	Biotite and muscovite	Variable; muscovite in Boomer cupola.
Associated dikes	Common granite-aplite dikes; sparse porphyritic and pegmatitic dikes. Aplite and pegmatite locally miarolitic.	Very sparse; one major dike zone of fine-grained porphyritic granite along Tarryall Creek.	Very sparse	Local pegmatites.
Inclusions	Very sparse. Local faint biotitic inclusions near contacts with metamorphic rocks.	Locally abundant inclusions of sharp-walled fine-grained light-colored biotite gneiss(?); sparse sharp-walled amphibolite.	Very sparse	Very sparse. Local sharp-walled amphibolite masses in Boomer cupola.

inferred. In the Redskin stock the contact between the porphyritic and fine-grained facies is gradational. Because the fine-grained rocks are in the center of the stock it is assumed that they finished crystallizing after the consolidation of the surrounding porphyritic granite. Granite-aplite also occurs in irregular bodies that grade into granular or porphyritic granite, particularly at the outer contact of the stocks. Examples are the outer zone of the China Wall pluton, local borders on the Redskin stock, and the Boomer cupola.

Minor facies of the Redskin Granite that were mapped are: (1) fine-grained porphyritic granite, (2) pegmatite, and (3) fine- to medium-grained equigranular granite. Locally, near the north end of the Redskin stock, a Pikes Peak(?) Granite breccia with apparent Redskin Granite matrix was also mapped. The fine-grained porphyritic granite in the Redskin pluton is very similar to certain dikes and irregular masses that intrude the Pikes Peak Granite. The fine- to medium-grained equigranular granite occurs in dikes and is probably related to the main granular granite facies of the Redskin Granite.

The varieties of the Redskin Granite compositionally are granite as defined by Tuttle and Bowen (1958), although under other modal classifications some of the rocks could be considered alkali quartz monzonites, granodiorites, or quartz diorites. The composition of the oldest variety of Redskin Granite (granular facies of the Redskin stock) falls near the dividing line in most modal classifications between granite and quartz monzonite, but the younger rocks range in composition from leucoalkali quartz monzonite to leucoalkali granodiorite and rarely to leucoalkali quartz diorite of some classification systems. At least part of this variation can be explained by changes in the "artificial granite" system Q-ab-or-H_2O, and it seems more logical to us to consider all the rocks as granites than to consider the progressively younger facies to be quartz monzonites, granodiorites, or quartz diorites.

Modal or chemical analyses of representative and average rocks of the four main facies are given in table 15.

GRANULAR GRANITE

The granular facies of the Redskin Granite, the dominant and oldest type to crystallize, forms the outer zone of the Redskin Granite and the inner zone of the China Wall cupola. It is inferred, also, that this facies should occur in the deep, nonexposed portions of the Boomer cupola (Professional Paper 608–A, pl. 1, section *C–C′*).

The granular facies is a nearly massive and homogeneous biotite granite (table 14). In thin section, the texture of the rock is hypidiomorphic granular, and point counts show that generally more than 95 percent of the rock consists of perthitic microcline, albite-oligoclase, and quartz, in that order of abundance. Biotite, muscovite, fluorite, and zircon are the main varietal or accessory minerals. The ratio of potassium-rich perthite to plagioclase is about 2:1 for most rocks of the granular facies (fig. 26).

The most abundant mineral is medium- to coarse-grained microcline microperthite of vein or patch type (fig. 27*A*) that occurs in subhedral grains that are xenomorphic against discrete plagioclase grains. The potassium feldspar phase of the perthite is pale pink and dusty; plagioclase lamellae are almost white and clear. The potassium feldspar contains small tabular crystals of plagioclase, some of which are cut by the albite lamellae of the perthite. Locally either the potassium feldspar or albite phases of the perthite apparently replaced discrete sodic plagioclase crystals.

The average potassium feldspar content of the perthite determined by microscopic point counting is about 79 percent; the range found was from 64 to 91 percent. The small range in proportion of potassium feldspar (or perthitic lamellae of albite) indicates that the perthite is of exsolution type.

Plagioclase, exclusive of that found in perthitic intergrowths, forms almost white subhedral to euhedral crystals which are polysynthetically twinned, generally by the albite law. The plagioclase is slightly finer-grained than the microcline perthite, but also has a wider range in grain

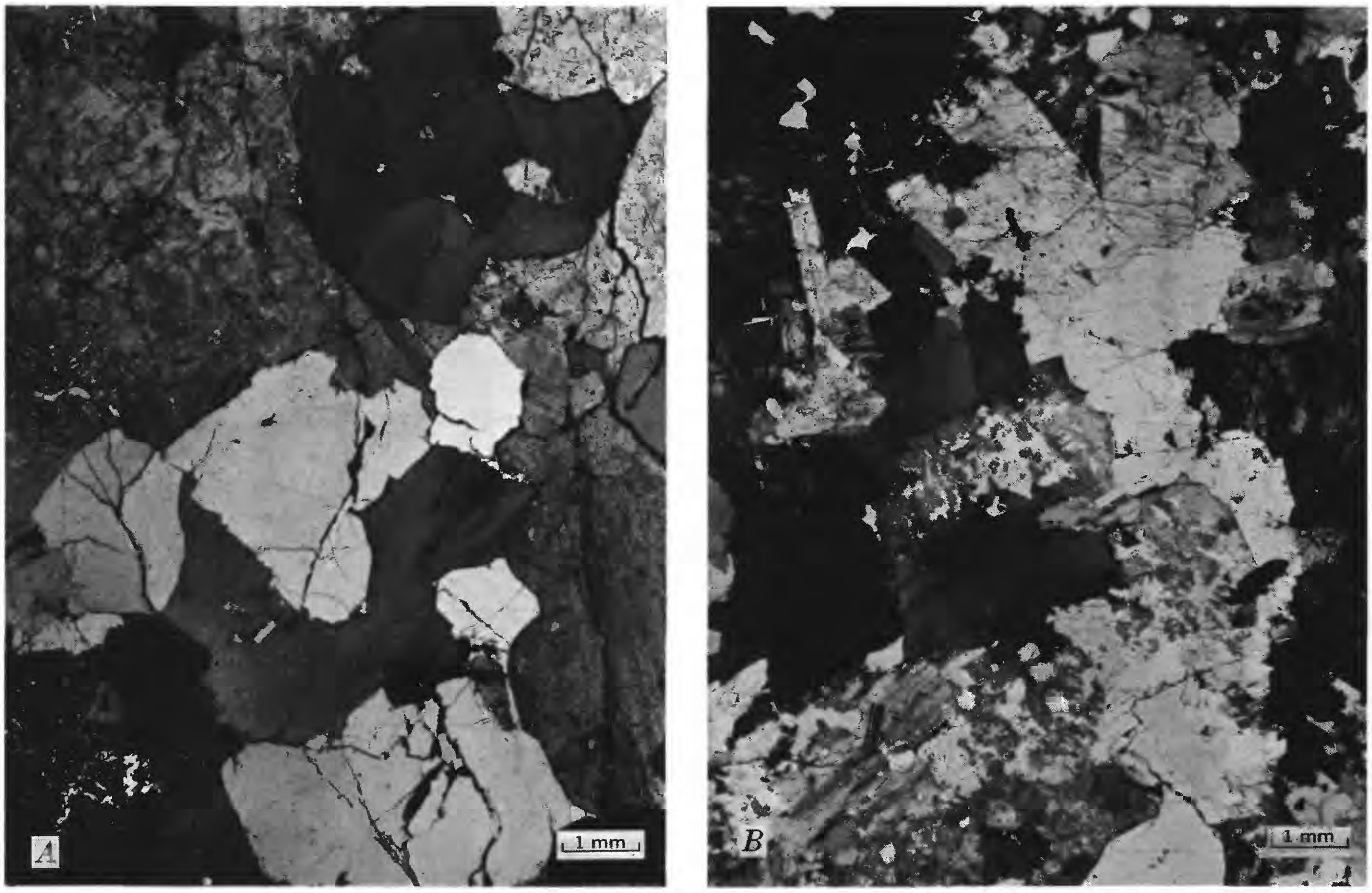


FIGURE 25.—Comparison of grain size and texture of Pikes Peak Granite (*A*) and of three facies of the

size. Many of the smaller plagioclase crystals are contained in potassium feldspar, or form aggregates between two potassium feldspar grains.

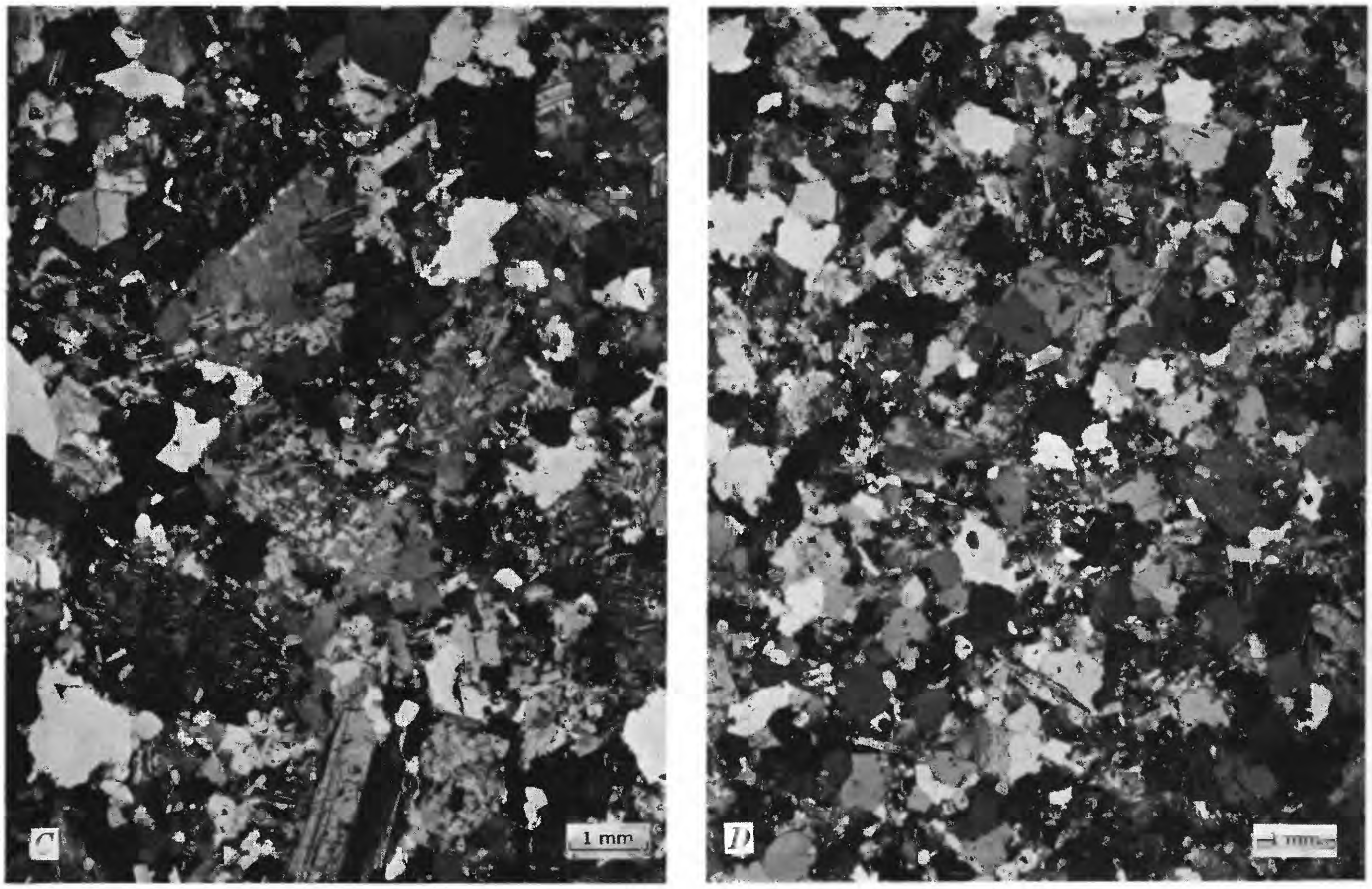
Composition of the plagioclase as determined by extinction angles measured on the universal-stage ranges from An_0 to An_{17}, but probably averages in the An_5–An_{10} range. The discrete plagioclase crystals are not obviously zoned, but an increase in extinction angles from the center to the edge in some grains, and concentration of alteration products in the centers of some grains indicate that the plagioclase is not uniform in composition and is sodic oligoclase in the centers.

Quartz generally occurs as subhedral to anhedral grains or aggregates; rarely, it is idiomorphic against potassium feldspar. Quartz also forms symplectic border zones around some of the relatively few biotite crystals which exist in the rock. The quartz also locally has lobate convex contacts against plagioclase and potassium feldspar and biotite.

Biotite typically forms euhedral to subhedral books of medium-grain size scattered evenly through the granite. Biotite is accompanied by a group of minerals which are mainly interstitial or occur with interstitial minerals, namely fluorite (fig. 27*B*), zircon (contained in the mica or fluorite), and locally muscovite. Generally muscovite is greatly subordinate to biotite; rarely is it dominant. Muscovite may occur as a thin rim on the biotite, in zones cutting across biotite crystals, or in crystals intergrown with biotite. The first two modes of occurrence, which are considered to be secondary or deuteric, are dominant. Of possible significance is the fact that two of the four high-muscovite rocks (based on point counts) are of unusual composition and contain appreciably more plagioclase than the average for the granular facies.

Very small crystals of fluorite, white mica, and topaz also occur in plagioclase, particularly in the cores of grains. In this mode of occurrence they are considered to be secondary or deuteric in origin, formed by alteration of the more calcic part of the plagioclase. Probably not more than one-tenth of the fluorite occurs in this fashion.

The textural relations of the principal minerals can be used to interpret the sequence of crystallization within the granular facies. Plagioclase occurs in randomly oriented small and moderate-sized tabular crystals included in, or partly mantled by, the potassium feldspar, in clusters of crystals between larger potassium feldspar grains and in small embayed remnants in quartz; it nowhere, however, appears to enclose either potassium feldspar or quartz. Locally included plagioclase grains are embayed by potassium feldspar or albite components of the alkali feld-



Redskin Granite (*B*, granular; *C*, porphyritic; *D*, fine grained). Crossed nicols.

spar (fig. 25*B*) and albitic perthite lamellae rarely vein the plagioclase tabular crystals included in potassium feldspar. The relations between quartz and potassium feldspar are less certain; quartz is locally idiomorphic against potassium feldspar, but it also locally appears to include or embay the feldspar.

The crystal relations suggest that, of the main components of the granular facies (discrete sodic plagioclase, perthitic microcline, and quartz), plagioclase may have begun to crystallize before quartz or potassium feldspar. Tentatively the quartz and potassium feldspar are regarded as crystallizing at about the same time with the slightly higher degree of crystallinity of quartz due to a greater inherent tendency towards idiomorphism. Biotite and its associates, zircon, and fluorite probably began to form about the same time as plagioclase. Most of the textures of the granular facies can be explained by crystallization from a melt, modified only slightly by deuteric recrystallization. The deuteric effects apparent are the formation of some muscovite, fluorite, and topaz, and, possibly, minor replacement relations involving quartz and potassium feldspar.

Porphyritic Granite

The porphyritic granite (table 14) is generally pale reddish orange to pale red in color and is massive to very weakly foliated. It has a seriate porphyritic aspect in hand specimen. As can be seen by comparing figures 25*B* and 25*C*, the larger crystals of the porphyritic facies are about as large as those of the granular facies, but there is a much larger proportion of fine-grained matrix quartz, feldspar, and biotite than in the granular rock. Most of the conspicuous phenocrysts of the rock are feldspar, but locally quartz also forms phenocrysts and the rock has a "quartz porphyry" aspect.

The rock is composed generally of nearly equal proportions of quartz, sodium plagioclase, and perthitic potassium feldspar which together make up about 95 percent of the rock; the rest is mainly biotite or muscovite (table 15; fig. 26). Fluorite, zircon, opaque minerals, topaz, and an alteration (?) mineral, kaolinite, in approximate decreasing order of abundance, comprise the accessories.

The potassium feldspar is mainly microcline microperthite, which forms subhedral phenocrysts or occupies an interstitial position in finer grained parts of the rock. The potassium feldspar phenocrysts are coarsely perthitic in the same fashion as potassium feldspar in the granular facies, but the finer grained potassium feldspars are noticeably less perthitic. On an average the perthitic feldspar contains about 92 percent potassium feldspar as determined microscopically.

TABLE 15.—*Modal (volume percent), chemical, and normative composition (weight percent) of representative and average rocks in the Redskin stock*

[Chemical analysts: Paula M. Buschman, Ellen S. Daniels, and Elaine L. Munson. Tr, trace; Ap. apatite; T, tourmaline; K, kaolinite; M, monazite. Leaders (...) indicate no data]

	Granular						Porphyritic							Fine grained				
Sample No. (fig. 24)	69A	69B	70	71	72		73	74	75	76	77	77A		78	79	79A	79B	
Field No.	M3-279	M4-15	BA-657	BA-822	BA-944	Aver-	TR-83	BA-872	BA-687	BA-719	BA-889	M4-153	Aver-	T1-20	T1-36	M4-87	T1-172	Aver-
Laboratory No.	D100430	D100431	H3601	H3602	H3603	age[1]	H3248	H3606	H3604	H3605	H3607	D100432	age[2]	-----	-----	D100390	D100389	age[3]
Modal composition																		
Quartz	26.7	29.9	27.8	39.8	31.6	31.9	32.8	38.2	32.9	27.8	25.5	26.3	29.6	28.8	27.0	30.8	29.4	29.4
Plagioclase	32.4	25.6	20.2	22.2	24.9	23.6	35.2	32.9	31.6	34.2	36.6	38.2	33.0	36.6	37.4	32.8	35.2	35.2
Potassium-rich perthite	38.2	40.5	46.0	32.0	40.0	40.6	27.3	25.6	30.3	33.4	32.0	30.1	32.4	27.3	29.2	28.2	30.4	29.4
Biotite	2.0	3.3	5.3	5.1	2.8	3.4	3.3	.6	3.2	3.1	4.2	4.5	2.8	4.8	4.0	5.9	3.5	2.8
Muscovite	.1	.1	.1	.2	.1	.4	.6	2.5	.7	.8	.8	.6	1.5	1.8	2.2	1.7	.4	2.4
Fluorite	.5	.4	.6	.6	.5	.5	.8	.2	.9	.7	.9	.3	.5	.4	.2	.5	.5	.5
Topaz	.2	.1	0	Tr	Tr	.1	0	0	.1	0	0	0	Tr	.1	0	0	0	Tr
Zircon	Tr	Tr	0	.1	Tr	.05	Tr	0	.1	Tr	Tr	Tr	Tr	Tr	Tr	0	.3	Tr
Opaque minerals	.1	.1	Tr	0	.1	.15	Tr	0	.2	0	0	Tr	.1	.2	Tr	Tr	.3	.1
Other	Tr-M(?)	---	0	0	Tr-Ap, T	Tr-Ap, K, T	0	0	0	0	0	---	Tr-K, Ap	0	0	Tr-M	---	Tr
An content	---	---	16-8	13-10	4-9	---	4-6	0-6	3-11	15-9	6-0	---	---	---	---	---	---	---
Percent potassium feldspar of perthite	81	79	80	78	81	---	85	93	94	87	94	96	---	26.8	---	---	---	---
Chemical composition																		
SiO_2	76.09	76.04	74.47	75.83	74.51	---	74.42	74.24	74.03	74.28	73.58	73.88	---	---	---	73.64	74.12	---
Al_2O_3	12.50	12.67	12.93	12.65	13.09	---	13.20	13.72	13.44	13.43	13.56	13.58	---	---	---	13.43	13.70	---
Fe_2O_3	.51	.34	.60	.36	.47	---	.85	1.08	.48	.52	.50	.56	---	---	---	.87	1.23	---
FeO	.90	.98	1.26	.90	1.08	---	.63	.41	1.17	1.03	1.17	.96	---	---	---	.99	.29	---
MgO	.02	0	.05	.02	.03	---	.05	.05	.06	.06	.05	.07	---	---	---	.08	.07	---
CaO	.63	.50	.76	.57	.75	---	.69	.80	.80	.70	.89	.71	---	---	---	.91	.50	---
Na_2O	3.73	3.85	3.72	3.79	3.81	---	4.16	4.29	4.18	4.24	4.17	3.87	---	---	---	4.00	4.20	---
K_2O	4.62	4.72	5.22	4.89	5.21	---	4.81	4.36	4.82	4.81	4.98	5.19	---	---	---	4.95	4.91	---
H_2O+	.30	.23	.20	.20	.18	---	.20	.33	.17	.17	.25	.39	---	---	---	.41	.45	---
H_2O-	.11	.06	.04	.07	.04	---	.13	.14	.06	.08	.05	.09	---	---	---	.08	.14	---
TiO_2	.07	.06	.13	.09	.11	---	.09	.09	.11	.09	.12	.13	---	---	---	.14	.12	---
P_2O_5	.01	.01	0	.01	.01	---	.01	.01	.02	.01	.01	.01	---	---	---	.01	.01	---
MnO	.03	.03	.04	.03	.03	---	.02	.01	.05	.05	.03	.04	---	---	---	.04	.01	---
CO_2	.01	.02	.01	.02	.01	---	0	.01	.01	.02	.01	.02	---	---	---	0	0	---
Cl	.02	.02	.02	.01	.01	---	.01	.01	.02	.02	.01	.02	---	---	---	.02	.02	---
F	.54	.51	.45	.39	.48	---	.43	.44	.52	.47	.51	.47	---	---	---	.57	.24	---
Subtotal	100.09	100.04	99.90	99.83	99.82	---	99.70	99.99	99.94	99.98	99.90	99.99	---	---	---	100.14	100.01	---
Less O	.23	.21	.19	.16	.20	---	.18	.19	.22	.20	.21	.20	---	---	---	.24	.10	---
Total	99.86	99.83	99.71	99.67	99.62	---	99.52	99.80	99.72	99.78	99.69	99.79	---	---	---	99.90	99.91	---
Normative composition																		
q	36.29	35.05	31.96	34.58	31.73	---	31.63	32.33	30.55	30.66	29.33	31.02	---	---	---	30.88	30.63	---
or	27.27	27.88	30.84	28.88	30.78	---	28.43	25.76	28.48	28.44	29.42	30.66	---	---	---	29.25	29.01	---
ab	31.40	32.40	31.31	31.93	32.15	---	35.08	36.21	35.20	35.70	35.19	32.58	---	---	---	33.68	35.37	---
an	0	0	.41	0	.08	---	0	.62	0	0	.49	0	---	---	---	.28	.66	---
c	1.40	1.26	1.04	1.15	1.17	---	1.12	1.73	1.38	1.27	1.15	1.63	---	---	---	1.42	1.27	---
en	0	0	.12	.05	.08	---	.12	.12	.14	.15	.12	.14	---	---	---	.20	.17	---
fs	1.16	1.46	1.68	1.25	1.47	---	.29	0	1.66	1.40	1.59	1.16	---	---	---	.94	0	---
fr	.83	.63	.93	.73	.99	---	.88	.90	1.07	.91	1.05	.97	---	---	---	1.17	.49	---
ap	.02	.02	0	.03	.02	---	.03	.02	.05	.03	.02	.02	---	---	---	.02	.02	---
fluorine	.13	.20	0	.04	0	---	.04	0	0	.02	0	0	---	---	---	0	0	---
il	.14	.12	.25	.17	.21	---	.22	.17	.21	.17	.23	.25	---	---	---	.27	.23	---
mt	.74	.49	.87	.53	.68	---	1.23	1.09	.70	.76	.73	.81	---	---	---	1.26	.62	---
other	---	---	.05	.07	.04	---	---	.37	.04	.08	.05	.03	---	---	---	---	.97	---

[1]Average of 50.
[2]Average of 53.
[3]Average of 12.

Most of the plagioclase occurs in fine- to medium-grained subhedral to euhedral tabular crystals, composed dominantly of plagioclase (An_5–An_{10}). Small tabular crystals are included in irregular fashion in coarser-grained potassium feldspar, and medium-grained crystals are partly mantled by potassium feldspar. As in the granular facies, some discrete plagioclase crystals are broken and have been veined by the potassium feldspar. A clear, nontwinned sodium-rich plagioclase is present in small amounts as a late mineral.

Quartz is present in various rocks as euhedral crystals, phenocrysts, and irregular aggregates of anhedral crystals. In some thin sections, the quartz phenocrysts have lobate outlines convex against the adjacent minerals suggesting replacement.

Generally, biotite and muscovite are almost equally abundant. The muscovite occurs as interstitial, euhedral crystals with or without associated biotite, and as irregular masses crosscutting biotite or potassium feldspar. Sparse sericite occurs as a separate phase or in aggregates with topaz and fluorite in plagioclase. Biotite is generally interstitial and primary, but some occurs in plagioclase crystals where it appears to be secondary and to have formed by replacement.

The accessory minerals are the same as in the granular granite and have the same microscopic relations. Fine-grained aggregates of kaolinite occur in sericite-topaz-fluorite aggregates and as a replacement product of feldspar.

The presence of late untwinned sodium plagioclase and the relatively common lobate contacts shown by quartz in the porphyritic facies contrast with scarcity of late plagioclase and well crystallized quartz in the granular facies and suggest somewhat more extensive late magmatic or deuteric effects than have been inferred in the granular facies. In general, however, most of the texture of the porphyritic facies can also be interpreted as due to crystallization from a melt.

Fine-Grained Granite

The fine-grained granite, well developed in the core of the Tarryall stock contains megascopically visible but fine-grained biotite and muscovite and scattered quartz or feldspar phenocrysts more than 1 mm across. The average modal composition, based on 17 analyses (not all given here), is similar to that of the porphytitic facies, but the fine-grained granite has a slightly higher average plagioclase content.

As seen microscopically, the relations of plagioclase and potassium feldspar are the same as those observed in rocks of the granular and porphyritic facies. Plagioclase occurs mainly as subhedral to euhedral tabular crystals with interstitial or mantling potassium feldspar. The amounts of perthitic plagioclase in the potassium feldspar are very low. Lobate borders on quartz suggesting replacement reactions are common.

Muscovite is generally more abundant than biotite but the proportions are highly variable. In muscovite-rich samples, most of the muscovite occurs as irregular replacements of the potassium feldspar.

Granite-Aplite

Granite-aplite forms irregular border zones in the Redskin stock, the outer zone of the China Wall cupola, all of the Boomer cupola, dikes in the granular facies, and irregular dikes in the older igneous and metamorphic rocks. Locally it grades into granites of the porphyritic facies or the granular facies.

The granite-aplite is a fine-grained rock which varies from almost white to very pale red in color. As seen megascopically its texture varies from granitic to aplitic; viewed microscopically the characteristic texture developed in the Boomer cupola and some other cupolalike bodies is micrographic. Particularly in dike rocks, the granite-aplite has local pegmatitic zones and the pegmatitic zones are miarolitic. Although the granite-aplite varies somewhat in composition and microscopic texture in its different modes of appearance, it is generally characterized by (1) high quartz content, (2) albite about as abundant as potassium feldspar or more so, (3) either topaz or fluorite as the main accessory, and (4) local aplitic and micrographic textures.

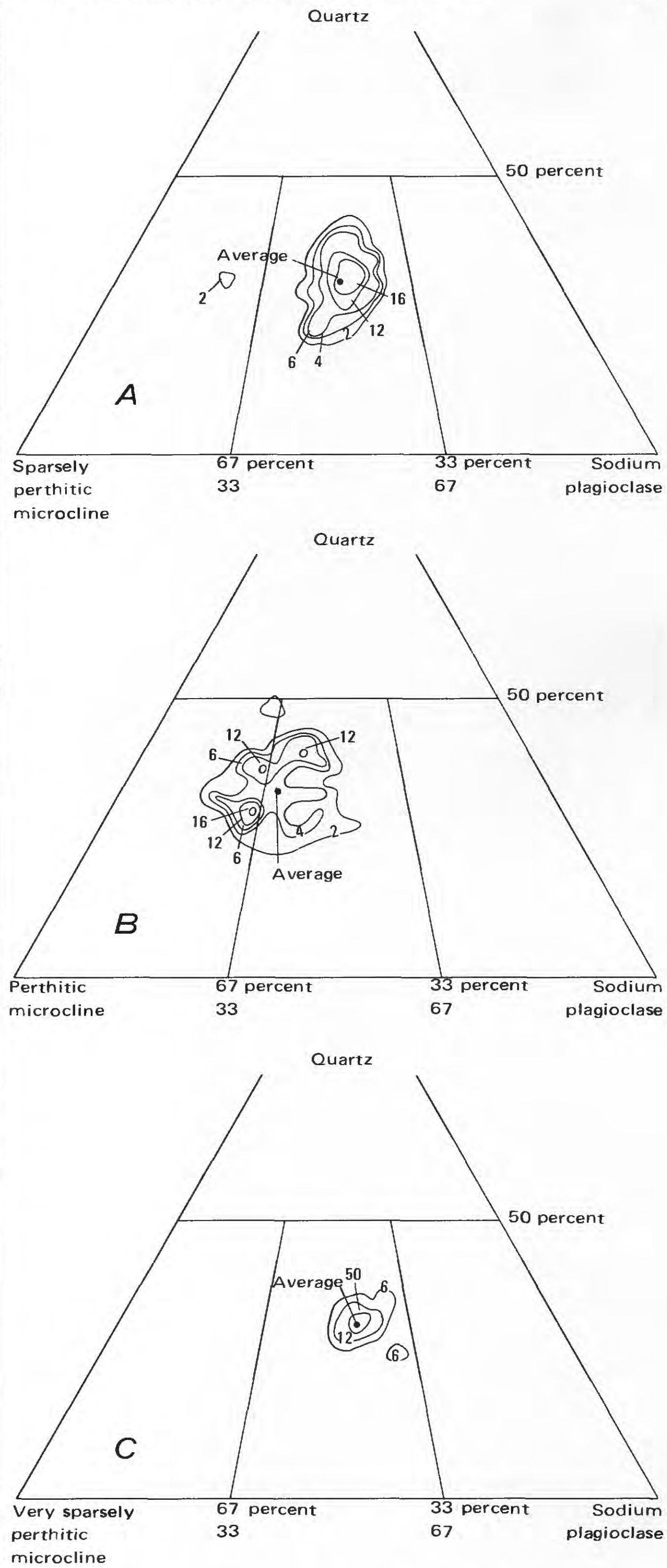


Figure 26.—Modal composition (quartz-plagioclase-potassium feldspar) of Redskin Granite in the Redskin stock. Contours are percent of samples. *A*, porphyritic facies; 53 samples. *B*, granular facies; 50 samples. *C*, fine-grained facies; 15 samples.

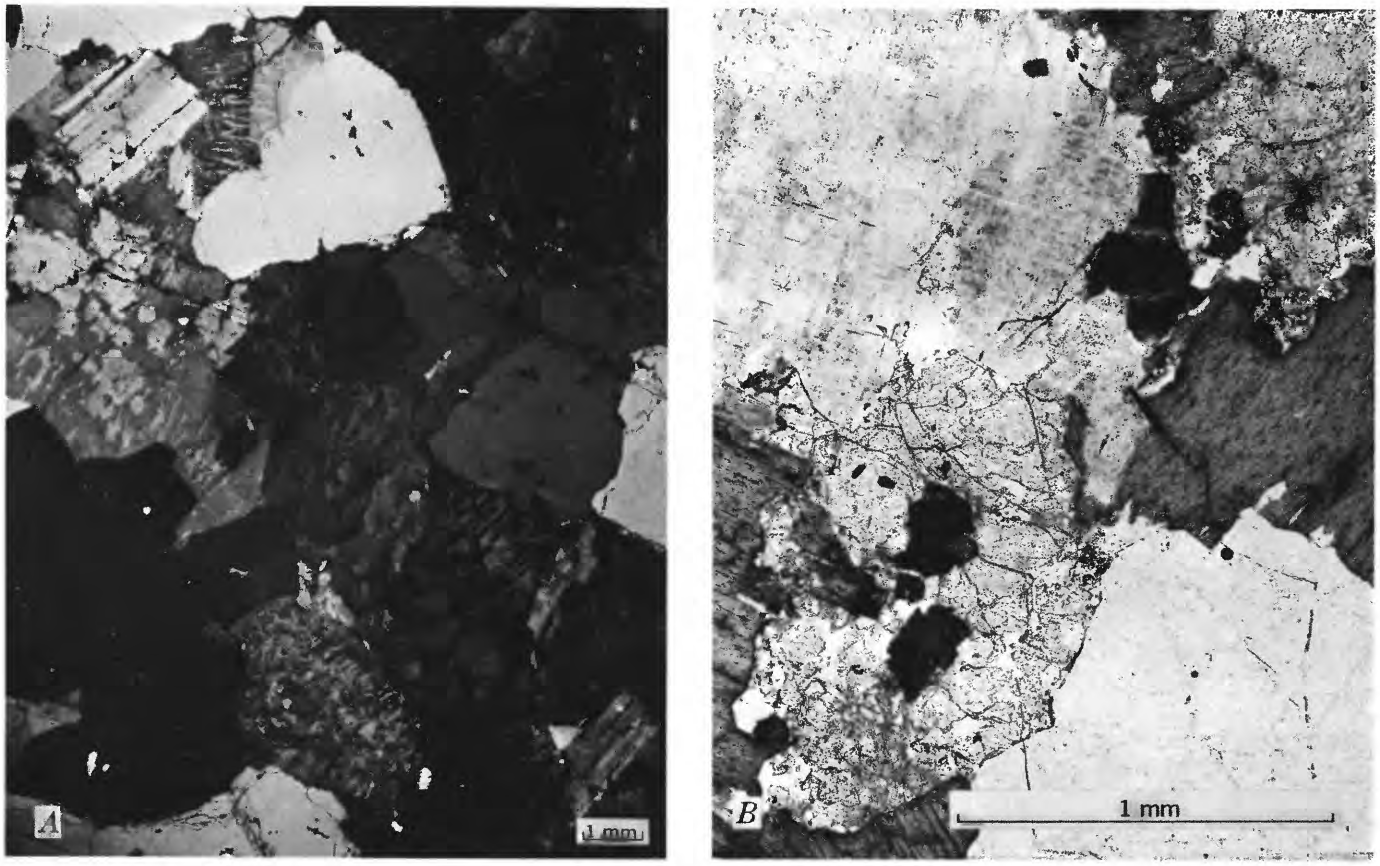


FIGURE 27.—Redskin Granite. *A*, granular facies showing perthitic potassium feldspar; crossed nicols. *B*, Interstitial fluorite.

GRANITE-APLITE OF THE BOOMER AND CHINA WALL CUPOLAS

The granite-aplite of the Boomer cupola and nearby dikes has been studied more than that of other localities because of the beryllim mineralization in the area. In hand specimen, the typical granite-aplite is pale red, massive, sugary textured, and has no visible mafic minerals. Very locally, dikelike zones in the granite-aplite grade into pegmatite. The granite consists chiefly of quartz, albite, very sparsely perthitic potassium feldspar, and muscovite, generally in that order of abundance (table 16). There is no primary biotite, but some of the white mica is faintly pleochroic and could have formed by leaching of biotite. There is also a very minor amount of pleochroic green mica occurring in secondary aggregates along the cleavage of the white mica. Fluorite and topaz are sparse; iron-bearing carbonates are found as late accessories, and some samples contain disseminated sphalerite, galena, and chalcopyrite.

Microscopic examination shows three main types of texture in granite-aplite of the Boomer cupola; hypidiomorphic granular, micrographic, and aplitic. The granular and micrographic textures are dominant, and both may be present in the same thin section. In the dominantly hypidiomorphic rocks plagioclase is the most idiomorphic constituent forming fine-grained euhedral to subhedral tabular grains; potassium feldspar shows a hyalo-ophitic relation with the plagioclase and is in subhedral to anhedral grains. Alkali feldspar and quartz both locally appear to replace the plagioclase, and quartz also replaces potassium feldspar.

Two types of micrographic texture are present. One type is of irregular vermicular form; it has apparently been formed by extensive replacement of tabular sodium plagioclase by quartz. The sodium plagioclase in this intergrowth is polysynthetically twinned, and the original tabular outlines of the plagioclase can be inferred from optical continuity of the plagioclase remnants. The second type consists of quartz and clear, untwinned albite intergrown in a radial or rosettelike form, which in places encloses a nucleus of older plagioclase or potassium feldspar (fig. 28).

The granite-aplite dike rocks that cut country rocks near the Boomer cupola are slightly finer grained than those in the cupola. They also differ in being slightly richer in plagioclase (table 16) and in having a dominant granular (hypidiomorphic) texture.

Muscovite, which is very abundant in both the cupola and associated dikes, tends to vary inversely with the potassium feldspar. The relations are indicated diagram-

TABLE 16.—*Modal (volume percent) and chemical and normative composition (weight percent) of representative samples of granite-aplite of the Redskin Granite*

[Chemical analysts: Margaret C. Lemon, Paula M. Buschman. Tr, trace. Leaders (...) indicate no data]

	Boomer cupola					Dikes near Boomer cupola		China Wall cupola		Dikes, other areas	
Sample No. (fig. 24)	80	81	82	83		84		85		86	
Field and laboratory Nos.	IV-4	IV-10a-4	B2-7-4	B2-7-5	Average[1]	1-1	Average[2]	BA-934	Average[3]	Ba-821	Average[4]
Modal composition											
Quartz	37.9	36.0	---	35.5	37.1	38.8	38.7	31.6	38.4	35.4	31.5
Plagioclase	26.1	30.1	---	35.4	32.2	38.5	40.0	40.2	33.6	30.0	35.1
Potassium feldspar	27.4	27.0	---	18.4	24.0	18.8	14.9	22.0	23.4	33.8	31.4
Biotite	0	0	---	0	.1	.3	.1	3.8	3.3	.8	.8
Muscovite	8.0	6.3	---	10.5	6.0	3.6	6.1	.7	.6	0	.9
Fluorite	Tr	.4	---	.1	.15	Tr	.2	.2	.1	0	<.1
Topaz	0	0	---	0	Tr	0	0	.7	.4	Tr	[6].1
Zircon	0	0	---	0	Tr	0	0	.81	.2	0	0
Opaque minerals	.5	.3	---	.1	.15	0	0	0	0	0	0
Other	.1	0	---	0	Tr	0	0	---	---	---	Tr
Chemical composition											
SiO_2	76.79	77.48	76.16	77.07	[5]76.88	77.66	---	74.35	---	77.96	---
Al_2O_3	12.51	11.70	12.87	12.18	12.32	12.94	---	14.07	---	12.19	---
Fe_2O_3	.85	1.64	.73	.79	1.00	.10	---	.64	---	.08	---
FeO	.40	.47	.86	.69	.61	.27	---	1.21	---	.47	---
MgO	.01	.03	.05	.03	.03	.02	---	.01	---	.01	---
CaO	.12	.21	.37	.38	.27	.13	---	.56	---	.15	---
Na_2O	3.52	3.37	3.97	3.31	3.54	5.07	---	3.96	---	3.86	---
K_2O	4.75	3.77	3.33	4.03	3.97	3.45	---	3.72	---	4.76	---
H_2O+	.46	.66	.48	.42	.51	.19	---	.29	---	.10	---
H_2O-	.19	.18	.31	.21	.22	.04	---	.07	---	.03	---
TiO_2	.03	.02	.02	.02	.02	.02	---	.04	---	0	---
P_2O_5	.01	.01	.01	.01	.01	.01	---	.01	---	0	---
MnO	.02	.06	.03	.02	.03	.03	---	.04	---	.02	---
CO_2	.01	.01	.03	.02	.02	.01	---	.01	---	.01	---
Cl	.01	0	.01	.01	.01	.01	---	.02	---	.01	---
F	.13	.16	.23	.27	.20	.03	---	.96	---	.10	---
Subtotal	99.81	99.77	99.46	99.46	99.64	99.99	---	99.95	---	99.78	---
Less O	.05	.07	.10	.11	.08	.01	---	.40	---	.04	---
Total	99.76	99.70	99.36	99.35	99.56	99.98	---	99.55	---	99.74	---
Normative composition											
q	38.18	43.41	39.89	42.15	---	34.71	---	36.1	---	37.00	---
or	28.05	22.26	19.67	23.82	---	20.38	---	22.2	---	28.12	---
ab	29.67	28.52	33.50	27.89	---	42.80	---	33.5	---	32.57	---
an	0	0	0	0	---	.24	---	0	---	0	---
c	1.60	2.08	2.75	2.40	---	.80	---	3.5	---	.71	---
en	.02	.07	.09	.07	---	.05	---	---	---	.01	---
fs	.03	0	1.00	.62	---	.44	---	1.7	---	.78	---
fr	.25	.50	.47	.94	---	.06	---	.8	---	.21	---
ap	.04	.04	.02	.02	---	.02	---	---	---	0	---
fluorine	.07	.04	0	.04	---	0	---	.4	---	0	---
il	.05	.05	.04	.05	---	.04	---	---	---	.06	---
mt	1.23	1.62	1.06	1.13	---	.15	---	.9	---	.12	---
other	.06	[7].53	.05	.07	---	---	---	---	---	.02	---

[1]Average of 12.
[2]Average of 5.
[3]Average of 4.
[4]Average of 8.
[5]Average of 4 analyses given.
[6]Excludes one dike with >2 percent topaz.
[7]Hematite.

matically on a quartz-plagioclase-potassium feldspar diagram (fig. 29) by contours showing the ratio:

$$\frac{\text{Muscovite} \times 100}{\text{Muscovite} + \text{potassium feldspar}}.$$

Pegmatitic rocks are found in several places in the cupola and in layers subparallel to the walls of the dikes. The main pegmatite zone of the cupola is near the Boomer vein (Hawley, 1969), which itself locally is pegmatitic and grades into quartz-potassium feldspar pegmatite. The pegmatites are composed essentially of quartz and perthitic potassium feldspar. Locally the perthite includes small euhedral plagioclase crystals resembling those found in the normal granite-aplite. Although the quartz is of massive appearance, it locally shows evidence of replacement origin in the preservation of skeletal remnants of coarse-grained alkali feldspars. The composition of the pegmatite, its local occurrence, and the inclusion of sparse tabular plagioclase grains similar to those found in adjacent granite suggest a late stage dilational emplacement.

The granite-aplite of the China Wall cupola is similar to that of the Boomer cupola in hand specimen appearance, in local microscopic development of micrographic quartz-albite, and higher albite than potassium feldspar content. It differs mainly in that it contains biotite and has less muscovite. The biotite occurs partly in interstitial crystals but also in thin and narrow plates that are as much as one-half inch long, which cut across feldspar crystals and hence are believed of late origin. A granite-aplite

FIGURE 28.—Quartz-albite intergrowth. K, potassium feldspar; M, muscovite; Q, quartz; P, plagioclase; mi, micrographic intergrowth; km, potassium feldspar grain partly replaced by muscovite. Crossed nicols.

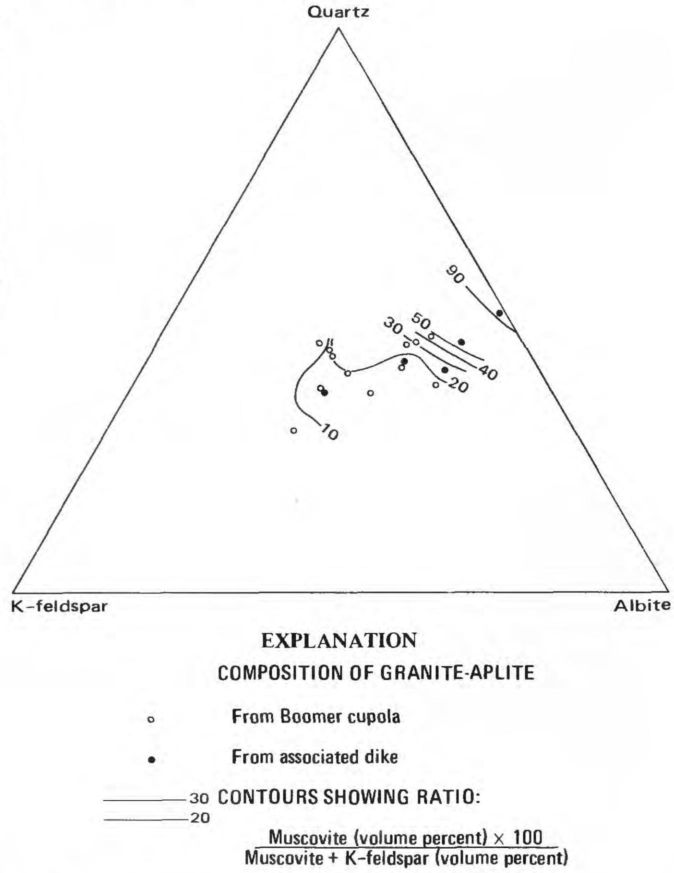


FIGURE 29.—Modal composition (quartz-potassium feldspar-albite) and variation in muscovite-potassium feldspar ratio in granite-aplite from the Boomer cupola and associated dikes.

exposed as a marginal facies to the Redskin stock near the Mary Lee mine (sec. 22, T. 11 S., R. 72 W.) is a muscovitic rock very similar petrographically to that of the Boomer cupola.

GRANITE-APLITE DIKES

The granite-aplite also forms dikes in the granular granite of the Redskin stock and in older igneous and metamorphic rocks near the stock. A major concentration of granite-aplite dikes is in the central and west part of sec. 16, T. 11 S., R. 72 W. Dikes exposed near the center of sec. 16 show at least locally that granular medium-grained Redskin Granite grades through sparsely porphyritic, finer granites, into typical granite-aplite with local pegmatitic and miarolitic zones. These dikes have their origin in the granular facies of the Redskin stock, and granular granite forms the parts of the dikes nearest the contact of the stock; the boundary shown on the map (pl. 1) between granular granite and fine-grained granite in two large dikes is gradational. Farther south along the same segment of the main contact in the northeast part of sec. 21, T. 11 S., R. 72 W., dikes paralleling the contact and near the granular facies of the Tarryall lobe are medium grained and granular in texture; similarly oriented dikes farther from the contact are fine grained. The fine-grained rocks exposed farther from the contact are believed to grade downward into medium-grained granular rocks similar to those found in dikes near the contact.

The granite-aplite in dikes ranges from pale pink to almost white in color, and from essentially structureless to strongly banded with quartz and pegmatite layers. The few dike samples studied in thin section have a considerable range in composition. Although similar megascopically to granite-aplite of the cupolas, microscopic examination shows that micrographic textures are rare in the dikes and that textures typically range from hypidiomorphic granular to aplitic with grains in xenomorphic arrangement showing strongly sutured contacts. Potassium feldspar is generally more abundant than albite and muscovite is generally more abundant than biotite (table 16). Some rocks contain topaz as the most characteristic accessory, and in some very fine grained almost white aplites (such as BA-981) topaz is very abundant and occurs as anhedral, apparently primary, crystals scattered through the rock (fig. 30).

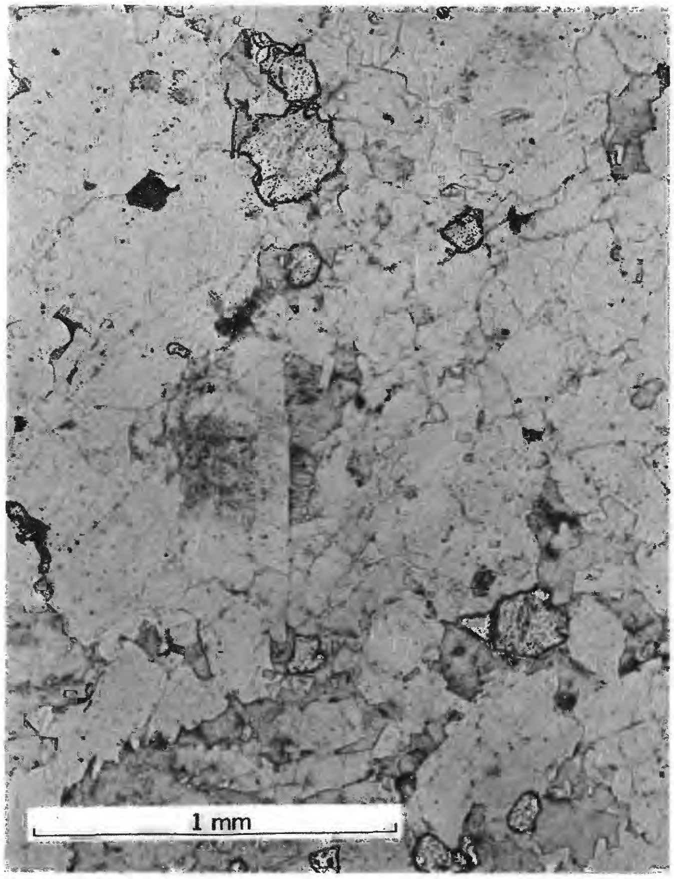


FIGURE 30.—Topaz-bearing granite-aplite dike. Plain light.

SUMMARY

The Pikes Peak and Redskin Granites are generally nearly massive reddish-hued rocks that were emplaced late in the Precambrian history of the region. Although granite and quartz monzonite dominate the Pikes Peak and related rocks, minor facies of rocks ranging from gabbro to peralkalic granite indicate an extensive intrusive series.

The details of chemical composition of the Pikes Peak and Redskin Granites are important to the origin of the greisen beryllium deposits of the region (Hawley, 1969), are of general petrologic interest and warrant summary, but to keep the report balanced and in logical order, composition and petrology of Pikes Peak and related rocks are discussed after the following sections on Structure, Tertiary Rocks, and Geologic History.

STRUCTURES IN THE PRECAMBRIAN ROCKS

Foliation is ubiquitous in the Precambrian metamorphic rocks of the southern Tarryall region, and cleavage is recognized in places. Lineation is widespread in the metamorphic rocks. The major structures of the region reflect, mainly, folding of the layered gneiss and amphibolite units, the nearly concordant emplacement of the Boulder Creek(?) Granodiorite and the strong disruptive effects of the intrusion of Silver Plume(?) Quartz Monzonite. Faulting had a relatively minor structural effect, though some faults have had a long intermittent history of movement. Joints are abundant in all of the Precambrian rocks.

FOLIATION AND CLEAVAGE

The foliation of the metasedimentary rocks at most places is subparallel to the compositional layering of ancient sediments. This is shown on a small scale by the parallelism of foliation with calc-silicate and quartzose layers, and on a large scale by parallelism of foliation with major rock units, such as the fine-grained biotite gneiss, sillimanitic biotite-muscovite gneiss, and sillimanite-cordierite-quartz gneiss. The large amphibolite units also show the parallelism of compositional layering and foliation but the significance of this is less certain, as they may have formed from either sedimentary or igneous precursors.

At a few places it is possible to find a foliation or cleavage that cuts across compositional layering, which indicates either a locally different mode of deformation or a second period of deformation. An axial plane cleavage or foliation is locally developed in the sillimanitic biotite-quartz gneiss in the central parts of local tight fold structures. A secondary alinement of micaceous minerals was noted in varvelike layering in the layered gneiss in NE¼SE¼ sec. 28, T. 11 S., R. 72 W., where mica plates lie at an angle of about 20° to the apparent compositional layering. Broken or cataclastic folds of east-northeast trend, which cut across old foliation, are present nearby, so there is local evidence of superposition of planar structures and multiple deformation. These cataclastic structures may have resulted from deformation at a shallower crustal level than that at which the dominant plastic deformation occurred.

The crudely oval stocks of the Silver Plume(?) Quartz Monzonite have produced enveloping domal structures in adjacent orthogneiss and paragneiss. The regional trend of the bedding foliation in the gneisses is disturbed near the stocks, so that the foliation of the gneisses is conformable to the shape of the stocks. This conformability could have been produced by the forceful emplacement of the stocks or by the recrystallization of the gneisses near the stocks to yield a new, superposed foliation.

LINEATION

The layered gneisses and Boulder Creek(?) Granodiorite of the region show several types of small-scale lineations, including the parallel axes of small folds, warps, and crinkles, mineral alinements, boudins, and rarely, slickensides. Mineral lineations are the most abundant type and are manifested by quartz, biotite, sillimanite, and hornblende. Lineations in the Boulder Creek(?) orthogneisses are, in general, parallel to those in the layered gneisses.

Plots of lineations of all types show that most plunge gently to the north-northeast (fig. 31*A*). Lineation maxima (5.0 percent) are found at about 40° N. 25° E., and at 40° N., and other minor concentrations plunge at about 30° toward N. 50° E., and at moderate angles toward the northwest. Very few lineations plunge to the south.

The maximum at about 40° N. 25° E., corresponds closely to the plunge of the main Round Mountain synclinal axis (pl. 1; fig. 2). The very minor N. 50° E. lineation is parallel to a weakly developed fold set that is younger than the dominant fold set. Other small-scale lineations characterize secondarily deformed rocks near the Silver Plume(?) plutons.

The greater structural complexity of the parts of the region with Silver Plume(?) plutons is emphasized by comparisons of figures 31*A*, *B*, and *C* where lineations from the Puma Hills were separated from those northeast of the hills. The rocks in the Puma Hills are mainly in the northwesterly homocline and were not as strongly deformed by the intrusion of the Silver Plume (?) Quartz Monzonite as were rocks in the Badger Flats area.

FOLDS

Fold structures with wavelengths varying from less than an inch to several miles are developed in the gneissic rocks of the region. The largest folds are the Round Mountain syncline and the Tarryall anticline. Both of these folds, and related minor folds and mineral lineations, were formed by plastic deformation under deep or catazonal conditions at about the time of emplacement of the Boulder Creek(?) Granodiorite. The emplacement of the Silver Plume(?) Quartz Monzonite several hundred million years later strongly deformed the older igneous and metamorphic rocks and disrupted the older structures. The Round Mountain syncline, a moderate to steeply plunging fold of northeasterly trend, is the most important structural element of the south-central part of the area. The fold is delineated by changes in the foliation and is outlined by lithologic layering. An asymmetric phacolithic mass of Boulder Creek(?) Granodiorite occupies part of the axial region. Although both the Round Mountain syncline and the Tarryall anticline are shown on the main geologic map (pl. 1), the distortions caused by the Silver Plume are extensive; both folds are much more readily seen on an interpretative map showing the pre-Silver Plume(?) distribution of the layered gneisses and the Boulder Creek(?) Granodiorite (fig. 11).

The Round Mountain syncline can be traced from a point near the northern edge of the Stoll Mountain batholith for a distance of about 4 miles, where it is cut off by the Redskin stock. The subparallel Tarryall anticline can be traced on the generalized map (fig. 2) from the Tarryall Mountains batholith southward for about 5 miles, where it appears to die out in the northeasterly dipping homocline. The wave length of the major fold system indicated by these folds is approximately 8 miles.

Smaller folds of the same bearing and plunge are found in the dominantly homoclinal southern part of the region. Examples include folds on the southwest flank of Badger Mountain and those northwest of the top of Stoll Mountain.

Other fold structures of mappable size were formed during intrusion of the larger plutons of Silver Plume(?) Quartz Monzonite. Examples include the fold that plunges gently to the southwest in the NE¼ sec. 5, T. 12 S., R. 72 W., and the troughlike structure in sec. 2, T. 12 S., R. 72 W., that lies between the Tappan Mountain and Firefly plutons. Drag folds with a reversed sense in gneisses near Silver Plume(?) plutons are believed to indicate the forcible intrusion of magma comprising these bodies; they may have formed as indicated diagrammatically in figure 32.

The response of different gneissic rock types to the stresses which produced folding can be surmised from a study of the folds. Minor folds are particularly irregular, even ptygmatic, in the sillimanitic biotite-muscovite gneiss and migmatite unit, supporting the idea that these rocks were partially melted. Amphibolites, on the other hand, composed primarily of more refractory minerals (hornblende and calcic plagioclase), commonly show the effects of fracture rather than of plastic deformation. A few outcrops show minor folds in amphibolite, but these are tight, angular folds or tiny incipient folds at the margin of fractured blocks of amphibolite. The most deformed sample of amphibolite observed in this study seems to reflect both competent and plastic behavior during deformation; tight folds involving thin hornblende and feldspar folia (less than one-fourth-inch thick) were apparently injected plastically into a fracture in a thicker (2-in.) hornblende-rich band which had itself been folded competently. The response of calc-silicate rocks to deformation was similar to that of the amphibolite, although the calc-silicates also formed large- and small-scale boudins in the surrounding rock.

Small-scale folds in the granitic gneiss of Boulder Creek(?) age are rare and consist of steplike warps along northwest-trending axes. This type of fold was observed only in this rock unit, and only at a few outcrops. These warps resemble minor shear zones, 5 to 15 inches wide, within which foliation is markedly steepened. These features might have formed as a semi-competent response to stresses when the granitic gneiss was crystalline but still at a high temperature.

FAULTS

Faulting probably began in pre-Silver Plume time, and was active intermittently in the Precambrian, both before and after the intrusion of the Pikes Peak and Redskin Granites. The most prominent faults are the Badger Flats, Webber Park, and Pulver Gulch which represent sets that

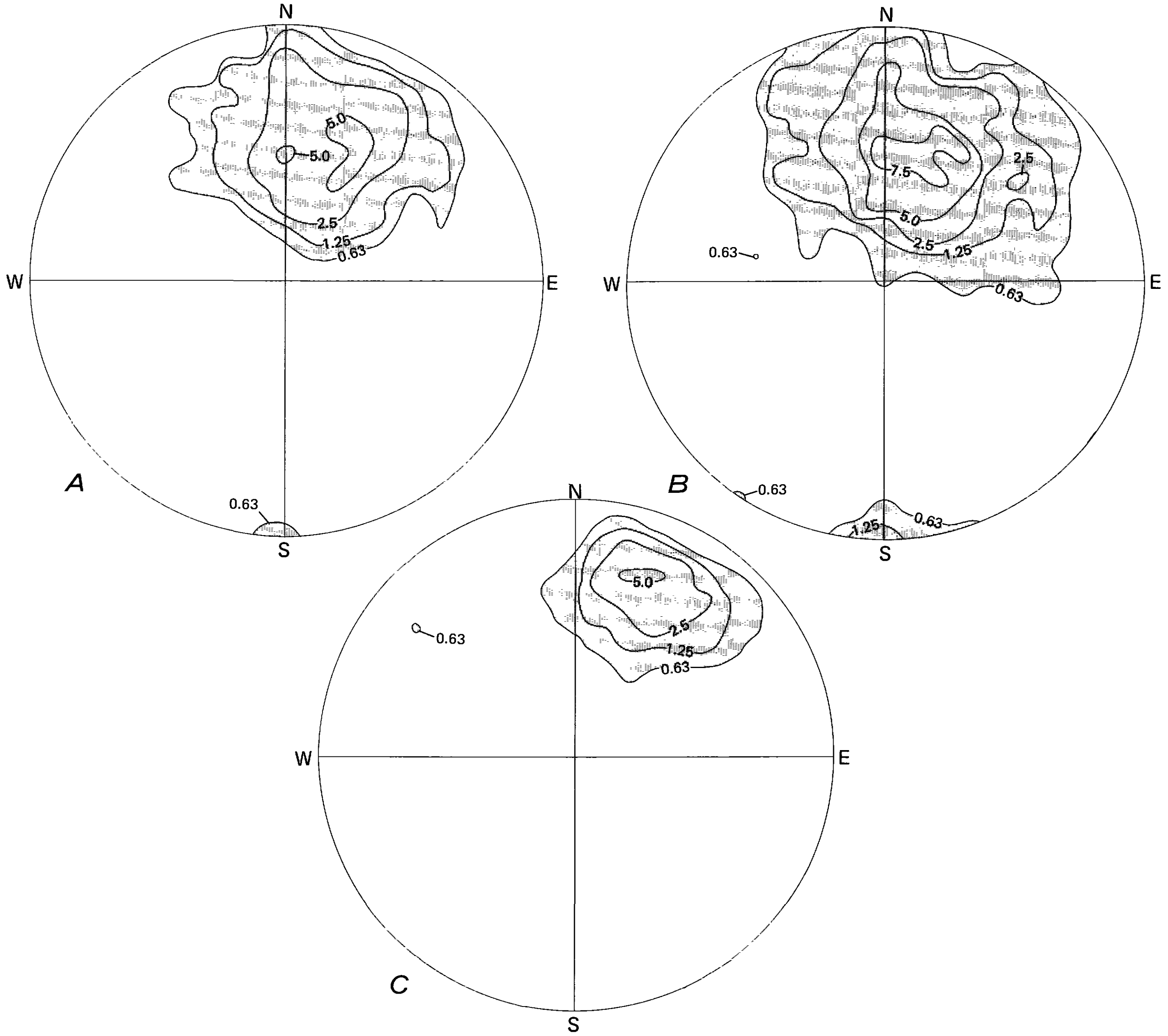


FIGURE 31.—Contour diagrams of lineations in the layered gneiss and Boulder Creek(?) Granodiorite. Lower hemisphere plot; contours are percent of poles. *A*, 815 lineations, southern Tarryall region; includes all lineations of diagrams *B* and *C*. *B*, 469 lineations, mainly northeast of the Puma Hills. *C*, 346 lineations in the Puma Hills.

strike north-northwest and northwest. The Precambrian ancestry of these faults and associated small structures is inducated by the fact that they localized the mineralization related to the Pikes Peak and Redskin Granites.

The Badger Flats fault zone contains numerous steeply dipping, closely spaced faults that strike from north-northwest to almost north. These shears cut the igneous and metamorphic rocks west and south of the Redskin stock. The fault is generally poorly exposed, except in a few prospect pits, particularly in secs. 21 and 28, T. 11 S., R. 72 W., but the continuity of the zone is shown by topographic lineaments developed in rocks weakened by erosion. The offset on the fault is shown by displacement of the granodiorite gneiss body just south of the Boomer mine and probably also by the offset of the granitic gneiss-quartz diorite contact in the SW¼ sec. 28, T. 11 S., R. 72 W. The apparent offset of the Silver Plume(?) pluton in the NE¼ of the same section is better explained by post-fault intrusion of the Silver Plume(?) Quartz Monzonite. Specifically, the dikelike extension of the pluton to the northwest along the fault zone is believed to indicate post-fault quartz monzonite emplacement.

While movement on the Badger Flats fault may pre-date the Silver Plume(?) plutonism, it is at least as old as the Redskin Granite, as dikes of Redskin Granite were intruded along subsidiary faults and the main fault localized greisen-type mineralization in sec. 28, T. 11 S., R. 72 W.

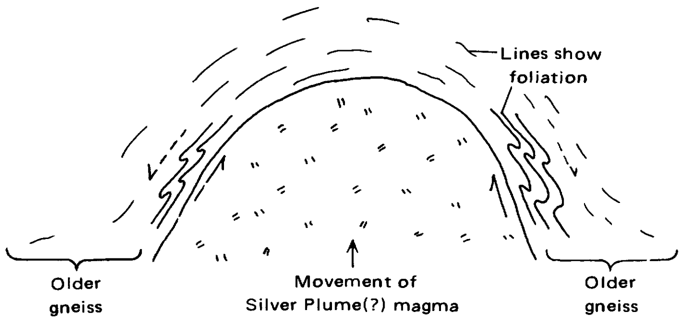


FIGURE 32.—Formation of reverse-type drag folds by magma emplacement.

The Badger Flats fault apparently dies out to the north in a set of faults that strikes slightly west of north. One of these faults is inferred to cause the topographic alinement through Tarryall; others are slightly mineralized and are exposed in prospect pits and shallow shafts east of Tarryall.

The Webber Park fault is largely covered by alluvium but its position is known from displacement of the main amphibolite layer and other lithologic contacts about two miles west of Tarryall. The fault strikes about northwest to west-northwest and has an apparent right-lateral displacement. The fault is inferred to extend into the northwest corner of the Tarryall quadrangle and to join with a strong northwest-striking fault which contains a barite-rich vein in the SE¼ sec. 6, T. 11 S., R. 72 W. Other barite veins are found in a well-developed set of northwesterly faults about 1½ miles northeast of the Webber Park fault.

The strong topographic alinement extending northwest along Pulver Gulch and through Wilkerson Pass defines the position of the Pulver Gulch fault. This fault has produced no apparent offset of Precambrian rock bodies, but rocks along its course are highly sheared and hence more easily eroded. Immediately southeast of the present map area a barite vein occurs along the trend of the fault, on the John Caylor ranch at the head of Rocky Gulch.

The main fault zone in the younger granitic rocks is exposed in the Pikes Peak and Redskin Granites about one-half mile east of Tarryall Creek and parallel to it. This fault locally contains quartz veins, and subsidiary structures contain fluorite-barite veins with very small amounts of copper minerals.

Elsewhere in the Pikes Peak or Redskin Granites small faults or shear zones of northeast and northwest-striking sets contain fluorite or barite-bearing veins. The abundant fluorite of the Pikes Peak and Redskin Granites and the occurrence of fluorite-bearing veins in and near the granite bodies strongly suggest an age near that of the Pikes Peak for those structures.

JOINTS

All of the Precambrian rocks are jointed, and there is a fairly simple major joint pattern with steep northeast and northwest sets and a nearly flat set. In detail, however, the jointing is very complex, and joints probably were formed in several episodes beginning in Precambrian time.

Joint studies were made in two main groups of rocks: (1) the metamorphic orthogneiss and paragneiss, and (2) the youngest Precambrian igneous rocks, particularly the Redskin Granite (fig. 33).

The similarity between joint patterns for the relatively young Precambrian granites and for the older metamorphosed rocks is quite clear. The strongest joint set in each case strikes about N. 30° W. and dips very steeply to the east. (Its pole is at about N. 60° E.) Other maxima are similar, but not identical, as there is a nearly flat set and nearly vertical joints of northeasterly strike obvious in both groups.

The many joints oriented normal to lineations in metamorphic rocks (cross joints) do not show up as obvious maxima, but are included in the broad enlargement of the 1 percent contour in the north-northeast part of the diagram. There is also a nearly vertical N. 30° E. joint orientation in the metamorphic group, particularly, that may be a longitudinal joint of the main deformation.

The origin of some individual joints or joint sets can be inferred from observations. As one example, the origin of cross joints in metamorphic rocks can reasonably be assigned to the deformation that produced the foliation and lineation. Another example involves the nearly flat joint set in the Redskin or Pikes Peak Granite. These joints are parallel to many flat dikes of the granite, and so could be inferred to be joints that formed nearly at the time of granite consolidation. On the other hand, flat joints also could be loading release joints, so unless there is other evidence, such as veinlet material on the joint surfaces, an origin cannot be assigned from the flat orientation. Joint sets that extend without noticeable deflection across several rock types are significant in indicating the minimum possible age of jointing. For example, nearly vertical north-south, east-west joints well exposed in cliffs south of U.S. Highway 24 on the western side of the Puma Hills cut all rock units in that region—layered gneiss, Boulder Creek(?) Granodiorite, and Silver Plume(?) Quartz Monzonite.

ROCKS AND DEPOSITS OF TERTIARY AND QUATERNARY AGE

The Precambrian bedrock of the region is locally covered by a veneer of younger material, particularly in the lowlands and valleys. These younger deposits are mainly of Quaternary age but include scattered remnants of Tertiary volcanic rocks and deposits.

Tertiary rocks and deposits.—Volcanic rocks and alluvium of Eocene and Oligocene age are exposed in several parts of the southern Tarryall region. Rhyolitic ash-flow tuff crops out at several localities in the southeastern and

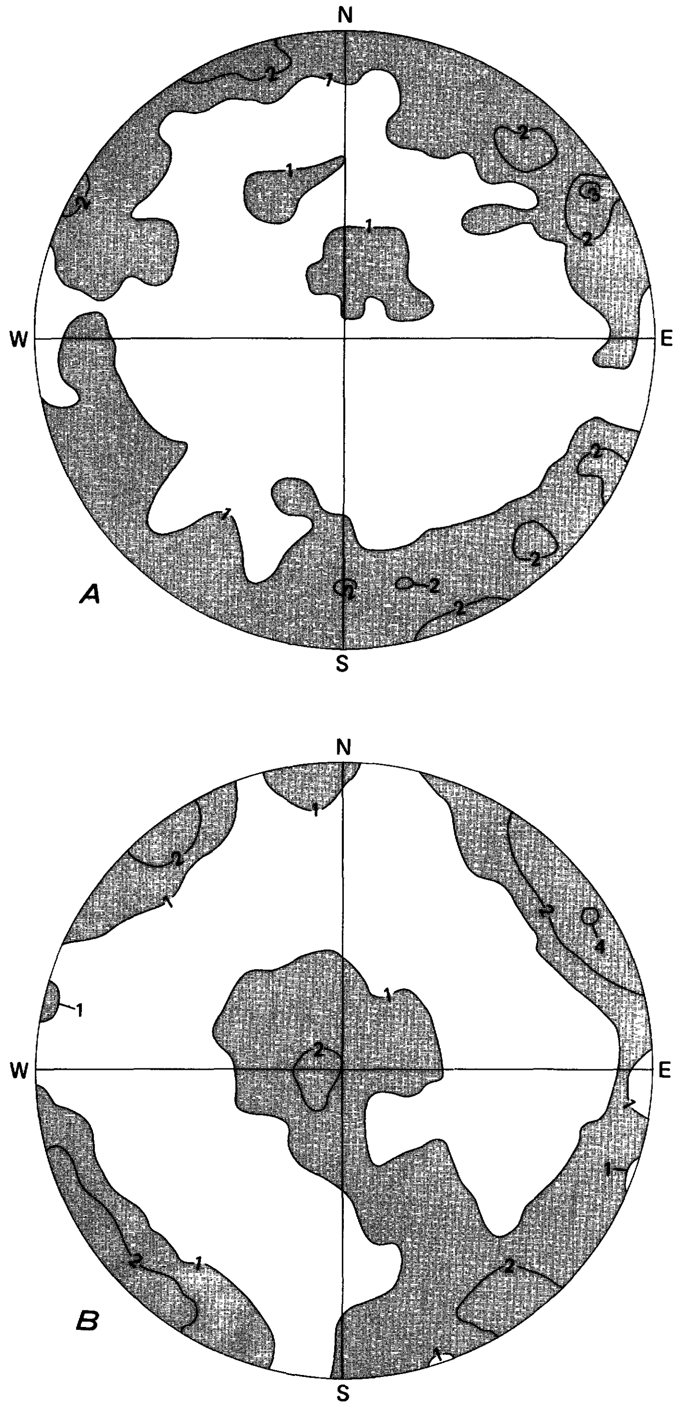


FIGURE 33.—Joint orientation diagrams. *A*, Plot of 826 joints (poles in lower hemisphere) in the layered gneiss and Boulder Creek(?) Granodiorite; contours are 1, 2, and 3 percent. *B*, Plot of 787 joints (poles in lower hemisphere) in the Pikes Peak and Redskin Granites; contours are 1, 2, and 4 percent.

south-central part of the area, including (1) near Tappan Gulch in sec. 6, 7, 18, T. 12 S., R. 71 W.; (2) near Pulver Gulch in sec. 13, T. 12 S., R. 72 W.; and (3) near the Boomer mine in sec. 21, T. 11 S., R. 72 W. Several of these occurrences are on the flanks of Tappan and Pulver Gulches, suggesting that the ash flows were deposited in valleys very similar to those of the modern drainage. In the Florissant region, 10 miles east of this area, similar ash flows, called trachyte by MacGinitie (1953), have been found to dip beneath the Florissant Lake Beds, correlated with the Antero Formation (Stark and others, 1949) of South Park (R. C. Epis, oral commun., 1968). These isolated occurrences of ash-flow tuff are all erosional remnants of the Wall Mountain Tuff (Epis and Chapin, 1974), which was extruded about 35 M.Y. ago.

In the southwestern part of the region, a coarse reddish-brown andesitic breccia, probably of laharic origin, is exposed in the low barren hills southwest of Elevenmile Canyon Reservoir. This rock is correlated with the Thirtynine Mile Andesite (Epis and Chapin, 1974), which has been dated at 34 m.y. The andesitic breccia is overlain locally by ash-flow tuff of rhyolitic composition and varying degrees of welding; correlation of this tuff with specific units of the Thirtynine Mile volcanic field has not been attempted.

The Wall Mountain Tuff of Tappan Gulch and the Boomer area overlies boulder deposits of variable character. In Tappan Gulch the tuff overlies a boulder deposit that is very rich in granite of Pikes Peak and probably Redskin age. The boulders are as much as 10 feet across and are rounded. Northwest of the Boomer mine, near the northwest corner sec. 21, tuff overlies a deposit with dominantly Boulder Creek(?) and Silver Plume(?) boulders.

These boulder deposits are of considerable geomorphic significance. Boulders of Redskin Granite in Tappan Gulch indicate that an ancestral Tarryall Creek drainage flowed into an ancient South Platte River much farther south than it does now. This is fully in accord with the underfit of the small stream to the wide valley in Tappan Gulch. The present abrupt eastern swing of Tarryall Creek north of Tappan Mountain may have been caused by stream capture of an ancestral Tarryall Creek.

Boulder deposits also are found in places where there are no volcanics, particularly in and north of Pulver Gulch. One of the ancient stream channels can be traced north-northwest of Pulver Gulch in secs. 10 and 11, T. 12 S., R. 72 W.

The age of the boulder deposits is uncertain and several ages may be represented. Similar boulder deposits (Echo Park(?) Alluvium) in the Thirtynine Mile volcanic field fill paleovalleys incised into an erosion surface of late Eocene age (Epis and Chapin, 1968, p. 60). Badger Flats may be a portion of this surface, which underlies the Echo Park Alluvium and the Wall Mountain Tuff and has been recognized over an area of about 5,000 square miles in central Colorado (Epis and Chapin, 1968, p. 56).

The youngest Tertiary deposits are gravels on gently sloping upland pediment surfaces which are well developed south of Tarryall. These gravels may correlate with gravels of Miocene and Pliocene age described by Epis and Chapin (1974).

Quaternary deposits.—Three types of Quaternary deposits were distinguished during mapping. The older alluvium and colluvium occur, respectively, in and near the modern stream courses and on moderately steep and largely forested slopes. High-level boulder deposits exposed at several places near Tarryall Creek are believed to be almost as old as the Tertiary gravel pediment deposits; some may even be as old as the Tertiary boulder deposits associated with the ash-flow tuff. The youngest deposit is the recent alluvium along modern streams.

GEOLOGIC HISTORY

The oldest rocks of the southern Tarryall region comprise the layered gneiss unit and are the metamorphic equivalents of a thick series of dominantly argillaceous sedimentary rocks which also contained minor interlayers of impure carbonate and perhaps basic igneous rock. Neither the source of the sediments nor their age of deposition is known. These ancient rocks were buried to depths of about 20 km, where increased temperature and pressure produced mineral assemblages indicative of the sillimanite-potassium feldspar grade of regional metamorphism. Temperatures during metamorphism were high enough (650–700°C.) to produce anatectic migmatites by the partial melting of parts of the metasedimentary sequence. Plastic deformation and recrystallization during the period of elevated temperatures produced a foliation approximately parallel to the compositional layering of the original sediments, and several types of lineations, including the alinement of high-temperature minerals. Plastic folding of the layered gneisses along northeast-trending axes also occurred at this time.

The emplacement of the Boulder Creek(?) Granodiorite accompanied this period of metamorphism and deformation, as suggested by the parallelism of the fabric and structure of the Boulder Creek(?) orthogneiss and the layered gneiss, and local by deformation of microcline phenocrysts which were crushed and recrystallized to polycrystalline clots of microcline and discontinuous microcline-rich folia. Other phenocrysts of microcline were broken and the fractures healed with quartz and microcline microveinlets. Synkinematic plutonic rocks of Boulder Creek age have been recognized in other parts of the Front Range and have been dated at approximately 1.69–1.72 billion years (Hutchinson and Hedge, 1967), a date which also serves as a minimum age for the regional metamorphism and plastic deformation.

The oldest and most mafic Boulder Creek(?) rock of the southern Tarryall region, the quartz diorite gneiss, may have resulted from the contamination of a more granitic magma by reaction with biotite paragneiss wallrocks. Relations suggestive of assimilation are the great abundance of biotite paragneiss inclusions in the quartz diorite gneiss and the common though not ubiquitous occurrence of the quartz diorite gneiss as a border facies of larger quartz monzonite or granodiorite gneiss plutons.

The generally concordant form of many of the Boulder Creek(?) bodies, the high metamorphic grade of the rocks they intrude, and the lack of contact metamorphic effects suggest that these earliest plutons were emplaced at about the catazonal level of metamorphism, according to the terminology of Buddington (1959). It seems probable that the magmas from which these plutons crystallized were produced by the more thorough melting of metasedimentary gneisses at levels deeper in the catazone.

The fact that the regional foliation and lineation trends are only rarely and weakly displayed in the quartz monzonite of Elevenmile Canyon and in the Silver Flume(?) Quartz Monzonite indicates that these rocks were emplaced very late in the period of regional deformation or thereafter. Some of the smaller Silver Plume(?) bodies are sharply crosscutting, and their emplacement was locally guided by faults or joints. Forcible intrusion of some of these plutons produced small folds and deflections in foliation in the older rocks near the plutons, all of which indicate emplacement at a shallower crustal level, probably in the mesozone of Buddington (1959). The 1.46-b.y. age of the quartz monzonite of Elevenmile Canyon, the oldest massive quartz monzonite of the Tarryall region, falls within the range of ages determined for Silver Plume rocks elsewhere in the Front Range (Hutchinson and Hedge, 1967).

Zoned, discordant plutons of Pikes Peak age were intruded between 1.1 and 1.0 billion years ago (Hutchinson and Hedge, 1967); the Redskin Granite is a late member of that series (Hawley and others, 1966). The discordant contacts, generally massive structure, and local miarolitic facies of these youngest granitic rocks indicate that the Pikes Peak magma series is posttectonic and probably was emplaced within the epizone (Buddington, 1959).

The part of the geological record represented by the latest Precambrian, all of the Paleozoic and Mesozoic, and the earliest Tertiary are missing in the southern Tarryall region, but adjacent regions permit general extrapolation. The region was eroded to a peneplain before the deposition of the earliest Paleozoic strata (Upper Cambrian Sawatch Quartzite), a relation well exposed just west of Manitou Springs, Colo., 30 miles to the southeast. Tectonically downwarped arkosic strata of late Paleozoic age in the Deckers embayment to the east and correlative arkosic strata in South Park to the west show that the area was tectonically active in late Paleozoic. Possibly some of the faults of Precambrian ancestry were reactivated during this time. Reverse faulting, including the development of the Elkhorn thrust immediately west of the area in the eastern part of South Park (Sawatzky, 1964), occurred during the Laramide uplift of the Front Range.

Another extensive erosion surface was developed in Eocene time, upon which the volcanic rocks of the Oligocene Thirtynine Mile Andesite were deposited. Uplift of the Front Range, as indicated by the elevation and segmentation of the Eocene surface, has been the major event through the remainder of Cenozoic time; no glacial deposits occur in the area, and the balance of the geologic record is preserved in pediment gravels, alluvium, and colluvium of Quaternary age.

CHEMICAL COMPOSITION AND PETROLOGY OF THE PIKES PEAK GRANITE AND ASSOCIATED ROCKS

Because of the association of greisen-type beryllium deposits with the Redskin Granite, documented in Hawley (1969), special chemical and mineralogical analyses were made on the Redskin Granite and other granites of Pike Peak age, and geologic literature was searched for descriptions and data concerning granites with associated greisen deposits. The results of these special studies are given in the following sections of this chapter.

The chemical analyses show that the Redskin Granite and at least some facies of the Pikes Peak Granite are alkalic peraluminous granites characterized by unusual trace-element abundances of elements like tin, lithium, and beryllium and are similar to so-called tin granites recognized elsewhere. In general the granites are also characterized by abnormally high fluorine contents and by iron-rich biotite similar in composition to that found in pegmatite, greisen, and other greisen-bearing granite.

Physical relations show clearly that the Pikes Peak and related rocks were emplaced as liquid melts. More speculatively it is postulated that their crystallization was strongly influenced by content of volatiles, principally water and fluorine, components also important in the origin of the related greisen.

CHEMICAL COMPOSITION

The main rock units of the Pikes Peak magma in the southern Tarryall region are quartz monzonite and granite, which range in SiO_2 content from about 70 to slightly over 75 percent; minor units include granodiorite with about 65 percent SiO_2 and still more basic gabbro.

Although only partially mapped and sampled for this report, the Pikes Peak Granite of the main Pikes Peak batholith is known to range in composition from granodiorite or quartz monzonite to granite (Hutchinson, 1960a; Gotthard Kraus, written commun., 1960; tables 9, 12, this report). On the average it is likely more granitic in composition than most large quartz-bearing batholiths.

PIKES PEAK GRANITE IN THE TARRYALL MOUNTAINS BATHOLITH

The Tarryall Mountains batholith is composed of granite characterized by a generally low content of CaO, by silica greater than 72 percent, by a higher than normal concentration of fluorine (table 11), and locally by higher than normal concentrations of several other trace elements including tin, beryllium, and rubidium (table 17).

Major rock-forming elements.—The coarse subequigranular granite is slightly less siliceous and more calcic than the centrally distributed coarse porphyritic granite as summarized below and shown by the analysis of table 11. The subequigranular facies is of calc-alkalic type, while the coarse porphyritic granite is of alkalic type—terms modified from calc-alkali and alkali of Nockolds (1954).

Range in partial chemical composition (weight percent)

	Coarse subequigranular granite (four analyses)	Coarse porphyritic granite (three analyses)
SiO_2	72.30–74.35	74.38–75.86
CaO	.99– 1.20	.54– .88
Na_2O	3.35– 3.56	3.19– 3.31
K_2O	5.30– 6.00	5.19– 5.27

Trace elements.—The abundance of fluorine in the rock is shown directly in the weight percent analysis (table 11) and indirectly in the normative composition, where it is reflected in normative fluorite (Fr), and in some cases where it is very abundant as normative fluorine.

Because of the method of calculation of the rock norm—which assigns CaO first to fluorite, then to plagioclase—the plagioclase actually found in the rock is more calcic than would be inferred at first glance from the norm, which in some cases indicates pure albite.

In terms of trace elements, the coarse subequigranular Pikes Peak Granite unit is characterized, relative to most granites of comparable bulk composition, by higher amounts of beryllium, cerium group rare earths (cerium plus lanthanum plus neodymium) lead, rubidium, and by a slightly anomalous tin content (table 17). Beryllium is markedly enriched relative to comparable low calcium granitic rocks, and in fact is higher in this unit than in the more siliceous, coarse porphyritic Pikes Peak Granite. Barium and the cerium group rare earths are higher in this unit than in either the Pikes Peak units of the Tarryall Mountains batholith or in any of the Redskin Granite units, and barium is probably slightly higher than in most comparable granite (barium = 840 ppm in low calcium granitic rocks, Turekian and Wedepohl, 1961).

The coarse porphyritic granite is strongly enriched in tin relative to most granites (about 15 ppm vs. 3 ppm), and is likewise somewhat enriched in lithium and rubidium (table 17). It contains less cerium-group rare earths (608 ppm cerium plus lanthanum plus neodymium vs. 729

ppm) and less barium (about 600 ppm vs. 1,000 ppm) than the coarse subequigranular Pikes Peak. It is the most strongly enriched in tin among the varieties of the Pikes Peak Granite in the Tarryall Mountains batholith indicating that not only Pikes Peak derivative rocks, such as the Redskin Granite, are tin granites (Hawley and others, 1966) but also that late facies of the Pikes Peak itself may be strongly enriched in trace elements.

REDSKIN GRANITE

The Redskin Granite of the Redskin stock, China Wall cupola, and Boomer cupola is alkalic granite which shows small but consistent compositional differences among the facies of the unit.

Major rock-forming elements.—Chemically, the granular Redskin Granite is an alkalic granite that is about as siliceous as the coarse porphyritic Pikes Peak Granite. It differs, however, in being slightly more sodic, less potassic and in having a very slightly smaller content of femic elements, as shown by the individual analysis (table 11, 15) and the comparison (in weight percent) below:

	Granular Redskin Granite	Porphyritic Pikes Peak Granite
	(Average of five)	(Average of three)
SiO_2	75.39	75.34
Al_2O_3	12.77	12.58
CaO	.64	.70
K_2O	4.93	5.26
Na_2O	3.78	3.26
FeO	1.02	1.26
Fe_2O_3	.46	.48
MgO	.02	.06
F	.47	.48

The porphyritic and fine-grained facies of the Redskin Granite are both slightly less siliceous and more sodic than the granular facies (table 15), but are similar to it in abundance of femic components and fluorine.

The granite-aplite of the Boomer cupola is a very siliceous rock with low amounts of CaO and femic constituents (table 20). Fluorine is less abundant generally than in the granular, porphyritic, and fine-grained facies of the Redskin Granite. The siliceous nature of the rock is emphasized by the norms which show quartz (q) dominant over either of the next two most abundant normative minerals (ab and or). The abundant muscovite is reflected in the norm by corundum (cor). Dike rocks near the Boomer cupola, as represented by sample 1-1, are like the cupola rock in silica content but are more sodic and less potassic.

Only one granite-aplite from the China Wall cupola has been analyzed chemically; this rock is less silicic and more sodic than the rock of the Boomer cupola (table 16). Comparison of modes of the analyzed specimen with others from the China Wall cupola suggests, however, that the analyzed rock was not as siliceous as other rocks in the cupola, and the close correspondence of average modes of the granite-aplite from the two cupolas may indicate a closer general agreement in chemical composition than indicated by the single chemical analysis.

Granite-aplites from dikes elsewhere in the area are at least locally very siliceous rocks, as shown by analysis of BA-281 (table 16) from a dike cutting the granular phase of the Redskin Granite in the Redskin stock.

The high silica content of dike rocks like samples 1-1 and BA-821 (table 16) is significant genetically. Unlike the cupola rocks where some late-stage metasomatism is indicated by abundant muscovite and late quartz-albite intergrowths, the aplitic to granitic textures of the dike rocks and their sparsity of alteration features indicate little modification of a magmatic composition. In turn this implies that the very high silica content of some of the rock is a magmatic characteristic.

Trace elements.—The porphyritic Redskin Granite is enriched more than any other unit of the Pikes Peak or Redskin Granite in several of the trace elements that belong to the greisen suite, namely lithium, rubidium, and tin (table 18). It also is relatively rich in beryllium, its content being exceeded only by the fine-grained granite of the Redskin stock. The granular rock type is also enriched in rare elements.

SUMMARY OF TRACE ELEMENTS IN THE PIKES PEAK AND REDSKIN GRANITES

In general beryllium, lithium, niobium, lead, rubidium and tin are enriched in the Redskin and Pikes Peak Granites compared with many granites of similar bulk chemical composition as represented, for example, by the low calcium granitic rocks of Turekian and Wedepohl (1961). The abundance of tin, lithium, rubidium and beryllium in the Redskin Granite was previously pointed out (Hawley and others, 1966, p. C144–C146). It was noted that the Redskin particularly is a "tin granite," as defined by Westerveld (1936), the tin granites being similar in bulk composition to their parent rocks but enriched in certain rare elements, specifically, tin, lithium, tungsten, bismuth, copper, cobalt, and uranium. Because of the lack of sensitivity of the analytical methods used, the abundance of tungsten, bismuth, uranium, molybdenum, and zinc are not known in either the Redskin or Pikes Peak, but all these elements are locally enriched in greisens of the area. Copper, another element locally enriched in the greisens and one mentioned by Westerveld, is less abundant in most facies of the Redskin than in comparable granite, but is markedly enriched in granite-aplite of the Boomer cupola.

Another strongly diagnostic element in both the Pikes Peak Granite and Redskin Granite is fluorine, which is present chiefly in fluorite, topaz, biotite and muscovite. Fluorine averages almost one-half weight percent in most facies of both granites. This content is at least five times more than that in most rocks of comparable bulk compo-

TABLE 17.—*Semiquantitative spectrographic analyses of trace-element composition (parts per million) of Pikes Peak Granite, Tarryall Mountains batholith*

[Analysts: N. M. Conklin, J. C. Hamilton, and R. G. Havens. N.D, not determined. Leaders (...) indicate no data]

Sample localities (fig. 18)	Field No.	Laboratory No.	Ag	Ba	Be	Ce	Co	Cr	Cu	Ga	La	Li[1]	Mo	Nb	Nd	Ni	Pb	Rb[1]	Sc	Sn[1]	Sr	Y	Yb	Zr
Coarse subequigranular Pikes Peak Granite																								
1S-------	M1-50	D101303	0	1,500	7	700	0	0	10	50	300	45	0	70	700	0	50	200	7	---	100	100	10	150
2S-------	M2-30	D120158	0	1,500	7	500	0	0	1.5	50	200	35	0	70	70	0	50	230	7	4	100	70	7	300
3S-------	M2-107	D120161	0	1,000	7	200	0	3	3	50	200	40	0	70	70	0	50	250	7	---	100	100	15	150
4S-------	M2-43	D120159	0	1,000	5	300	0	0	1.5	50	150	48	0	50	70	0	50	280	7	5	100	100	10	150
5S-------	M1-6	D120157	0	700	[2]200	500	0	1.5	2	50	200	68	0	70	70	0	50	220	10	4	70	70	10	200
6S-------	M1-58	D101304	0	1,000	7	500	0	0	5	70	200	60	0	70	300	0	100	240	7	---	150	150	15	150
7S-------	M2-98	D120160	0	1,500	5	150	0	0	3	50	100	34	0	50	70	0	50	230	7	6	150	100	10	150
8S-------	M2-81	D101306	0	1,500	7	500	0	0	2	50	200	41	0	70	300	0	50	190	7	---	150	100	10	150
9S-------	TR-74	H3247	0	700	7	700	0	1.5	3	30	300	N.D.	0	70	300	0	30	---	15	7	70	150	15	300
11S-------	M3-227	D114195	0	700	7	300	0	0	3	50	200	41	0	70	150	0	50	460	7	9	150	150	10	200
12S-------	M3-232	D114196	0	500	3	200	0	0	2	50	100	52	0	50	150	0	50	400	10	12	100	100	10	300
13S-------	M4-179	D114329	0	700	7	200	0	0	2	20	150	42	0	50	0	0	30	480	5	11	70	100	10	200
14S-------	T1-98	D114192	0	700	7	300	0	0	2	70	150	68	0	70	150	0	30	480	7	7	100	100	10	150
Average-----------------			0	1,000	6.4	388	0	.5	3	49	188	48	0	64	184	0	49	305	8	7	108	107	11	196
Medium- to coarse-grained Pikes Peak Granite																								
15S-------	FP-3	D120165	0	700	0	500	0	0	2	50	200	28	0	50	150	0	30	120	7	2	100	100	10	300
16S-------	FP-5	D101307	0	300	5	200	0	0	3	50	70	41	0	50	70	0	50	150	5	---	30	100	10	300
Average-----------------			0	500	2.5	350	0	0	2.5	50	135	35	0	50	110	0	40	135	6	2	65	100	10	300
Coarse porphyritic Pikes Peak Granite																								
17S-------	M2-13	D120155	0	500	5	500	0	0	2	50	200	72	0	150	150	0	70	350	7	15	70	50	7	150
18S-------	M2-36	D101305	0	500	3	200	0	0	3	50	100	99	0	70	70	0	50	280	5	---	70	70	10	150
19S-------	M1-9	D120154	0	1,000	2	700	0	5	3	70	200	68	0	70	150	0	70	300	10	10	150	200	30	200
20S-------	M1-36	D101302	0	700	5	300	0	0	[2]50	50	150	62	0	100	70	0	70	350	7	---	70	150	15	150
21S-------	M4-238	D120156	0	500	5	500	0	0	0	70	150	70	0	70	70	0	50	290	5	20	70	100	15	150
22S-------	TR-96	D114330	0	700	5	200	0	0	2	30	150	66	0	50	0	0	50	700	7	13	70	100	15	200
23S------	M3-156	D100428	0	500	3	200	0	1	2	30	200	100	0	70	0	0	30	860	7	---	70	200	20	200
Average-----------------			0	628	4	371	0	1	2	50	164	77	0	83	73	0	56	447	7	15	81	124	16	171

[1]Quantitative determination.
[2]Not included in average.

sition (Correns, 1956, p. 184; Turekian and Wedepohl, 1961, table 2; and Burnham, 1967, p. 41). Experimental evidence (Burnham, 1967, p. 40–41) suggests that the fluorine content now found in the granite closely approximates the fluorine content of the magma, as partitioning of fluorine strongly favors the melt rather than the aqueous phase. The experimental data and the uniform distribution of fluorine minerals suggest that large portions of Pikes Peak and Redskin magma had a primary fluorine content of about 0.6–0.7 weight percent. Chlorine exists in the comparable rocks in amounts of only about 0.01 to 0.04 percent, but its greater tendency to enter the aqueous phase (Burnham, 1967, p. 40) suggests that it was higher than this in the magma, but perhaps less abundant than fluorine.

The granite-aplite facies of the Redskin Granite shows a particularly interesting relation in trace element chemistry—namely that although it is the host of the most important greisen ore deposits, it contains less of certain greisen component elements (like beryllium, lithium, rubidium, and fluorine) than do other main Redskin facies. The granite-aplite of the Boomer cupola is, however, enriched in sulfophile elements like silver, copper, and zinc relative both to the Redskin-Pikes Peak and to common granites (table 18). Some other granite-aplites, particularly dike rocks, have a vanishingly small trace element content, a fact that probably correlates with their sparse content of trace-element "collector" minerals like biotite.

TABLE 18.—*Comparison of semiquantitative spectrographic analyses of trace elements of greisens in the Redskin Granite, Pikes Peak Granite, and some other granites (in parts per million)*

[Spectrographic sensitivity shown in parentheses; N, no samples above spectrographic limit; Tr, trace]

	Redskin Granite[1]				Pikes Peak Granite[1] (Tarryall Mountains batholith)	Average low-calcium granites[2]
Facies-----	Granular	Porphyritic	Fine-grained	Granite-aplite		
Number of analyses---	15	21	7	5	22	
Elements:						
Ag (1)---	0	0	0	Tr	0	0.037
Be (1)---	6	7	9	5	5	3
Cu (1)---	5	6	4	40	3	10
Li (1)---	90	110	88	50	54	40
Mo (5)---	N	N	Tr	N	N	1.3
Nb (10)--	110	70	70	40	69	21
Pb (10)--	60	40	30	160	50	19
Rb (60)--	712	796	663	473	320	170
Sn (10)--	15	18	14	15	9	3
Zn (200)-	N	N	N	120	N	39

[1]Analysts. N. M. Conklin, J. C. Hamilton, and R. G Havens.
[2]Data from Turekian and Wedepohl (1961).

CHEMICAL COMPOSITION OF BIOTITE IN THE PIKES PEAK AND REDSKIN GRANITES

The very low ratio of MgO to $FeO+Fe_2O_3$ in the bulk analyses of Pikes Peak and Redskin Granites (tables 11, 15) suggests that biotites in these rocks must be very iron rich types, and inference confirmed by the analyses of three pure biotite separates (table 19). One biotite (TR-96) was

TABLE 19.—*Chemical composition of biotite from Pikes Peak, Redskin, and other granites with associated greisen*

[Analyses by V. C. Smith, U.S. Geol. Survey (BA-657, 687, and TR-96); Brown (1956), granite of Mourne Mountains; Jacobson and others (1958, p. 15) Nigerian granite. Tr, trace; leaders (...) indicate not determined]

Biotite from-	Redskin Granite		Pikes Peak Granite	Granite, Mourne Mountains, Ireland	Biotite granite, Liruei, Nigeria
Field No.----	BA-657	BA-687	TR-96	-------	-------
Serial No.---	D101503	D101504	D101505	-------	-------
SiO_2---------	35.37	35.47	34.77	35.40	37.38
Al_2O_3--------	18.06	18.42	18.34	11.82	11.89
Fe_2O_3--------	4.55	7.29	3.27	9.52	4.38
FeO----------	24.93	20.79	25.68	25.09	28.65
MgO----------	.49	.82	.97	.95	.22
CaO----------	.00	.27	.46	Tr	.16
Na_2O---------	.85	1.10	.68	1.54	.39
K_2O---------	9.09	8.69	9.26	9.02	8.78
H_2O+ --------	2.31	2.39	2.03	3.64	1.84
H_2O- --------	.11	.35	.05	.00	.67
TiO_2---------	2.17	2.02	2.15	2.14	1.84
P_2O_5---------	.01	.03	.03	---	---
MnO----------	.66	.77	.55	.67	.41
Cl-----------	.20	.11	.17	---	.09
F------------	2.24	2.68	2.75	---	4.36
S------------	---	---	---	---	.03
Li_2O---------	---	---	---	---	.77
Subtotal--	101.04	101.20	101.16	---	100.94
Less O--	.99	1.15	1.20	---	1.86
Total-----	100.05	100.05	99.96	---	100.08

from the coarse porphyritic Pikes Peak Granite, the other two from the granular (BA-657) and porphyritic (BA-687) Redskin Granites.

The compositions of biotites from Pikes Peak and Redskin Granites fall in a very small area on a triangular diagram of the type used by Foster (1960, fig. 11) in a plot of biotite and other trioctahedral micas (fig. 34). Foster's diagram uses (Mg),(Al^{+3}+Fe^{+3}+Ti^{+4}), and (Fe^{+2}+Mn^{+2}) as corners and shows that the great bulk of naturally occurring trioctahderal micas cluster around a Mg:Fe^{+2} ratio of 1:1. The only values given by Foster that are extremely poor in MgO are micas from pegmatites and greisen.

That the values from the Pikes Peak and Redskin are not completely unique is shown by the inclusion of two other analyses of biotites from granite (table 19; fig. 34). One is from the Mourne Mountains of Ireland (Brown, 1956), the second from Liruei, Nigeria (Jacobson and others, 1958). Like the Pikes Peak and Redskin, both the Mourne Mountains and Nigerian granites have associated greisens. Although the analyses plot closely on the triangular diagram, the Mourne Mountains and Nigerian biotites are much less aluminous than those from the Pikes Peak and Redskin Granites (table 19).

The biotites from the Pikes Peak and Redskin are also characterized by high contents of niobium, tin, and zinc as well as lithium, rubidium, and cesium (table 20). Calculations based on the approximate abundance of biotite in the Pikes Peak and Redskin Granites (about 5 and 3 percent respectively) and the amounts of trace elements in both granite and biotite show that essentially all the tin and lithium of the rocks are in or very intimately associated with biotite, but that niobium and rubidium are largely elsewhere, with rubidium most likely in the feldspar. Beryllium and lead likewise are largely elsewhere in the rocks. The sensitivity of the spectrographic method for zinc (200 ppm) is too low for detection of zinc in the rocks, but calculations based on the amount of zinc in biotite indicates that the Pikes Peak and Redskin Granites contain at least 20 ppm zinc.

PETROLOGIC INTERPRETATION OF THE PIKES PEAK GRANITE AND ASSOCIATED ROCKS

Sharp contacts and other geologic criteria show that the rocks of the Pikes Peak were emplaced as liquid magma; geologic criteria also suggest a late Precambrian emplacement which has been confirmed by radiometric age determinations. The discordant habit of the plutons and the presence of local miarolitic facies are compatible with intrusion at fairly shallow depth.

The main trend in compositional variation known in the series is from granodiorite to alkalic granite. The presence of comagmatic gabbro as well as indirect evidence point, however, to a mafic parent magma. Chief among the indirect lines of evidence is the association of the Pikes Peak batholith with a large positive gravity anomaly (Qureshy, 1958, 1960).

Besides ultimate origin of the Pikes Peak magmas, major petrologic problems of the Pikes Peak-Redskin association include (1) the causes of variation of major and trace elements, (2) zoning of the plutons, (3) origin of the progressively finer-grain size of the intrusives, and (4) the type of relation which exists between the granite and associated ore deposits, particularly the greisens (Hawley, 1969). Field data, mineralogy, and the studies of the artificial granite system by Tuttle, Jahns, Burnham, and others permit some speculations on these problems. It is believed that volatiles such as water and fluorine had a strong influence on the chemical and mineralogic variation and possibly on grain-size variation and zoning.

ORIGIN AND EMPLACEMENT

Textural and structural criteria indicating that the Pikes Peak and Redskin Granites were emplaced as fluid magma are poorly developed planar flow structures of the granites and absence of cataclastic or shear foliations, common granular textures (both equigranular or seriate), local abundance of sharp-walled inclusions, and knife edge contacts of the granite with surrounding older igneous and metamorphic rocks. Compositional evidence for a magmatic origin is the similarity of the composition of the granite to minimum thermal compositions in the artificial granite system (Tuttle and Bowen, 1958, p. 75-80).

The crudely oval shape of the plutons, local inclusion zones suggesting wall rock screens, absence of lateral deformation, and the epizonal nature of the granite suggest in general that granite emplacement was either by cauldron subsidence or by bodily uplift of wallrock segments along ring faults.

SOME ASPECTS OF VARIATION IN THE PIKES PEAK MAGMA

Systematic variations in texture, mineralogy, and trace and bulk element composition are found in rocks of the Pikes Peak magma, providing data equal in importance to field relations in the interpretation of several petrologic problems.

The general variation pattern shows a decrease in grain size, an increase in silica and total alkalies, and a decrease in the components of mafic minerals, along with decreasing age. Muscovite and rare trace elements tend to increase in abundance in the younger members of the Pikes Peak. It is inferred that the major mineralogic and chemical differences between facies of the series reflect reactions between crystal and liquid magma. Minor varia-

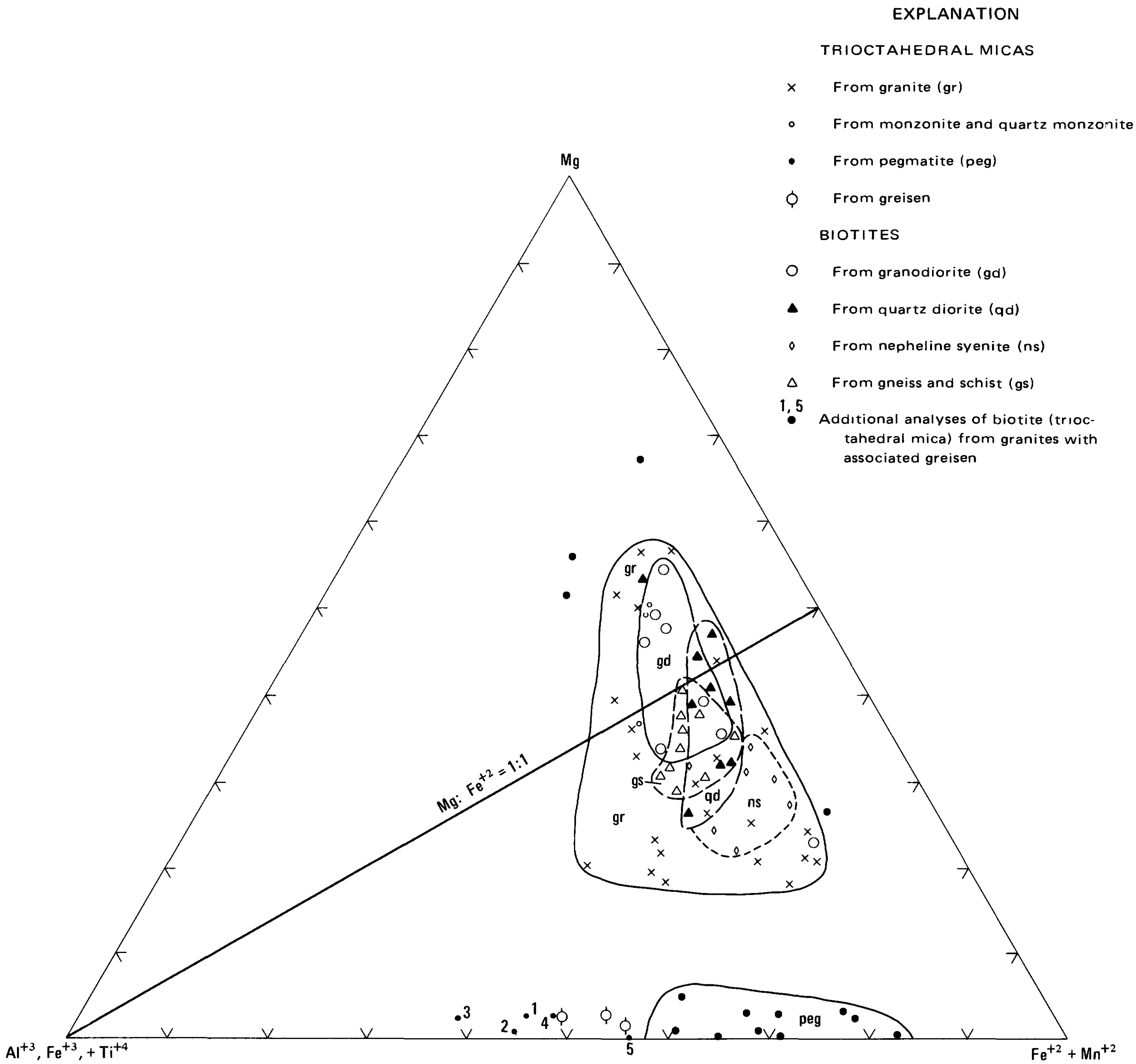


FIGURE 34.—Diagram showing chemical composition and geologic relations of biotite. From Foster (1960) and additional analyses: 1, D101503, Redskin Granite; 2, D101504, Redskin Granite; 3, D101505, Pikes Peak Granite; 4, granite of Mourne Mountains (Brown, 1956, p. 79); 5, granite of Nigeria (Jacobson and others, 1958, p. 15).

TABLE 20.—*Spectrographic analyses (in parts per million) of trace-element composition of biotite*

[Analysts: G. W. Sears, Jr. (semiquantitative), J. C. Hamilton (Sn), Harriet G. Neiman (Li, Rb, Cs). Ag, As, Au, B, Bi, Cd, Ga, Hf, Hg, In, Mo, Ni, Pd, Pt, Re, Sb, Ta, Te, Th, Tl, U, and W looked for but not found]

	Pikes Peak Granite	Redskin Granite	
Field No.	TR-96	BA-657	BA-687
Laboratory No.	D101505	D101503	D101504
Ba	300	150	500
Be	5	7	7
Ce	200	<200	200
Co	7	3	5
Cr	0	1	5
Cs	50	52	79
Cu	1.5	1	2
Ga	<200	<200	<200
La	150	70	150
[1]Li	2,200	2,400	3,900
Nb	500	700	500
Nd	150	70	150
Pb	30	30	50
[1]Rb	2,325	2,150	2,400
Sc	150	50	70
[1]Sn	300	360	600
Sr	10	0	15
V	10	15	15
Y	150	70	100
Yb	<15	<7	<15
Zn	500	700	700
Zr	150	150	300

[1]Quantitative determination.

tions between and within facies seem to correlate with inferred volatile content of the magma.

VARIATION IN THE PIKES PEAK GRANITE AND ASSOCIATED GRANODIORITE

The variation in the Pikes Peak Granite, including the quartz monzonite of the Pikes Peak batholith exposed in the northeastern part of the region and the granodiorite of Wellington Lake, is meaningful when plotted on a silica variation diagram (fig. 35). Al_2O_3, K_2O, and Na_2O increase to a maximum at the composition of quartz monzonite, then decrease in a fairly regular fashion to virtually identical values for the medium- to coarse-grained and porphyritic granites of the Tarryall Mountains batholith. All other common constituents decrease fairly regularly in the series; fluorine, however, increases very slightly throughout.

These variations are common ones in granite series and are directly reflected in the mineralogy. The decrease in calcium is indicated by the plagioclase composition, which changes from andesine in the granodiorite through oligoclase in the quartz monzonite and coarse subequigranular granite to albite in the most siliceous rocks. FeO and Fe_2O_3 generally decrease in the Pikes Peak rocks, but they do not decrease proportionately with MgO.

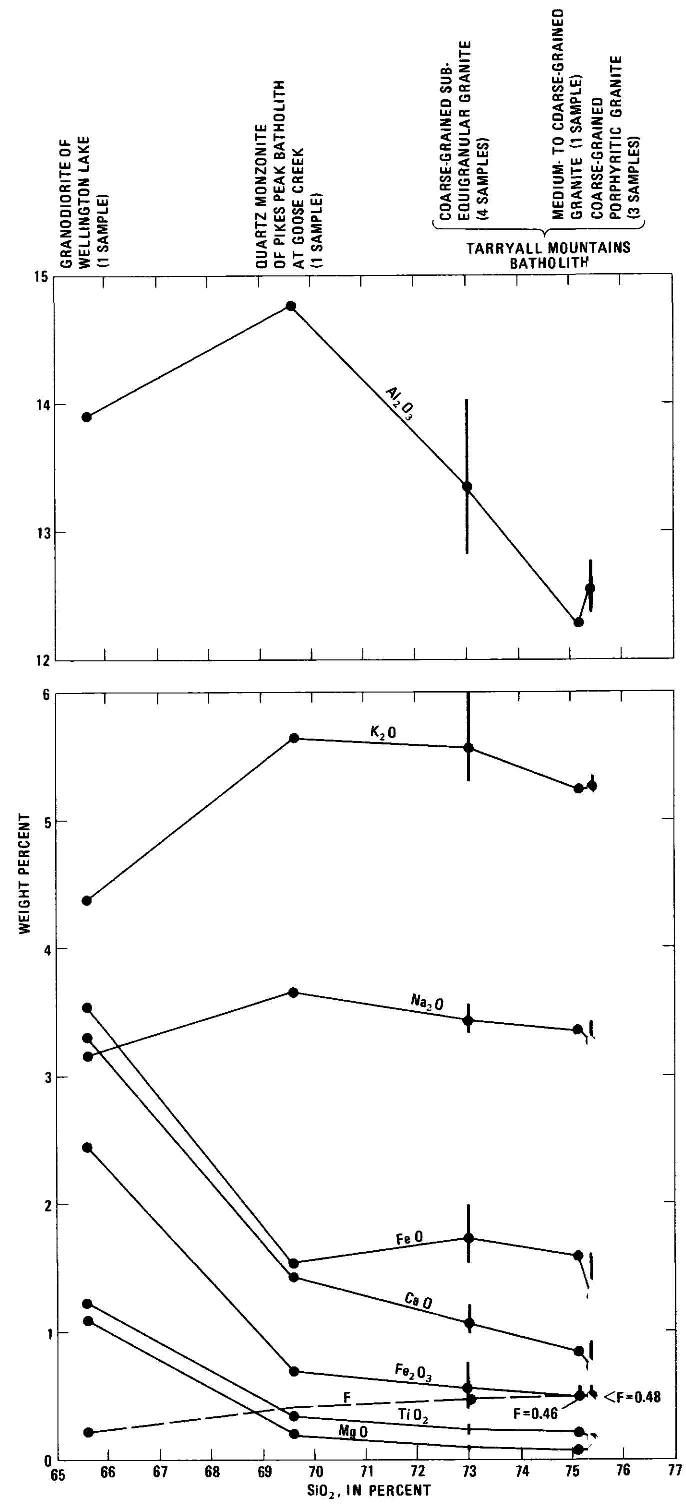


FIGURE 35.—Silica variation diagram, Pikes Peak Granite and associated granodiorite. Vertical line shows range in values; point within the line shows numerical average.

VARIATION IN THE PIKES PEAK GRANITE OF THE TARRYALL MOUNTAINS BATHOLITH AND IN THE REDSKIN GRANITE

The type of variation documented by the preceding section and expecially by figure 35 characterizes the main members of the Pikes Peak magma. However, there is an irregular variation of SiO_2 with age of crystallization in the Pikes Peak Granite of the Tarryall Mountains batholith and in the Redskin Granite; furthermore, SiO_2 varies only slightly, so that plots of the Tarryall Mountains and Redskin rocks on a silica variation diagram are virtually meaningless. Instead, the granites of the Tarryall Mountains batholith, the Redskin stock, and small associated cupolas can be divided into seven main units which can be arranged into a time sequence of crystallization, partly on the basis of crosscutting relations and partly on indirect criteria. These units are named below and for convenience in discussion are referred to by number in the rest of this section.

Pikes Peak and Redskin units in order of decreasing age of crystallization:

1. Coarse-grained subequigranular Pikes Peak Granite,
2. Coarse-grained porphyritic Pikes Peak Granite,
3. Medium- to coarse-grained Pikes Peak Granite,
4. Granular Redskin Granite,
5. Porphyritic Redskin Granite,
6. Fine-grained Redskin Granite,
7. Granite-aplite (Redskin).

Two units, 3 and 7, are of uncertain position in the sequence but unit 3 is certainly older than 4 and unit 7 younger than 4. The term "age of crystallization" is used to emphasize that some of the differences among the rocks, in terms of both apparent age and composition, are not necessarily caused by multiple intrusion but may be due to differences in times of freezing of adjacent portions of magma.

GRAIN SIZE VARIATION

The Pikes Peak and Redskin Granites of the southern Tarryall region show a sequential decrease in grain size. The oldest rock in the local series (unit 1) has a seriate or pegmatitic texture in which the largest crystals are measured in centimeters or inches; the youngest members, fine-grained (6) or granite-aplite (7) varieties of the Redskin, are composed of grains mostly less than 1 mm across. Rocks of intermediate age (units 2–5) are medium grained or have medium-grained matrices.

MINERALOGIC VARIATION

The rocks of the Tarryall Mountains batholith and nearby plutons of Redskin Granite show generally regular variations in ratio of microcline to sodium plagioclase, in biotite-muscovite ratio, and in composition of microcline. A decrease in the microcline perthite-sodium plagioclase ratio is shown graphically in figure 36 and by the average modal analyses of table 21.

The generally regular variation in biotite-muscovite ratio is indicated by ratios computed from the average modal analysis:

	Pikes Peak Granite			Redskin Granite			
				Redskin stock			Boomer cupola
Units............	1	2	3	4	5	6	7
Biotite / Muscovite	26	8	∞	8.5	2	1	0

Individual rocks show a much greater range of course, but virtually all specimens of the Pikes Peak Granite and the granular facies of the Redskin Granite (unit 4) are essentially biotite granites, while the rocks of the younger Redskin facies (units 5, 6, 7) are mainly 2-mica or muscovitic. Accessory minerals vary only slightly; zircon may possibly be slightly more abundant in the four oldest members, but fluorite shows no significant variation, except that it is significantly less in unit 7.

A regular variation is also found in the amount of potassium feldspar host in microcline perthite. The variation is most striking and best demonstrated in the Redskin stock (fig. 37) where the microcline perthite of the granular facies (unit 4) has more visibly exsolved plagioclase than does microcline of the two finer grained facies (5 and 6). Both the fine-grained facies of the stock and the granite-aplite of the Boomer cupola, which is not plotted on figure 37, have negligible amounts of visibly exsolved perthite.

The microcline-perthite of the Pikes Peak Granite of the Tarryall Mountains batholith (units 1 and 2) has a very slightly higher average content of exsolved plagioclase than does the granular facies of the Redskin Granite (about 77 vs. 79 percent potassium feldspar host).

The granites of the Tarryall Mountains batholith and Redskin stock and associated cupolas are, in Tuttle and Bowen's terms (1958, p. 129), subsolvus granites; that is, they contain both potassium-rich and sodium feldspars as discrete crystals. The variation just demonstrated in the ratios and compositions of feldspars shows also that they can be further subdivided, in terms of Tuttle and Bowen's classification, into:

	Granite unit
Group II (Subsolvus):	
(A) ab of K-feldspar 30 percent[1]	....
(B) ab of K-feldspar < 30 and>15 percent	Units 1, 2, 3(?), and 4.
(C) ab of K-feldspar < 15 percent	Units 5, 6, and 7.

At the time of the publication of the Tuttle and Bowen volume (1958), little data was available on Group IIC rocks of undoubted magmatic origin; hence, their interpretation or even existence was in doubt. The Pikes Peak and Redskin Granites are undoubtedly magmatic, and the explanation of the change from IIB to IIC granites seems related in some way to depression of the alkali feldspar solidus onto the solvus. The position of the alkali feldspar solvus has been found to vary with pressure and composition (Luth and Tuttle, 1966); hence, it cannot be used as a temperature-indicator with any great precision. At the least, however, it appears to establish that the lime-poor Redskin facies, which corresponds very closely to the artificial granite system, must have crystallized below a temperature range of about 640°-680°C., and perhaps much below this.

[1]Although Tuttle and Bowen specify weight percent, the specific gravities of albite and orthoclase are so close as to make no appreciable error in substituting volume percent; for example, 77 volume percent potassium feldspar is about 76.4 weight percent.

TABLE 21.—*Summary of average modal composition (volume percent) of Pikes Peak Granite of the Tarryall Mountains batholith and of the Redskin Granite*

[Tr, trace]

Unit	Pikes Peak Granite of Tarryall Mountains batholith			Redskin Granite: Redskin stock			Redskin Granite: Boomer cupola
	1	2	3	4	5	6	7
Quartz	28 5	33.2	31.5	31.9	29.6	29.4	37.1
Sodium plagioclase	14 8	16 6	15.3	23.6	33.0	35.2	32.2
Microcline, variably perthitic	50.3	43.8	46.6	40.6	32.4	29.4	24.0
Biotite	5.5	5.2	5.8	3.4	2.8	2 8	.1
Muscovite	2	.6	0	.4	1.5	2.4	6.0
Fluorite	.4	.6	5	.5	.5	5	.15
Topaz	Tr	.1	0	.1	Tr	Tr	Tr
Zircon	1	.1	.1	.05	Tr	Tr	0
Opaque minerals	.1	Tr	.2	.15	.1	1	.15
Others	Tr	Tr	0	Tr	Tr	Tr	Tr

Analytic bases

Unit	Samples averaged	Thin sections	Points
1	17	33	33,000
2	9	18	18,000
3	2	4	4,000
4	50	100	100,000
5	53	53	53,000
6	15	15	15,000
7	12	12	12,000

The amount of potassium feldspar host in microcline crystals in the Redskin Granite, plotted in figure 37 against total microcline-perthite, shows a consistent general increase in exsolved plagioclase relative to microcline-perthite from the granular (unit 4) to the fine-grained (unit 6) facies. The porphyritic and fine-grained facies of the granite also contain more discrete plagioclase than does the granular facies; thus, a plot against total discrete plagioclase would show the oposite, that exsolved plagioclase varies inversely with discrete plagioclase. Since K_2O is essentially constant in all three facies (fig. 36) and Na_2O is only slightly more abundant in the porphyritic and fine-grained facies, the implication seems clear that the potassium feldspar that crystallized from the magma of the granular facies originally contained more dissolved albite than did the original potassium feldspar of the younger facies. Since this conclusion is based on microscopic work, it can be argued that a considerable amount of sodium plagioclase could still be contained in solid solution in the potassium-feldspar; i.e., it did not have a chance to exsolve in the porphyritic and fine-grained facies. That this is not the case is shown clearly by a comparison of the modal and the normative compositions of the different rocks:

	Unit 4 Granular facies		Unit 5 Porphyritic facies		Unit 6 Fine-grained facies	
	Modal	Normative	Modal	Normative	Modal	Normative
Quartz (Q)	31.9	33.9	29.6	30.9	29.4	30.8
Variably perthitic potassium feldspar (or)	40.6	29.1	32.4	28.5	29.4	29.1
Sodium plagioclase (ab)	23.6	31.8	33.0	35.0	35.2	34.5

The mode of the granular facies (unit 4) shows about 40 percent perthite and 24 percent discrete sodium plagioclase, and the norm shows, respectively, about 29 percent or and 32 percent ab. Approximately 25 percent of the perthite is sodium feldspar (fig. 37) and if a proportionate amount of sodium feldspar is subtracted from the perthite and added to the discrete ab, then there is a very good agreement between the mode and norm. In the fine-grained facies, the mode and norm are in agreement, showing that there is very little sodium feldspar contained in solid solution in the potassium feldspar.

The same test can be applied to the granite-aplite (unit 7) of the Boomer cupola, which has modal and normative compositions as follows:

	Modal	Normative
Quartz (Q)	37.1	40.9
Microcline (or)	24.0	23.5
Sodium plagioclase (ab)	32.2	29.9

CHEMICAL VARIATION

Although the compositions of most facies of the Pikes Peak Granite of the Tarryall Mountains batholith and of the Redskin Granite are very similar, consistent small variations exist. Chemical analyses show that the least silicic and most calcic rock is the coarsest grained and oldest unit—subequigranular Pikes Peak Granite (unit 1), and, in general, that the Redskin Granite is more sodic and aluminous than the Pikes Peak.

A linear plot of composition versus age of crystallization shows a very regular variation only in K_2O and F, both of which decrease in the age sequence, and a rather regular general decrease in total iron oxides and TiO_2 (fig. 38). Na_2O tends to increase generally and ever though there is a decrease in amount from units 5–6, a larger decrease in K_2O gives the effect of continued enrichment in

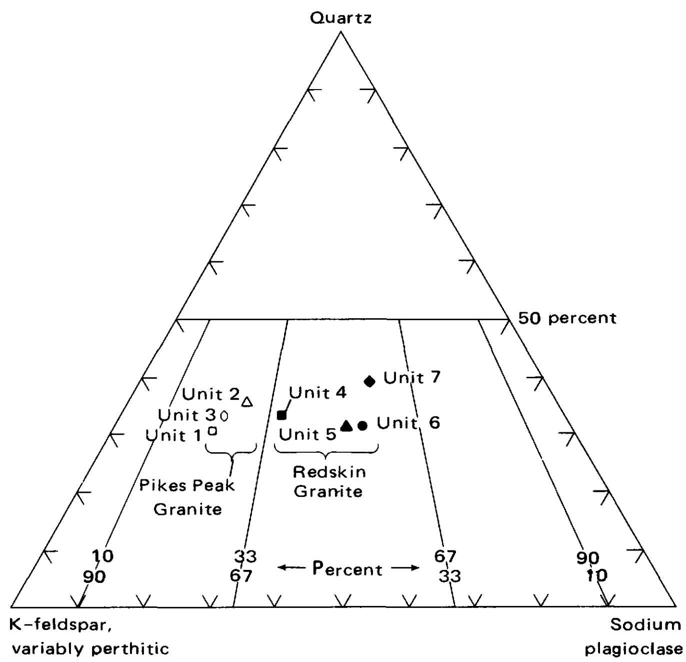


FIGURE 36.—Trend of average modal composition (potassium feldspar-plagioclase-quartz) in the Pikes Peak Granite of the Tarryall Mountains batholith, and in the Redskin Granite.

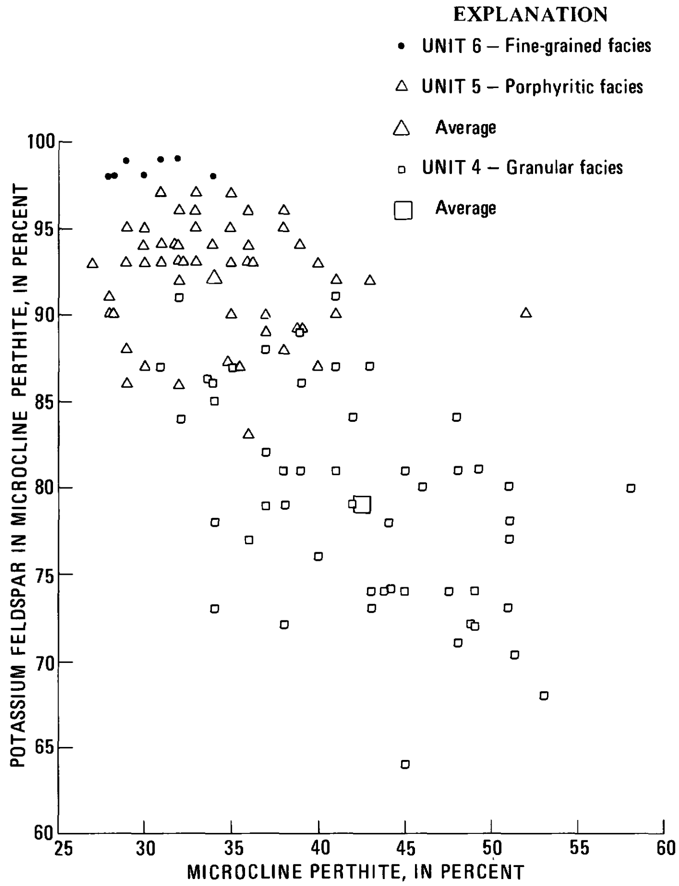


FIGURE 37.—Diagram showing potassium-feldspar content in perthite in the Redskin stock as determined microscopically.

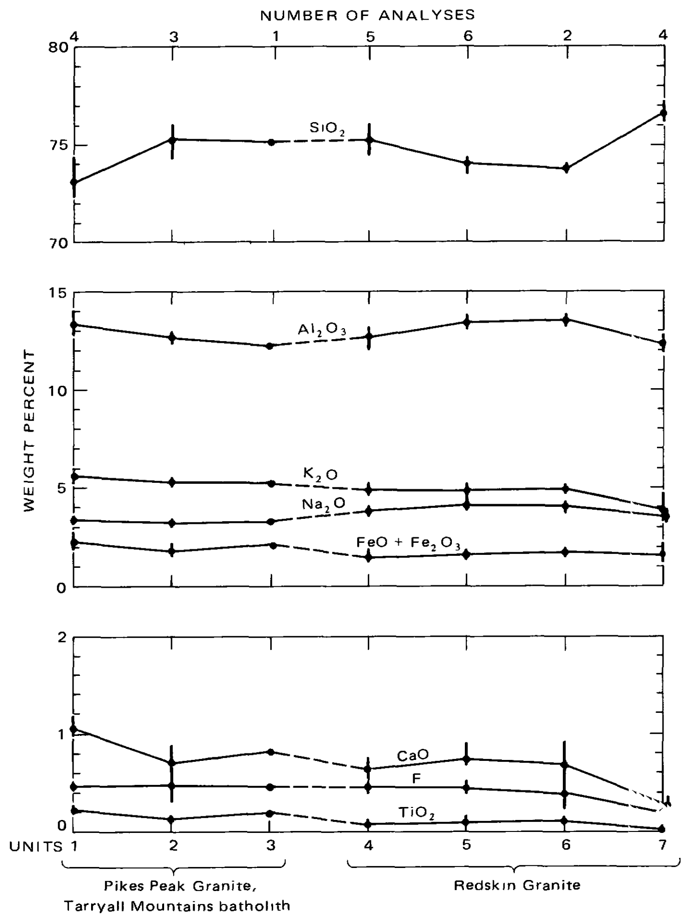


FIGURE 38.—Diagram showing chemical variation in the Pikes Peak and Redskin Granites plotted against age of crystallization. Vertical line shows range of values; point on line shows numerical average.

Na_2O. Silica varies irregularly, increasing to a maximum in the youngest Pikes Peak and oldest Redskin, then decreasing, but reaching a maximum in the Redskin granite-aplite, unit 7,

Regular variation in trace elements in the same series is found in rare earths and yttrium, as well as scandium (fig. 39). Unit 3 represented by only 2 samples—appears anomalously in the greisen-suite trace elements and high in zirconium for a Pikes Peak related granite, but it does fit well on curves for barium, rare earths, and scandium. Disregarding unit 3, it appears that lithium, rubidium, and tin tend to reach a maximum in unit 5, the porphyritic Redskin Granite. Comparing figures 38 and 39, it appears that beryllium varies inversely with SiO_2. This relation is not completely unexpected as Shawe and Bernold (1966) found that beryllium in volcanic rocks tended to vary directly with silica up to about 75 percent, but decreased above this. It should be pointed out that this does not necessarily mean that beryllium was less abundant in the magmas of very high silica content; for example, beryllium could have been tightly complexed by fluorine in these and thus not as readily available for inclusion in rock forming minerals.

SUMMARY

The Pikes Peak and Redskin Granites of the Tarryall Mountains batholith and the Redskin stock and related bodies show a sequential change from coarse- through medium- to fine-grained textures and parallel changes from biotite through two-mica or muscovite type and from relatively potassic to sodic granite. In this local series the average composition of plagioclase changes from oligoclase to sodium albite and the amount of perthitic plagioclase decreases while discrete sodium plagioclase increases.

Chemically the same series shows irregular variation of SiO_2 and Al_2O_3, but a gereral decrease in K_2O, CaO, F, and TiO_2 and a general increase in Na_2O. Of the trace elements only the rare earths and scandium vary regularly in the series; both tend to decrease.

Some regular variation patterns seem to emerge when the Pikes Peak and Redskin Granites are examined separately and with respect to the zonal pattern of the plutons. As an example, lithium, rubidium, and tin increase consistently towards the center of the Tarryall Mountains batholith; thus unit 3, which forms the discontinuous

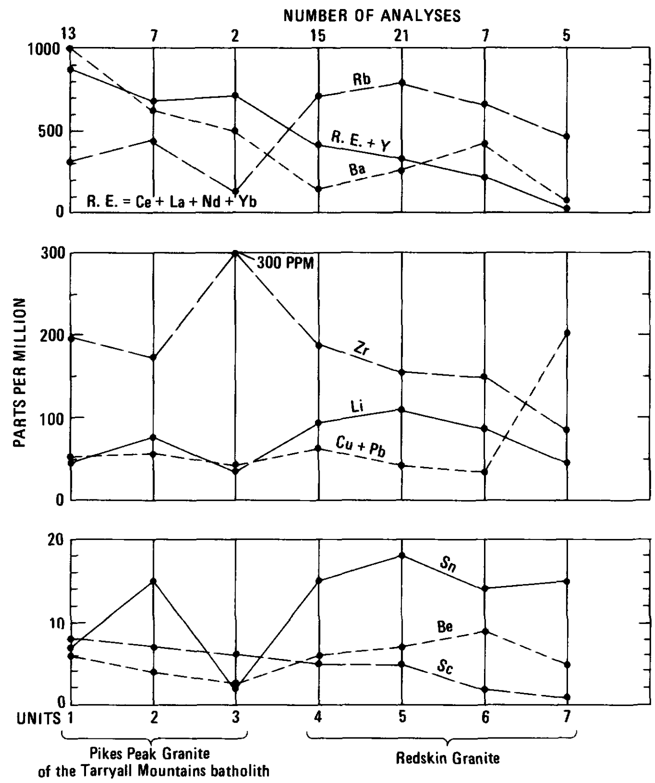


FIGURE 39.—Trace-element variation in the Pikes Peak and Redskin Granites ploted against age of crystallization.

border zone of the intrusive, has the lowest content of these elements and unit 2, coarse-porphyritic granite, the highest. Beryllium does not, however, show the same pattern but is most strongly enriched in the intermediate zone of the batholith (unit 1). In the Redskin stock beryllium increases and SiO_2 decreases going inward but most other elements show little variation or vary irregularly.

CAUSES OF VARIATION IN THE PIKES PEAK AND REDSKIN GRANITES

All facies of the Pikes Peak and Redskin Granites of the area are essentially composed of quartz, a sodium plagioclase, variably perthitic microcline, and biotite and (or) muscovite. Most are granites compositionally. The variations discussed, therefore, are minor ones. Furthermore, the variations found in the Tarryall Mountains batholith and Redskin stock are not well explained by classic modes of magmatic variation such as crystal settling or filter pressing, although some, such as the decreased CaO content of the youngest members of the granite series, undoubtedly reflect the early precipitation and incomplete equilibration of plagioclase in older members of the series.

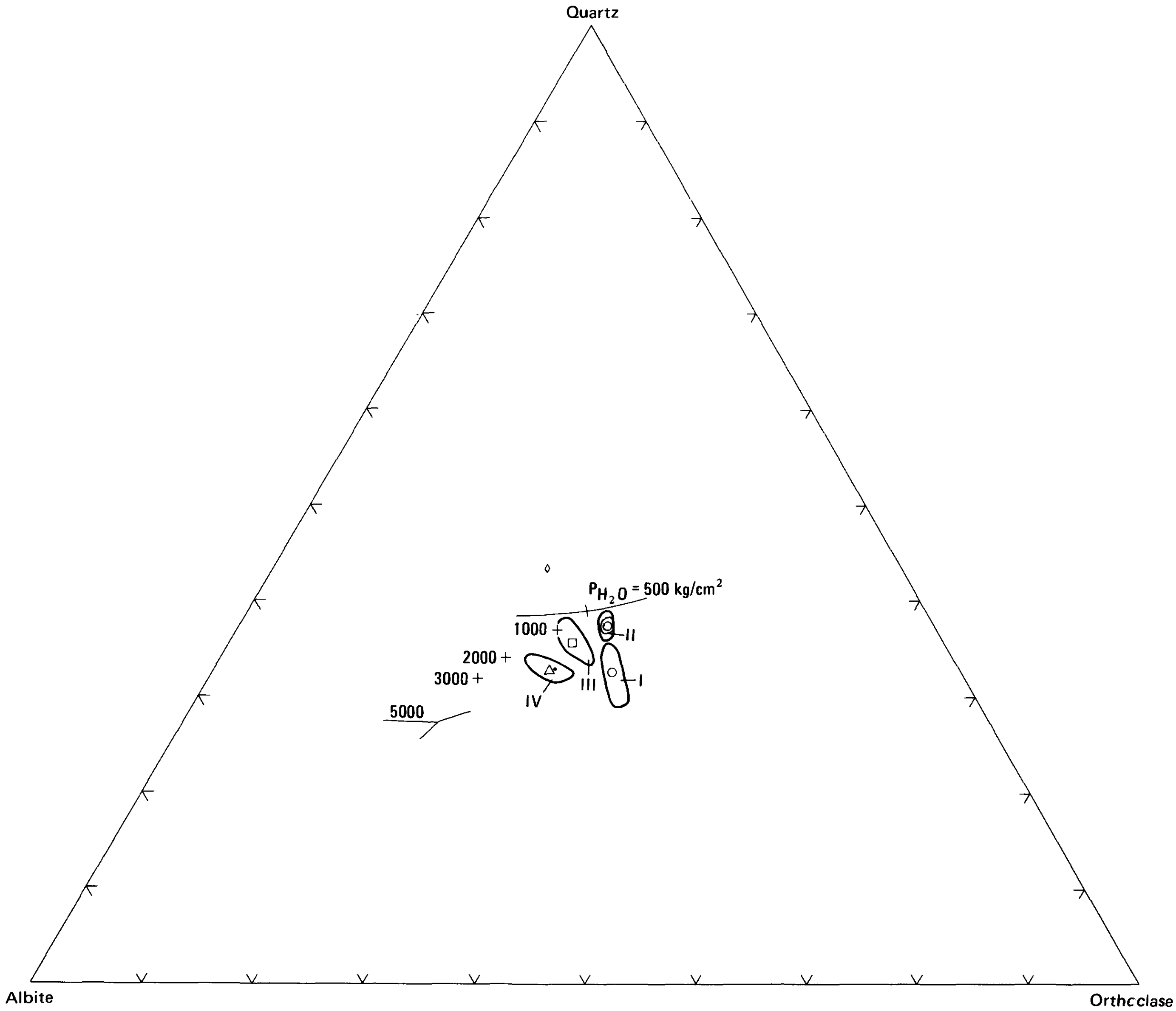
Comparison of the variation found in the Pikes Peak Granite of the Tarryall Mountains batholith and in the Redskin Granite with results of laboratory studies suggests either that water-vapor pressure and vapor transfer were important in determining the small variations in composition found in the local magma series or at least that they accompanied other systematic variations.

Because of their low lime content the compositions of the Pikes Peak Granite in the Tarryall Mountains batholith and Redskin Granite are very close approximations to the artificial granite system studied by Tuttle, by Bowen, and by others, as brought out by a series of triangular diagrams (figs. 40–42).

The composition of Pikes Peak Granite on both quartz- and anorthite-bearing diagrams shown (fig. 40, 41) lies much closer to low water-vapor pressure compositions of artificial granites (Tuttle and Bowen, 1958) than does the composition of the Redskin. This is shown in more detail on a Q–or–ab diagram (fig. 43) where some additional Pikes Peak analyses have been plotted. These additional analyses are from slightly more mafic varieties of the Pikes Peak Granite in the main Pikes Peak batholith and are taken from Hutchinson (1960a) and Gotthard Kraus (written commun., 1960). The Pikes Peak analyses fall in a linear zone which trends towards the quartz pole of the diagram. Perhaps significantly this zone is approximately coincident with the thermal trough that extends from the feldspar sideline to the minimum at 500 kg/cm² PH_2O in the artificial system. Luth, Jahns, and Tuttle (1964) showed that the bulk of granitic rocks (line *G–G′*) lie near this rather low water-vapor pressure trend, but that aplites (line *A–A′*) and pegmatites (line *P–P′*), inferred to form in higher water-vapor pressure systems, are displaced towards more sodic (higher water-vapor pressure) trends, as shown in figure 43. The granular, porphyritic, and fine-grained varieties of the Redskin Granite are more sodic than the Pikes Peak Granite and are in the inferred higher water-vapor pressure region.

The majority of natural granites lie on the feldspar side of the ab–or–Q diagram, and only the pegmatites plotted by Luth, Jahns, and Tuttle (1964) are on the quartz-rich side. They proposed (p. 769) that the siliceous nature of pegmatites could—"reflect selective loss of alkalies from the pegmatite systems during crystallization, most probably by diffusion through aqueous fluids coexisting with the silicate melts and their solid products."

The granite-aplite of the Redskin Granite, like granite pegmatites, also lies on the quartz-rich side of the diagram. In the cupola bodies, however, there is evidence of late stage addition of silica in the micrographic intergrowths of quartz and plagioclase, so it could be proposed that quartz was added rather than alkalies lost. In any event the fact that granite-aplite falls on the quartz-rich side of the diagram shows that an unusual variation mechanism must have operated, since this change involves differentiation across, and climbing out of, the thermal minimum region.



EXPLANATION

I	Compositional range of coarse-grained subequigranular Pikes Peak Granite	IV	Compositional range of porphyritic and fine-grained Redskin Granite
○	Average composition of I granite	•	Average composition of fine-grained type
II	Compositional range of coarse-grained porphyritic Pikes Peak Granite	△	Average composition of porphyritic type
(◎)	Average composition of II granite	◊	Average composition of Redskin Granite, granite-aplite in Boomer cupola
III	Compositional range of granular Redskin Granite	500 bars H_2O / 5000	Thermal minimum compositions in the system SiO_2–$KAlSi_3O_8$–$NaAlSi_3O_8$–H_2O at various water vapor pressures. From Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964)
□	Average composition of III granite		

FIGURE 40.—Compositions of Redskin and Pikes Peak Granites (Q–or–ab) and thermal minimum points in the system SiO_2–$KAlSi_3O_8$–$NaAlSi_3O_8$–H_2O.

ZONING

The Tarryall Mountains batholith, the Redskin stock, and the China Wall cupola are zoned plutons each consisting of partial or concentric shells of granite of slightly different texture and composition. Crosscutting relations between some granite units suggest that zoning resulted

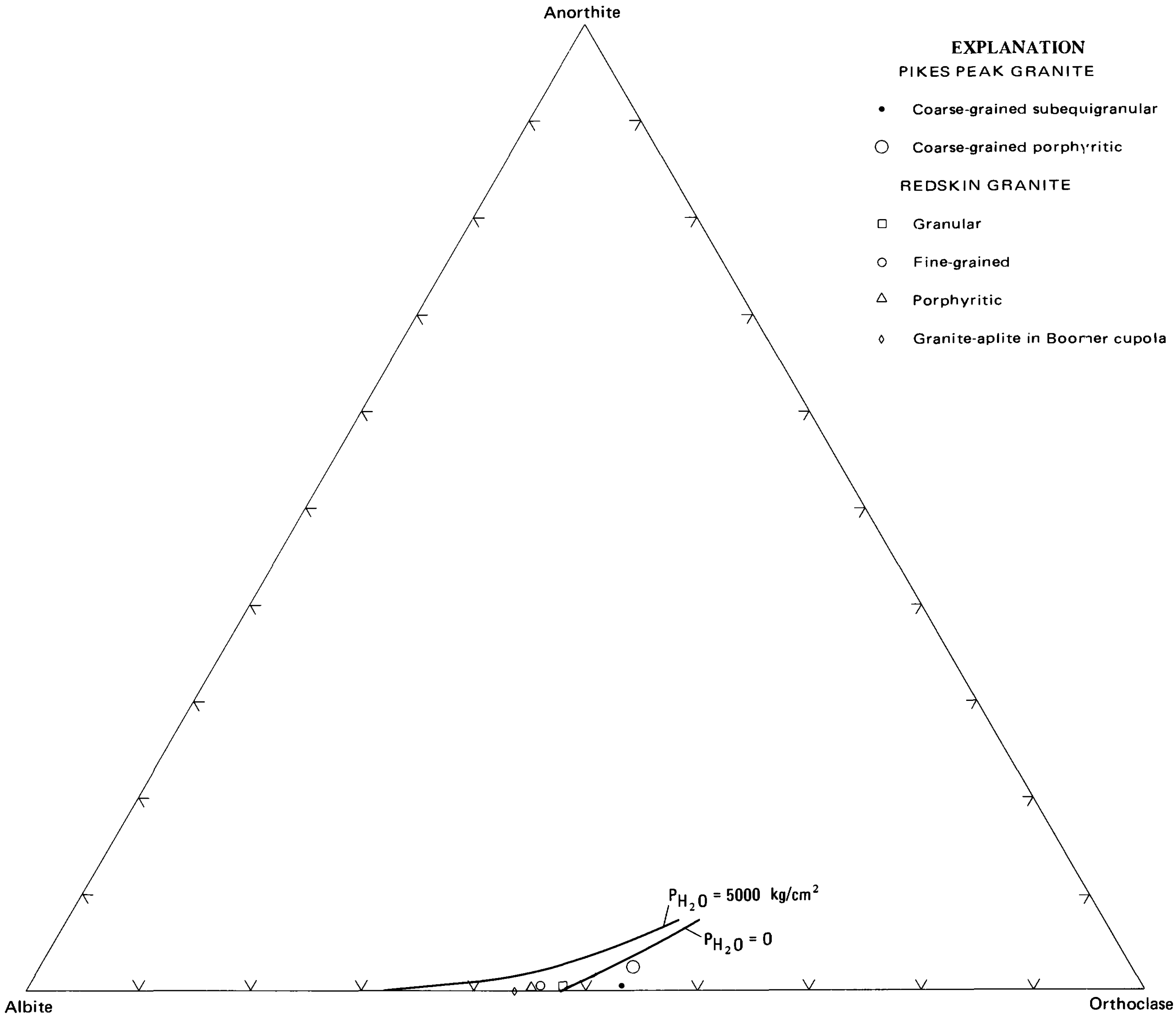


FIGURE 41.—Compositions of Redskin and Pikes Peak Granites (an–or–ab) and orthoclase-plagioclase boundary line in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–$CaAl_2Si_2O_6$–H_2O. Boundaries from Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964).

partly from multiple intrusion, but some of the granite units appear to intergrade so zoning also developed in part virtually in place.

The Redskin stock shows two types of compositional and textural zoning. In the first and general case, the granite in the stock tends to become finer grained, more sodic, and slightly less silicic inward. The outer zone of the stock, composed of the granular type of Redskin Granite, gradually changes inward through a zone of somewhat finer grained seriate porphyritic rock, to the fine-grained core. The seriate porphyritic Redskin Granite of the intermediate zone appears to cut across the outer zone at the northeast edge of the Redskin stock, so the porphyritic facies may be a separate intrusive. In contrast, the porphyritic granite appears to grade inward into the fine-grained central granite. The compositions of fine-grained and porphyritic granites are very similar, and it is proposed that the minor differences in composition and grain size reflect minor differences in crystallization history rather than multiple intrusion. The slightly higher muscovite content of the fine-grained granite and microscopic characteristics such as abundant replacement textures indicate that the inner zone granite crystallized from volatile-enriched magma.

The second, and local, type of zoning in the Redskin stock is found near lobes protruding southward from the

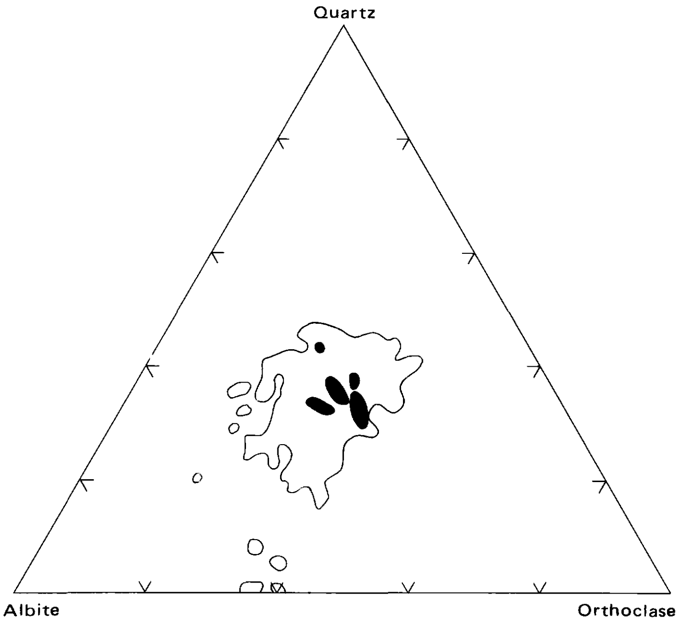


FIGURE 42.—Diagram showing comparison of compositions (Q–or–ab) of Pikes Peak and Redskin Granites with chemically analyzed granite. Lines indicate fields of distribution of normative ab–or–Q in 1,269 analyzed rocks containing 80 percent ab–or–Q (from Tuttle and Bowen, 1958, fig. 63). Solid black areas are compositional areas of Pikes Peak and Redskin Granites (fig. 40).

main body of the stock, as near the Mary Lee mine (Hawley, 1969, p. 32) also in secs. 14 and 23, T. 11 S., R. 72 W. and in dikelike zones originating in the stock. In this type of zoning, the granular Redskin is succeeded upward or outward by slightly finer grained seriate porphyritic granite or by granite-aplite with local pegmatitic facies. This same type of zoning is found in the China Wall cupola, and probably would be found also by deep exploration of the Boomer cupola. Granite-aplite in all marginal occurrences crystallized from extremely volatile-rich magma, as suggested by its content of muscovite, abundant replacement textures, pegmatitic zones, and the occurrence of associated beryllium deposits. Chemically, the granite-aplite is extremely siliceous and bulk compositions resemble those of zoned granitic pegmatites.

Zoning of the Tarryall Mountains batholith is similar in some respects to the zoning of the Redskin stock, but the outermost zone of the batholith is discontinuous and only envelopes the north part of the body. Neglecting the discontinuous outer zone which is heterogeneous and contains rocks strikingly like Redskin Granite, the pattern is a decrease in grain size, and an increase in muscovite content and porphyritic nature inward. In both the Redskin stock and the Tarryall Mountains batholith, the more muscovitic interior rocks are more sodic than the outer granite.

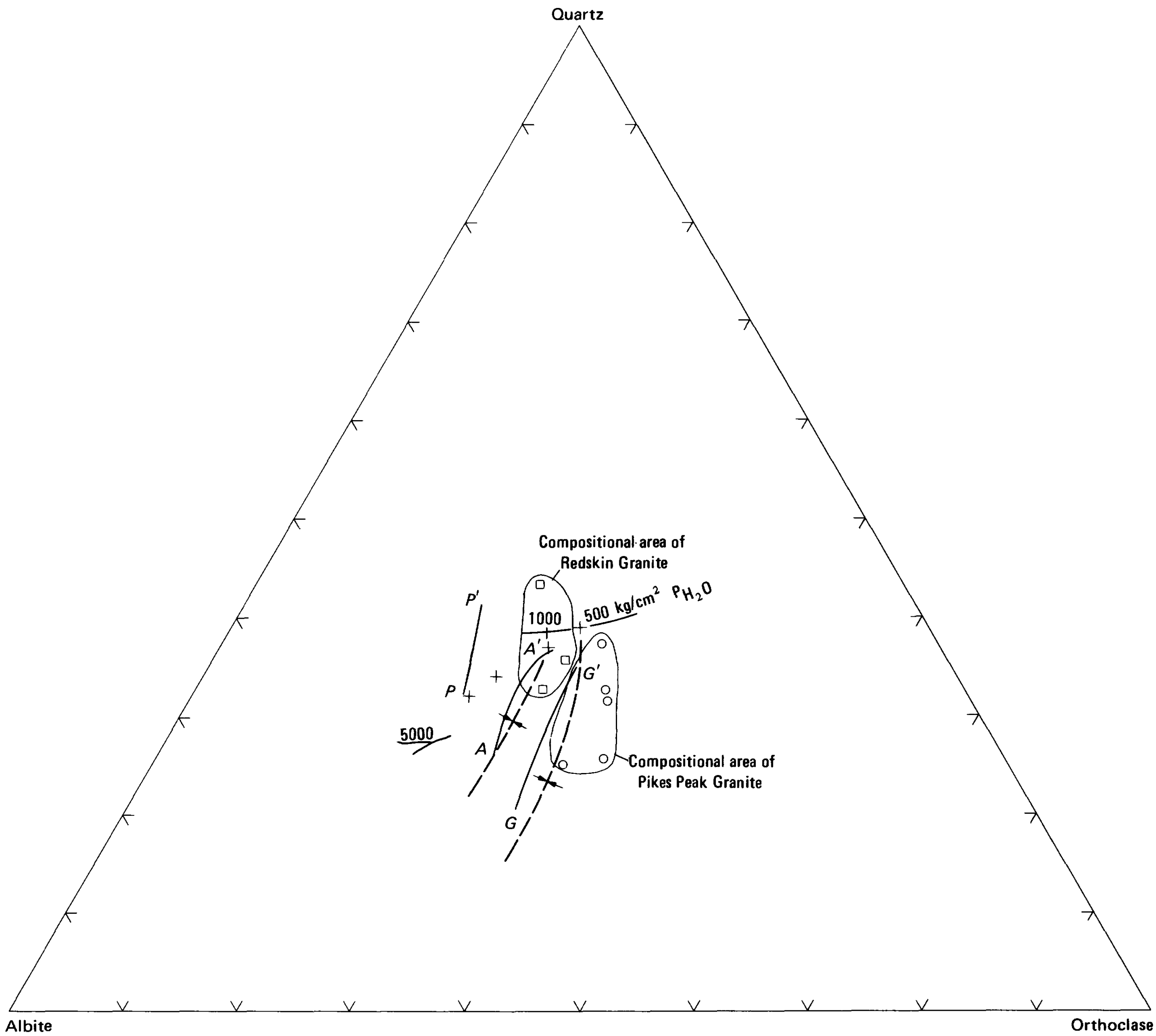
Large dikelike zones of the coarse porphyritic Pikes Peak Granite locally cut the outer coarse granite in the Tarryall Mountains batholith, but at most places the contact between the two rocks is gradational and difficult to define. Tentatively both the coarse subequigranular and coarse porphyritic granites are regarded as being emplaced at the same time, local crosscutting relations being explained by the inner portion of magma crystallizing more slowly and locally injecting the coarse subequigranular granite after its solidification. The mineralogic and chemical differences between the two facies are consistent with a higher volatile content in the inner zone magma.

In general the zoning patterns of the plutons are compatible with either one of two hypothetical types of volatile migration. The dominant pattern of the Redskin stock and Tarryall Mountains batholith is, like zoning explained by Vance (1961), caused by the inward accumulation of volatiles resulting from the more rapid crystallization of outer zone rocks. The local pattern of the China Wall cupola and other cupola-like bodies probably reflects upward volatile movement either by diffusion (Kennedy, 1955) or by actual movement of volatiles as a separate phase (Burnham, 1967).

ZONING AND VARIATION IN SOME OTHER GRANITE SERIES

Cornish plutons described by Exley (1959) and others are similar to the Redskin stock in chemical composition, mineralogy, and zoning; data from these bodies tend to confirm the concept of general but local accumulation of volatiles in pluton cupolas. Granite bodies described from Cornwall by Richardson (1923), Ghosh (1927, 1934), and Exley (1959 and 1961) are zoned and show increasingly finer grained and more muscovitic rocks in the central parts of plutons. For example, the Carnmenellis pluton described by Ghosh (1934) contains three main facies whose normative compositions fall about on the line of the normative compositions of samples from the Redskin stock (fig. 44). The oldest and coarsest grained facies is much more potassic and silicic than the Pikes Peak and Redskin Granites but the younger, finer grained, and more centrally located facies have normative compositions that are very similar to the granular and porphyritic facies of the Redskin stock. Modal and partial chemical analyses of rocks from the St. Austell pluton (Richardson, 1923; Exley, 1959) suggest that normative compositions of these rocks would fall on a nearby subparallel line, where the younger, finer grained, and more centrally located rocks are more sodic and less silicic than the older, coarser-grained rocks of the outer zones.

Other granite bodies show somewhat similar compositional or textural trends, although in many cases the published data are insufficient to show a correlation in more than one or two characters. The granites of the Mourne Mountains, Ireland, show a coarse- to fine-



EXPLANATION

Thermal minimum compositions in the system SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-H_2O at various water vapor pressures. From Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964)

G——G Approximate axis of area containing most granite compositions

P——P' Approximate axis of area containing pegmatite compositions

A——A' Approximate axis of area containing aplite compositions

A 500 A', 1000 Thermal minimum compositions in artificial granite system at 500 and at 1,000 kg/cm^2 water pressure — Dashed axial trough is the trough leading to the feldspar sideline. From Tuttle and Bowen (1958)

○ Compositions of Pikes Peak Granite

□ Compositions of Redskin Granite

FIGURE 43.—Comparison of compositions of Pikes Peak and Redskin Granites with granite, pegmatite, and aplite of Luth, Jahns, and Tuttle (1964).

grained sequence and change from biotite-hornblende to biotite granite (Richey, 1927). The almost circular granite pluton of northern Arran has a coarse-grained outerpart and crosscutting inner zone (Tyrrell, 1928). Although both facies are miarolitic, Flett (1942) noted that the inner fine-grained zone is characterized by greisen veins. In this country, the granite of the Llano region, Texas (Hutchinson, 1960d) is similar in age and composition to the Pikes Peak. Keppel (1940) described decreasing grain size inward in the Llano plutons, and data reported by Goldich (1941) support a general increase in Na_2O in younger fine-grained rocks of the Llano region. The Precambrian Lawler Peak Granite of Arizona has a sequence of coarse-grained biotite-muscovite granite, muscovite granite (locally berylliferous), and aplite-pegmatite (Anderson and others, 1955, p. 18–21). Although the Lawler Peak pluton is partly covered by younger rocks, the muscovitic facies seems to have a general central relation in the body. Grain-size decrease has been reported in a sequence of granite of the Australian tin province (Blanchard, 1947, p. 267–268), and in the sequential association of coarse-grained granite, medium-grained alaskite and aplite of the Ackeley batholith, Newfoundland (White, 1940, p. 969–973).

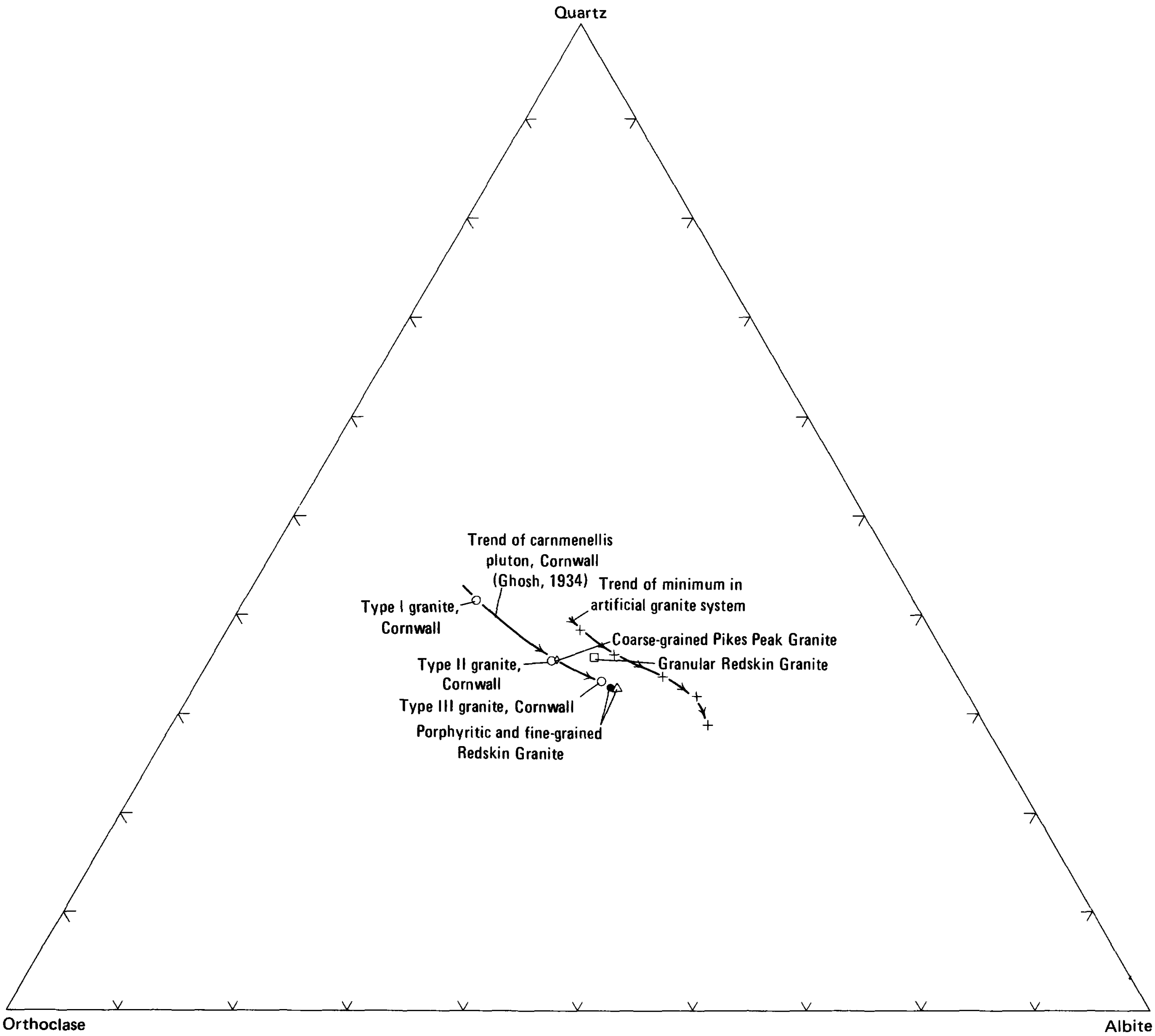


FIGURE 44.—Comparison of normative compositions (Q–or–ab) of the Pikes Peak and Redskin Granites and the granite from the Carnmenellis pluton, Cornwall.

These data indicate that the zoning and crystallization sequences similar to the Pikes Peak and Redskin Granites are fairly common and may, in fact, be characteristic of tin and beryllium-bearing granites.

ORIGIN OF FINE-GRAINED GRANITE

The most obvious variation in the Pikes Peak Granite of the Tarryall Mountains batholith and the Redskin Granite is the sequential decrease in grain size. Grain size in igneous rocks is determined by several factors which certainly include the rate of crystallization, diffusion rates, and perhaps others such as the rate of formation of crystal nuclei. Viscosity is important because of its influence on diffusion rates (Bowen, 1921, p. 316–317); time is also significant because it determines the effective radius of diffusion. Although many problems involving grain size, such as the fine-grained nature of chilled igneous borders, are answered by common sense, others are not. For example, Jahns (1955, p. 1087–1089) pointed out that giant crystals in pegmatite probably formed rapidly and not slowly as formerly supposed. Since then this view has been confirmed by experiments (Jahns and Burnham, 1958, 1962) which indicated that the giant crystals grew rapidly in a fluid of low viscosity because of high diffusion rates. The grain-size relations observed in the Pikes Peak and Redskin Granites and described elsewhere are likewise not explained simply. Although fine-grained facies locally border the plutons, most contacts show no evidence of chilling, and more important neither the local fine-grained border facies nor similar interior facies are of quenched composition. In general, they are unusual rocks whose chemistry and mineralogy suggest late crystallization from volatile-rich magma.

The most important aspect of the variation in grain size in the southern Tarryall region is its serial or gradual nature. This gradual nature suggests that, whatever its cause, the decreased grain size resulted from a serial cause, not from a catastrophic one. This is an important point because, in general, catastrophic type hypotheses have been preferred to explain the crystallization of fine-grained granites, and particularly of aplites. Thus, a commonly accepted view of the origin of fine-grained (aplitic) rocks associated with granites invokes rapid crystallization after emplacement and loss of volatiles (Emmons, 1940, p. 5–8; Vance, 1961, p. 1726). One variation of this hypothesis has been outlined in some detail by White (1940, p. 973 and 975):

"During the last stages of crystallization. . .the residual liquid became much enriched in the volatile constituents, with a resultant rapid increase in the internal vapor pressure. When the pressure of the overlying load was finally equalled. . .a boiling off. . .of the volatile components was the natural result. . .as soon as the boiling process became important, the *rate* of crystallization increased because removal of heat by escaping super-heated volatiles was *added* to normal removal of heat by conduction through the wall rock. The increased rate of precipitation resulted in a fine-grained rock—an aplite with a miarolitic texture due to entrapped gases."

Rapid or quenched crystallization was also postulated by Jahns and Tuttle (1963) who proposed three mechanisms for the formation of igneous aplites, namely: (1) temperature quenching or chilling, (2) pressure release quenching, and (3) compositional quenching. Pressure release quenching is essentially the mechanism proposed by Emmons (1940) and Vance (1961), and was believed by Jahns and Tuttle to account for the formation of most granitic aplites. Essentially it involves loss of volatiles caused by faulting or other mechanisms of pressure relief, and consequent shift of the solidus of the granite. Compositional quenching was proposed specifically to account for the formation of banded sodic aplite and giant-textured potassic pegmatite, and involves resurgent boiling and separation of the potassium feldspar into the gas phase, with nearly simultaneous crystallization of albite-rich aplite from coexisting silicate melt (see also Jahns and Burnham, 1958, 1962).

Although the origin of the fine-grained rocks of the Pikes Peak and Redskin Granites is still highly problematical, the conclusion seems inescapable that in many granite series, especially the tin-bearing types, increasingly fine-grained granites crystallized from increasingly volatile-rich magma. This judgement was anticipated by Exley (1959, 1961) who advocated a high volatile content for the melts that gave rise to the centrally located fine-grained granite in Cornish plutons. Exley (1959, p. 206) proposed that the late rocks were fine grained because of the tendency of abundant volatiles to shrink the temperature interval of crystallization, with "the result being analogous to supercooling".

Either of two hypotheses appears to explain at least in part the serial nature of the grain size change observed in the southern Tarryall region. One hypothesis is fairly simple and assumes that volatiles and grain size vary inversely because of the mechanism proposed by White (1940)—that is, that boiling off of excess volatiles caused rapid crystallization. Under this hypothesis, each facies in the sequence is assumed to have had a slightly higher volatile content than the preceding one, with rapidity of crystallization varying directly with volatiles. In effect, this combines a catastrophic type hypothesis with a gradual or serial variation volatile content.

Although straightforward, the boiling hypothesis does not appear to explain either the regular crystallization sequence of individual rock units or the age relations among the units. Except in aplitic varieties of the granite-aplite and aplite-pegmatite, microscopic textures suggest early crystallization of one or both feldspars, followed by quartz and more feldspar. Crystals of both feldspars are dominantly at least subhedral and some quartz crystals are subhedral to euhedral suggesting that most crystals had an opportunity to grow in contact with magma: they were not quenched.

The second hypothesis suggests that the regular decrease in grain size reflects a gradual increase in viscosity caused by a complex relation of bulk and volatile element composition and hence temperature of crystallization. The basis for this hypothesis can be visualized by plotting compositions of Pikes Peak and Redskin Granites on sections through the thermal minima at different water-vapor pressures (fig. 45) (Tuttle and Bowen, 1958, figs. 22, 23). Tuttle and Bowen (1958, p. 76–77) pointed out that the thermal deep would be a viscosity maximum, and this fact alone seems to account for some development of porphyritic texture—that is, if crystallization is isobaric and takes place with decreasing temperature, the early formed feldspar crystallizes in a much less viscous magma than does feldspar from magma approaching or on the quartz-feldspar join. In the diagram, the range of composition of the coarse subequigranular Pikes Peak Granite is plotted on the 500 kg/cm² curve, and the granular Redskin Granite on the 1,000 kg/cm² curve. It can be seen that the granular Redskin Granite has much more of a thermal minimum composition than does the coarse-grained facies of the Pikes Peak Granite, and if differences in bulk composition already leading to more difficult crystallization of the Redskin were enhanced by lower temperatures of crystallization caused by greater volatile content, a considerably finer grained rock might result.

A third hypothesis, that volatiles themselves increase viscosity, appears untenable but does offer another approach to the problem. The viscosity of a partly bonded liquid, such as a magma, is influenced chiefly by two factors, temperature and the degree of association or bonding. Decrease in temperature or increase in association tends to increase viscosity and to slow diffusion rates, while increase in temperature or decrease in association causes the converse. Acid magmas in general tend to be viscous because of the high silicon to oxygen ratio and the consequent sharing of oxygen atoms by adjacent silicate groups (Ringwood, 1955), and as pointed out earlier, granitic melts of near thermal minimum composition tend to be viscous because of their low freezing range. Volatile components such as OH and F tend to decrease viscosity because of the disruption of Si-O bonds in the melt (Buerger, 1948), but since volatiles also reduce the freezing temperature viscosity will also tend to increase. The net change in viscosity will thus be a function of temperature of crystallization and bond disruption—both factors being strongly influenced by volatiles.

The most closely applicable experimental evidence (Shaw, 1963) suggests that the disruptive effect of volatiles exceeds the temperature effect, and viscosity of a magma with a thermal minimum composition will tend to decrease with increasing volatiles. This is shown by figure 46 which is Shaw's figure 5—a diagram extrapolated from his results on the obsidian-H_2O system—on which is superposed the data on the ternary minimum from Tuttle and Bowen (1958) and Luth, Jahns, and Tuttle (1964).

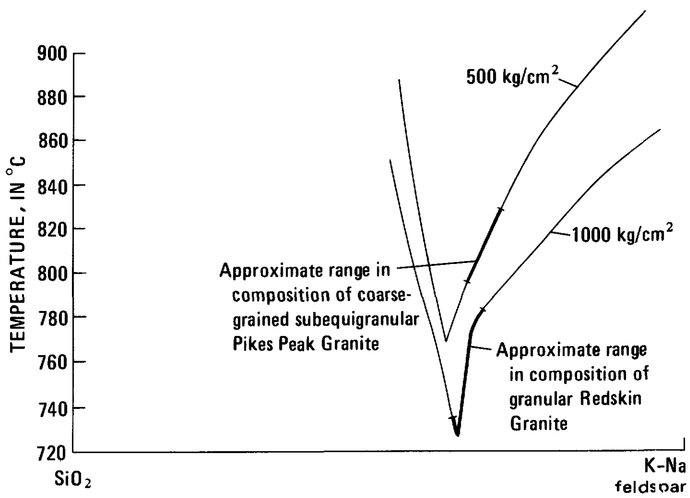


FIGURE 45.—Sections through thermal minimum compositions of granite at 500 kg/cm² and 1,000 kg/cm² water pressure. From Tuttle and Bowen (1958, figs. 22, 23).

RELATION OF GRANITES TO ORE DEPOSITS

The Pikes Peak and Redskin Granites have associated ore deposites of several types, including pegmatites (Haynes, 1965), greisens (Hawley, 1969) and veins rich in fluorite or barite. Most of the deposits are small, but some have been productive, and they are important genetically as a characteristic part of the Pikes Peak association.

The ore deposits in or near granite bodies of the area are linked to the granite first by spatial association, but also by the abnormal trace element content of several granite facies and by the similarity between the trace element suite of the granite and the composition of the associated ores. The Pikes Peak Granite and associated igneous rocks have long been known to contain local concentrations of rare tin and beryllium minerals (Cross and Hillebrand, 1885). Further evidence of a link between granite and ores is found particularly in the Boomer and some other cupola masses where there has been a strong tendency to form quartz-albite-muscovite granite near the greisens. The association of greisens with cupola-granites has been noted elsewhere, as in the Soviet Union (Ginsberg, 1959; Beus and Sitkin, 1959; and Zabolotnaya and Novikova, 1959), and in the Erzgebirge (Stemprok, 1960).

Although the nature of the relation between ore deposits and granite is speculative, it is probably related to the volatile-rich nature of the granite. Specifically, it is proposed that the greisens and beryllium deposits together with the metasomatic modifications of the later granites,

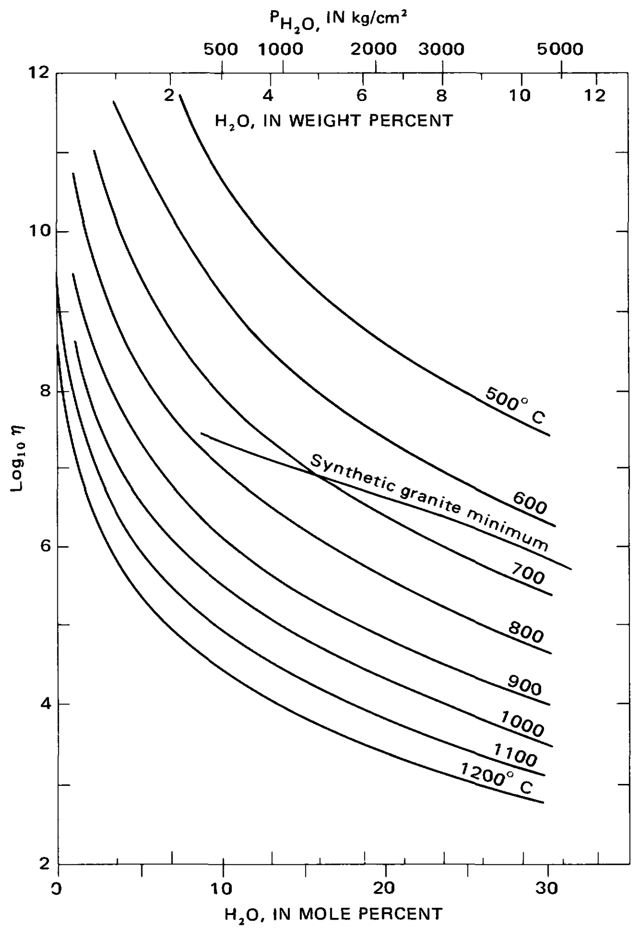


FIGURE 46.—Generalized graph of $\log_{10}\eta$ versus composition for framework silicate-H_2O systems, showing synthetic granite minimum from 500 to 5,000 kg/cm². η, coefficient of viscosity (gm/cm sec). From Shaw (1963), Tuttle and Bowen (1958), and Luth, Jahns, and Tuttle (1964).

the local miarolitic zones observed in aplites and pegmatites, and the fluorite vein deposits associated with the granites, represent the culmination of a trend toward volatile-rich magmas, and, in effect, are the final products of the crystallization of such magmas.

As shown in Hawley (1969) the greisen deposits, especially the beryllium-bearing types, have an especially close spatial association with the Redskin Granite. The beryllium-bearing greisens are in or at the contacts of certain facies of the granite; those in the cupolalike bodies are in granite with noticeable late stage metasomatic modifications.

Hypothetically the beryllium-bearing greisens are considered to be directly related to the crystallization of volatile-rich magmas, and although a detailed description of their origin is not justified here, three related problems are considered. One problem involves continuity (miscibility) of the magma and residual hydrothermal solutions. The second and third are considered together; namely, the state of the residual fluid, and the nature of reactions which can be expected to take place between the cooling fluid and the wall rocks (albitization, greisenization, and metal deposition).

It is concluded that, notwithstanding certain theoretical objections, a hydrothermal fluid did separate continuously from the magma during the late stages of cooling, probably because of high content of fluorine in the magma. It is also concluded that the critical or supercritical state of the fluid was not of major importance, but that greisenization and metal deposition would be favored by a more liquidlike state of the fluid characteristic of decreasing temperatures.

SEPARATION OF HYDROTHERMAL FLUIDS FROM MAGMA

The problem of separation of hydrothermal fluids from magma has been discussed by Tuttle and Bowen (1958, p. 84–89) and more recently by Burnham (1967, p. 37–43, 48–49). Tuttle and Bowen pointed out that if alkalies are at least equal to alumina in terms of the proportions necessary to form feldspar, there should be a continuous gradation from melt to solution in the granite system, but that a discontinuity may exist if there is excess alumina. As criteria for the relative abundance of alkalies versus alumina they proposed using the presence of normative metasilicate or acmite for excess alkalies, and normative corundum for excess alumina; they also noted that the results may not be directly applicable to a complex magma (Tuttle and Bowen, 1958, p. 89):

"This restriction may not apply to a complex system such as a granite magma in which many volatiles in addition to water are concentrated. Such a system concentrating lithia, carbon dioxide, sulfur, chlorine, fluorine, and many other materials may exhibit a continuous gradation even when alumina is present in excess of that amount required to combine with the alkalies to form feldspar."

Corundum is present in the norms calculated for Pikes Peak and Redskin Granites and thus a discontinuous separation of a residual solution is possible; however, there is no doubt that mineralizers other than water—for example, fluorine—are exceptionally abundant in the Pikes Peak so that a continuous gradation cannot be eliminated from consideration. Furthermore a modified method of norm calculation described here seems to indicate that alumina was essentially balanced by alkalies. Muscovite is represented in the conventional norm by a combination of corundum and orthoclase; in the modified method of calculation used on two analyses of the Redskin Granite, muscovite was allotted as the first normative mineral according to the amount of H_2O+, then the residual K_2O, Al_2O_3, SiO_2, and other components were allotted in normal order. Neither of the norms calculated by this method showed normative corundum; one showed a small amount of normative acmite and the second a trace of normative metasilicate.

Largely on the basis of more recent experimental work, Burnham (1967, p. 37–42) was much more skeptical of a continuous separation of hydrothermal fluids from the magma than were Tuttle and Bowen. Recognizing that muscovite is the main mineral that can, in effect, remove normative corundum, he examined the reaction,

$$3KAlSi_3O_8 + 2H^+ \leftrightarrows KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 2K^+$$

Potassium feldspar Muscovite Quartz

and questioned:

"* * * the extent to which muscovite crystallization and consequent alkali enrichment can proceed before mica ceases to crystallize and alkali feldspar becomes the stable phase." (Burnham, 1967, p. 41). He concluded that the aluminum-consuming reaction would not generally be important because either (1) the geologic conditions favoring high enough water pressures (H+) to drive the equation to the right are too rigorous, or (2) no alkali enrichment could take place if the displacement is caused by loss of K^+.

Nevertheless, the increasing muscovite-biotite and muscovite-orthoclase ratios of the younger granites suggest that the above reaction did go to the right, theoretically fixing any excess alumina in muscovite and possibly permitting the continuous separation of a hydrothermal fluid from the magma.

The influence of fluorine is also of critical importance. The bulk of the Pikes Peak and Redskin rocks studied have fluorine contents similar to fluorite-bearing pegmatites like the Harding, cited by Burnham (1967, p. 40–41). As pointed out earlier, experimentally determined partition ratios suggest that the present fluorine contents of most Redskin and Pikes Peak Granites closely approximate the magmatic abundance of fluorine. This is not believed, however, to be the case for the granite-aplites with associated greisens. These rocks show a depletion of greisen components like fluorine, lithium, and beryllium relative to the main granites. The spatial association of rare element-bearing greisens with these facies seems to demand a local source for the greisens, and we propose that this source was in a fluorine-rich aqueous solution that separated from the magma. Although based only on supposition, it may be that the relatively low crystallization temperatures of the granite-aplites allowed for a different partition ratio of fluorine between magma and solution than that found by Burnham (1967, p. 40–41).

The extremely high fluorine contents found in some other tin-granite bodies is also worthy of mention. The gilbertite granite in the St. Austell pluton, Cornwall, contains an average of approximately 1.5 percent fluorite (Richardson, 1923, p. 554), and hence contains at least approximately 0.75 percent fluorine. Jacobson, MacLeod and Black (1958) reported fluorine contents of 2–3 percent in local masses of Nigerian tin-granite. These are significantly higher than those values recorded elsewhere, but suggest that, locally, very high fluorine contents were developed in tin-granite magmas.

In summary, it is believed that geologic considerations such as the presence of fluorite-rich greisens associated with granites enriched in fluorine, as well as the abundance of muscovite in such granites, may outweigh experimental evidence and indicate that fluorine-rich aqueous solutions did separate continuously from late volatile enriched granite fractions to form the associated greisen ore deposits.

STATE OF THE HYDROTHERMAL FLUID AND GREISENIZATION

It has been generally concluded that critical phenomena are not involved in the late stages of crystallization of complex magmas (Morey, 1922, p. 226), but it has also been believed that extremely high pressures can result during crystallization of hydrous magma. Yoder (1958) pointed out that evidence for extreme pressures was generally not present, and that high pressures need not develop. Necessary conditions for the development of extremely high pressures in a cooling magma are strong, nearly impermeable walls, and the attainment of a univariant condition by the magma at a relatively early stage in its crystallization. But because of the hydrous, complex nature of a granite magma, Yoder (1958, p. 191) did not believe that early attainment of a univariant condition is likely:

"Recent experiments on basalts and granites suggest that the condition of univariancy is met early in the cooling of a relatively dry magma; the principal phases in both these major magma types appear together within a very narrow temperature interval when only several percent of crystals are present. With increasing water content, however, the principal phases appear together within a much larger temperature interval, and the condition of univariancy is probably met only in the final stages of cooling."

Even if critical phenomena are not involved in the separation of hydrothermal solutions, these solutions will undergo changes in properties due to changes in temperature and pressure. In the so-called supercritical region, fluids at relatively high temperatures or relatively low pressures will be characterized by a more diffuse type of aggregation than will solutions at lower temperatures and higher pressures. Because the non-volatile substances tend to have a higher solubility in denser fluids than do the volatile substances, which show the converse relation (Smith, 1953, p. 23, 34), and since the volatile substances tend to be acids and non-volatile substances bases, the intrinsic acid properties of residual solutions will change as a result of changes in temperature and pressure (Korzhinskii, 1957), in addition to changes caused by reaction.

It has been postulated (Beus and Sitkin, 1959, p. 37–40; Ginsberg, 1959, p. 8–9), specifically, that the intrinsic changes in the residual solutions cause a change in the late magmatic reactions, with earlier albitization succeeded by greisenization. The reasoning is that the denser and less volatile sodium would be less soluble in the more diffuse, higher temperature residual solutions than would potassium, and thus sodium would tend to be more easily precipitated (as albite) than the potassium (as muscovite). But with decreasing temperature and increasing liquid-like character of the fluids, the potassium would become relatively more insoluble, and muscovite would form in preference to albite, resulting in a change from albitization to greisenization.

Although there may well be other explanations for the change from albitization to greisenization noted in the rocks of the area, this explanation appears to resolve a conflict existing between experimental data and the mineral associations observed in the rocks. The tendency inferred from the late reactions which took place in the granite of the Boomer cupola seems to have been towards the formation of a quartz-albite-muscovite granite (fig. 28). But the data on the relative stabilities of albite, potassium feldspar, muscovite, and paragonite at about 15,000 psi (Hemley, Meyer, and Richter, 1961) indicate that the formation of such a rock would be unlikely because albite tends to decompose to paragonite (with either decreasing temperature or increasing acidity) *before* potassium feldspar alters to muscovite. The possibility of somewhat different behavior of sodium and potassium under different p-T conditions suggests that there is a region where albite is more stable with respect to hydrolysis than is potassium feldspar. Another possibility, of course, is that the relative stabilities are altered by components not present in the experimental systems. For example, the white mica of the granites is not an ideal muscovite but is an iron-rich muscovite, which would very likely have stability relations different from those of pure muscovite.

Regardless of the relative stability of potassium feldspar and albite with respect to hydrolysis, the general stability relations of potassium feldspar and muscovite, outlined by Hemley (1959), seem to be directly applicable to the case where secondary muscovite replaces potassium feldspar. Such a deuteric phenomenon was observed in most of the younger granites and extensively in the more locally developed greisens. At a given temperature and K^+/H^+ ratio potassium feldspar and muscovite may be in equilibrium, but with either declining temperature or a relatively higher H^+ content of the coeisting fluid, the feldspar will become unstable. In general the tendency for alteration increases with decreasing temperature, although at very low temperatures the slowness of the reaction rates may conceal this tendency. This type of alteration tends to deplete the hydrogen ion concentration of the coexisting fluid, and it seems likely that in greisenization, where all the feldspars are unstable, the reduction in acidity caused by reactions will be reflected in metal transport and precipitation. Thus the extent of alteration would be reflected in the amount of associated ore deposits.

SUMMARY

Close spatial and chemical ties indicate a direct genetic relation between certain facies of the Redskin Granite and associated greisen. Hypothetically the greisen deposits are believed to have formed from a dense, fluorine-rich fluid which separated continuously from magma at a late stage of crystallization. As the solution cooled and reacted with wall rocks, albitization yielded to greisenization with attendant metal deposition.

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CECIL D. ANDRUS, *Secretary*

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