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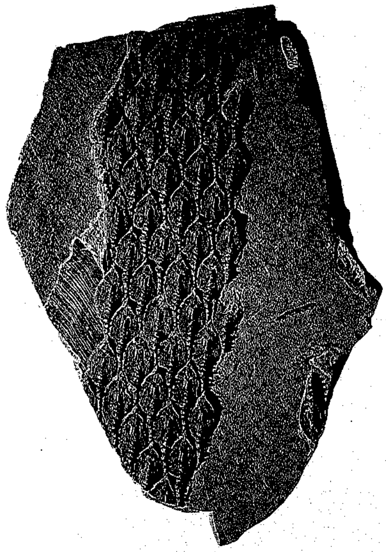

VOLUME 35 • 1988

BRIGHAM YOUNG UNIVERSITY GEOLOGY STUDIES

Volume 35, 1988

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A Publication of the
Department of Geology
Brigham Young University
Provo, Utah 84602

Brigham Young University Geology Studies is published by the Department of Geology. This publication consists of graduate student and faculty research within the department as well as papers submitted by outside contributors. Each article submitted by BYU faculty and outside contributors is externally reviewed by at least two qualified persons.

Cover: *Lepidodendron* sp. from the Manning Canyon Shale Formation. Donated by Gary Harris to the BYU paleobotanical lab.

ISSN 0068-1016
12-88 600 35388

Petrology of the Mt. Pennell Central Stock, Henry Mountains, Utah

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ABSTRACT

The Mt. Pennell central stock and surrounding laccoliths consist of four intrusive rock types that display eight textural variations. Diorite porphyry was emplaced first followed by progressively more felsic syenite porphyry, soda syenite porphyry, and granite porphyry. Granite porphyry displays sharp contacts against older rock units whereas earlier units show gradational contacts and are therefore likely co-magmatic.

Integration of all data, particularly sequential changes in both major and trace element concentrations together with sequential zoning of feldspar phenocrysts, indicate that the rock types resulted from differentiation of a parent magma in a single zoned magma chamber. Underplating by hot mafic magma possibly played a major role in causing the evacuation of differentiated magma from the zoned chamber, apparently from the bottom upward.

INTRODUCTION

Intrusive rocks in the several laccolithic mountains on the Colorado Plateau (fig. 1) have been studied by many investigators. Data compiled thus far show many similarities between these igneous complexes. Diorite porphyry is present as the dominant rock and forms stocks and tongue-shaped laccoliths that radiate a mile or so from the central stock. Where more than one rock type is present, the intrusive sequence proceeds from intermediate composition diorite toward more felsic rocks. These and other similarities have led some investigators to conclude that igneous processes in the several complexes were similar, if not the same. At least two models of petrogenesis have been proposed to account for the observed diversification of rock types; however, only one of them accounts for the intermediate toward more felsic intrusive sequence.

Ekren and Houser (1965) proposed differentiation of a mafic parent magma to account for a compositional sequence ranging from microgabbro through quartz monzonite in the Ute Mountains (fig. 1). The La Sal Mountains contain rocks ranging in composition from diorite porphyry to a silica-rich aegirine granite (Hunt and Waters 1958). No simple differentiation trend is evident, and a complex mechanism involving anatexis of amphibolitic basement and filter pressing has been proposed.

Gilbert (1877) conducted the first scientific investigation of the Henry Mountains. Butler and others (1920) visited the Henry Mountains and briefly described the gold-bearing fissure veins. Hunt and others (1953) made the most comprehensive study of the Henry Mountains to date. Engel (1959) studied the hornblendic inclusions from several locations in the Henry Mountains. Magnetic data (Affleck and Hunt 1980) support Hunt's field interpretation that laccoliths and bysmaliths are shallow structures radiating from more deep-seated stocks. Jackson and Pollard (1988) interpret structural data from the southernmost three Henry Mountains as not supporting the presence of deep-seated stocks in these intrusions; they did not study Mt. Pennell.

This paper documents four intrusive rock types occurring in the central stock of Mt. Pennell, the middle of the three main Henry Mountains. Field relations together with petrographic and compositional data suggest the path of magmatic diversification was probably different from that of the La Sal Mountains but similar to the trend followed by rocks of the Ute Mountains. A model of petrogenesis is proposed to explain both the diversification trend and the intrusive sequence of the igneous rocks in Mt. Pennell.

Editors note: Fieldwork was accomplished during 1981 while laboratory analysis and the bulk of writing were completed in 1983.

ACKNOWLEDGMENTS

I am especially grateful to my wife and family for their support and patience. To Myron Best I am indebted for

A thesis submitted to the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree of Master of Science, August 1983.

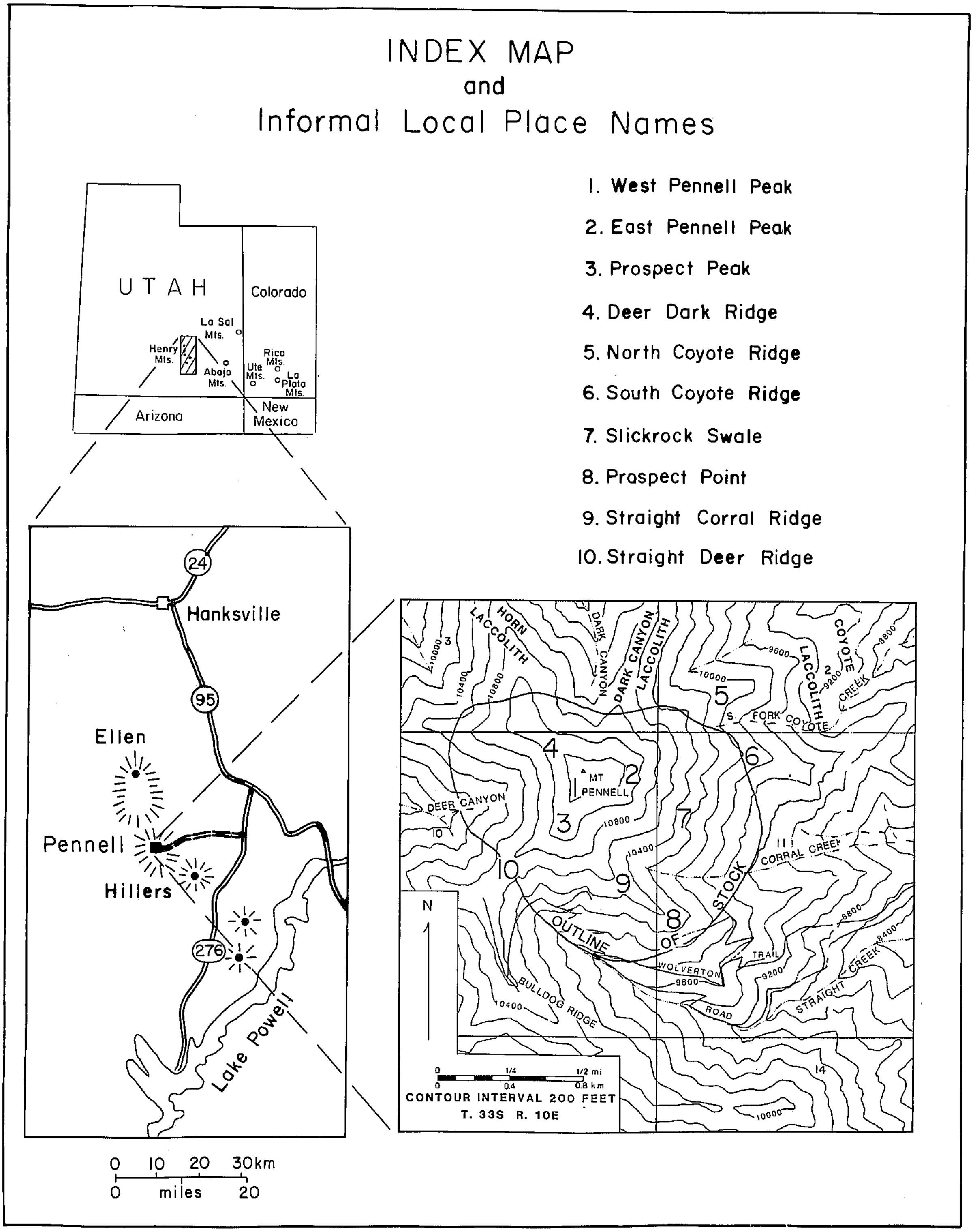


FIGURE 1.—*The Henry Mountains lie near the geographic center of a north–south-trending, diamond-shaped structural basin. The basin is approximately 100 miles long and 50 miles wide. It is bounded on the west by the Waterpocket Fold and the southern tip of the San Rafael Swell, and on the east by the Colorado and Muddy Rivers. Exposed rocks in the basin range are from Permian through Quaternary in age. The Cretaceous Mancos Shale is host for nearly all of the bulbuous laccolithic intrusions with Jurassic rocks hosting only a few. For more detailed stratigraphy and regional structure see Hunt and others (1953).*

Table 1. Classification of rock units (after Irvine and Baragar 1971). Presented in order of intrusive sequence from oldest to youngest.

Rock Suite		Intrusive Equivalent of Irvine and Baragar	Classification of Hunt and others (1953) * Engel (1959) +	This Paper
Sub-Alkaline	Calc-Alkaline	Calc-Alkaline Diorite Porphyry	Diorite Porphyry *+	Diorite Porphyry
Sub-Alkaline	Calc-Alkaline	Calc-Alkaline Quartz Diorite Porphyry		Quartz Diorite Porphyry
Alkaline	Potassium Series	Potassium Syenite Porphyry		Weakly Porphyritic Syenite
Alkaline	Potassium Series	Potassium Syenite Porphyry	Monzonite Porphyry * Augite-Monzonite + Porphyry	Common Syenite Porphyry
Alkaline	Potassium Series	Potassium Syenite Porphyry	Monzonite *+ Porphyry	Coarsely Porphyritic Syenite
Alkaline	Sodium Series	Soda Syenite Porphyry		Soda Syenite Porphyry
Sub-Alkaline	Calc-Alkaline	Calc-Alkaline Granite Porphyry		Granite Porphyry

his insightful critiques, provocative discussions, and persnickety editing. I am indebted to C. B. "Charlie" Hunt for his direction in the early stages of this project, open exchanges, and editing. A special thanks goes to Drs. K. C. Bullock, A. C. Waters, and E. B. Ekren for reviewing the manuscript, to Drs. D. T. Griffen, W. R. Phillips, and J. R. Bushman for their dialogue and access to laboratory equipment, and to Dr. W. P. Nash and Dave Filar of the University of Utah for microprobe analysis. I thank the following persons and organizations for financial assistance: Charlie and Alice Hunt, BYU Alumni, Brigham Young University, Utah Geological Association, and Associated Energy Corporation.

INTRUSIVE SEQUENCE AND FIELD RELATIONS

Intrusive rocks on Mt. Pennell are all porphyries and range in composition from calc-alkaline diorite and granite to alkaline syenite (table 1). Field observations indicate that the rocks are predominantly co-magmatic because of gradational contacts between them and the sequence of magma intrusion from earliest to latest was diorite, syenite, soda syenite, and granite. Diorite occurs in two textures, diorite porphyry and quartz diorite porphyry. Syenitic rocks display three textural variations: weakly porphyritic syenite, common syenite porphyry, and coarsely porphyritic syenite. Soda syenite and granite have only one texture each. The rocks have been classified using the method of Irvine and Baragar (1971), but extrusive names have been replaced with intrusive equivalents and textural modifiers have been added (table 1). For brevity, the term porphyry commonly is omitted in the text.

The intrusive rock bodies on Mt. Pennell occur in four different geometric shapes: irregularly shaped bulbous masses, tongue-shaped laccoliths, concentric dikes, and radial dikes. The margin of the central stock is outlined by a 30-m-wide concentric fracture zone at the diorite-syenite contact, which coincides with an abrupt change in topographic slope. This suggests the syenite stock may have been elevated as a rising piston by late magma intrusion.

An approximate relative volume for each of the rock units has been extrapolated from area of exposure and presented in table 2.

DIORITE PORPHYRIES

Initial voluminous intrusion of diorite magma arched sedimentary beds upward over a central stock and then intruded the strata laterally to form tongue-shaped laccoliths that radiate more than a mile outward from the central stock (Hunt and others 1953, p. 90). Diorite is now found only in laccoliths because later intrusions of syenite magma displaced it from the area of the central stock (plate 1).

Diorite is characterized by equant plagioclase phenocrysts about 3 mm across and by smaller prismatic hornblende phenocrysts in a light gray aphanitic matrix. As much as 1% mafic inclusions that average 10 cm in

Table 2.

Rock Unit	Estimated Volume (in percent)
Granite Porphyry	2
Soda Syenite Porphyry	15
Coarsely Porphyritic Syenite	6
Common Syenite Porphyry	33
Weakly Porphyritic Syenite	
Exotic Blocks and Other	8
Quartz Diorite Porphyry (in laccoliths)	2
Diorite Porphyry (in laccoliths)	34

Hunt and others (1953, p. 144) estimated volume of intrusive rock in the laccoliths and sills of Mt. Pennell as 1.18 cubic miles (4.92 cubic kms), and 2.25 cubic miles (9.37 cubic kms) in the central stock. Volume of the stock was calculated to a depth equal to structural relief of the dome using the assumption of vertical walls. Relative volumes of rock units within the stock have been extrapolated from areas of exposure.

diameter are distributed randomly or as clusters throughout any given laccolith (Hunt and others 1953, p. 160). The mafic inclusions are predominantly hornblende with lesser amounts of Fe-Ti oxides, clinopyroxenes, and feldspars. Some display gneissic structure with foliation defined by alternating layers rich in hornblende and feldspar.

Locally, on North and South Coyote Ridges and on Straight Deer Ridge, diorite porphyry contains a few percent quartz phenocrysts. Definite contacts between diorite and quartz diorite are nonexistent, which suggests that the quartz diorite is merely a slight compositional and textural variant of the diorite.

WEAKLY PORPHYRITIC SYENITE

The first syenite magma to be emplaced in the stock formed weakly porphyritic syenite. It was clearly intruded by later magmas that formed common and coarsely porphyritic syenites on west Pennell Peak, but the contacts are irregular and gradational, indicative of a co-magmatic relationship. In the field, this unit is light gray and displays an apparent aphanitic "sugary" texture.

COMMON SYENITE PORPHYRY

Magma that formed common syenite intruded diorite in the pre-exisiting laccoliths in a pattern apparently controlled locally by fractures. Contacts range from sharp, in dikes lying outside of the stock, to gradational near the stock. This unit also intrudes weakly porphyritic syenite in at least one locale, but the contact is not sharp. The main outcrop occupies an area of over 70% of the western half of the central stock and can be traced continuously from south of Prospect Point to Deer Dark Ridge. Minor radial and concentric dikes intrude diorite in all laccoliths except the Dark Canyon laccolith.

Common syenite is not homogeneous in texture or composition, and was originally mapped as three separate units on the basis of phenocryst size. The three variants generally grade into each other although sharp contacts between them can be found locally. Contacts between the three variants are well displayed on Deer Dark Ridge. In the field, common syenite porphyry appears similar to diorite porphyry. However, common syenite has distinctly larger but less euhedral feldspar phenocrysts than diorite, and a generally darker gray and slightly coarser, yet still aphanitic, matrix. Rarely, a clinopyroxene phenocryst can be recognized in hand sample. On Straight Deer Ridge, common syenite displays unusual characteristics: phenocrysts are aggregated together with longest dimension aligned in swirl-like patterns, light and dark gray matrices are incompletly mixed, and fragmented inclusions of diorite are intermixed with clusters of alkali-feldspar phenocrysts. On Deer Dark Ridge, common syenite displays intra-intrusive characteristics with abundant local changes in foliation direction, sharp discordant contacts between masses with differently oriented foliations, and slickensides along the contacts. Mafic inclusions have a similar character and mode of occurrence as in diorite.

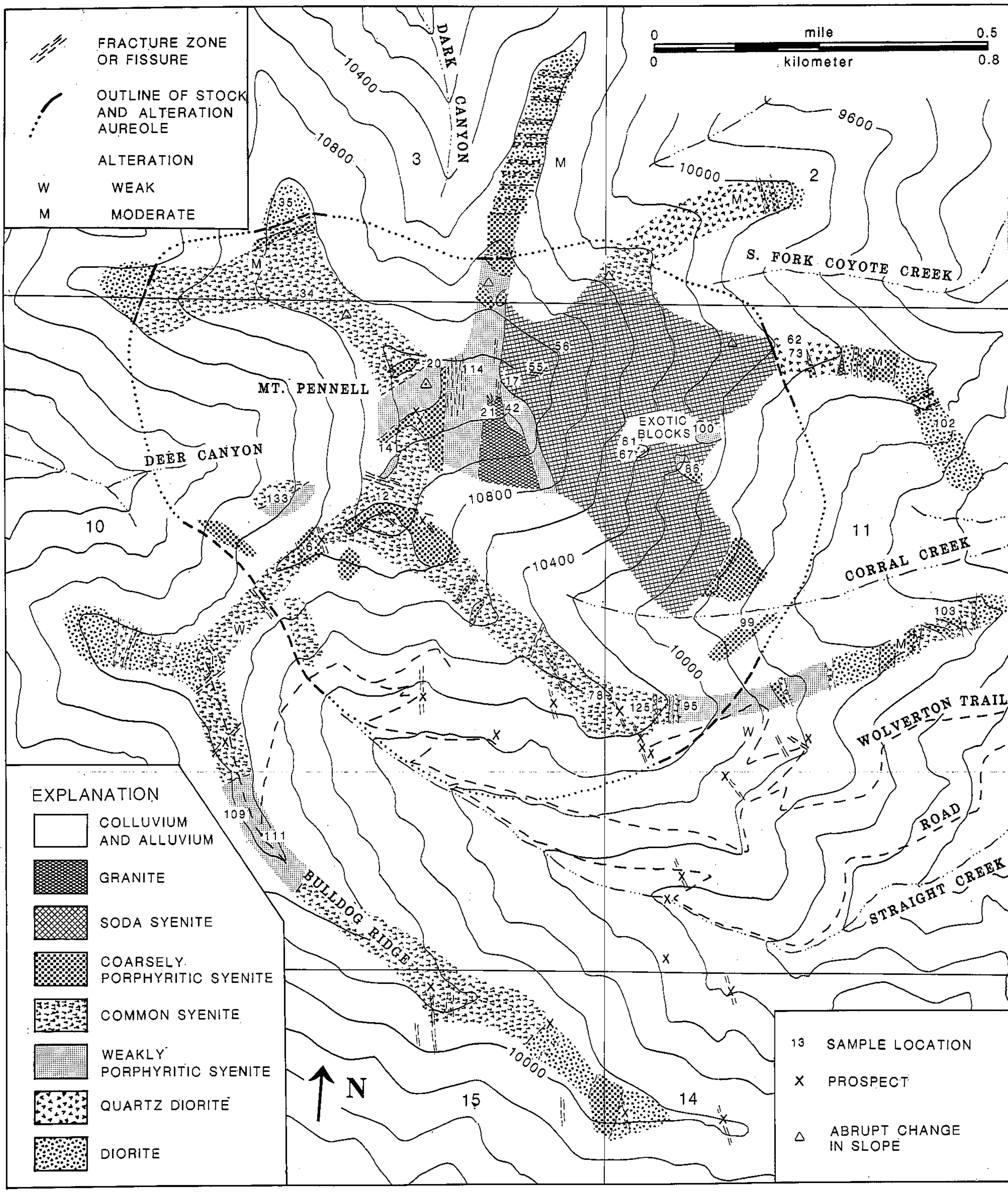
COARSELY PORPHYRITIC SYENITE

Coarsely porphyritic syenite is found in concentric dikes oriented parallel to concentric fractures in diorite laccoliths and in the main body of common syenite. Because of limited exposure, dip of the dikes could not be determined to verify whether they might be cone sheets. Radially oriented dikes cutting the central stock are found on Prospect Peak, Prospect Point, Straight Corral Ridge, and Bulldog Ridge. They are predominantly coarsely porphyritic syenite with the exception of a 1-m-wide microcrystalline felsic dike on Prospect Point.

In the field, coarsely porphyritic syenite is distinquished by large (average 1.6 cm) euhedral, tabular K-rich alkali-feldspar phenocrysts set in a brownish aphanitic matrix. The rock also contains smaller, equant, less potassic alkali feldspar, clinopyroxene, and hornblende phenocrysts. In dikes, the large tabular K-rich alkali feldspars are aligned parallel to contacts. This rock is texturally homogeneous throughout any single outcrop. Mafic inclusions are virtually absent.

Magma that formed coarsely porphyritic syenite clearly intruded previously described rocks. Contacts have fine-grained "chilled" margins and are planar as if controlled

PLATE 1


FRACTURE ZONE OR FISSURE
OUTLINE OF STOCK AND ALTERATION AUREOLE
ALTERATION
W WEAK
M MODERATE
mile
0 0.5
kilometer
0 0.8
DARK CANYON
S. FORK COYOTE CREEK
MT. PENNELL
DEER CANYON
EXOTIC BLOCKS
CORRAL CREEK
WOLVERTON TRAIL
ROAD
STRAIGHT CREEK
BULLDOG RIDGE
10400
10800
9600
10000
EXPLANATION
COLLUVIUM AND ALLUVIUM
GRANITE
SODA SYENITE
COARSELY PORPHYRITIC SYENITE
COMMON SYENITE
WEAKLY PORPHYRITIC SYENITE
QUARTZ DIORITE
DIORITE
N
13 SAMPLE LOCATION
X PROSPECT
ABRUPT CHANGE IN SLOPE

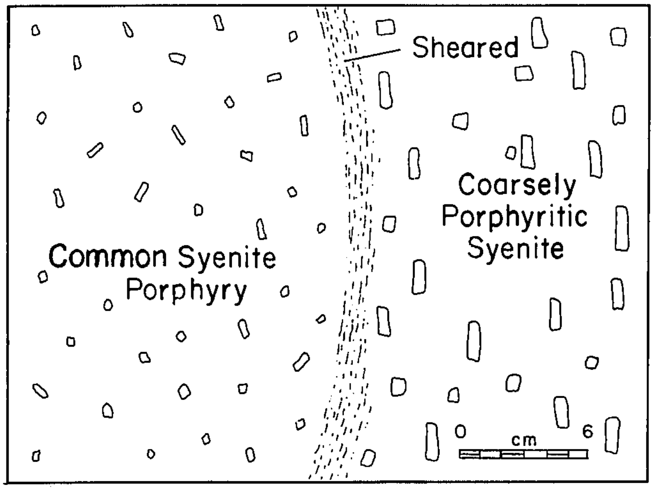


FIGURE 2.—*Coarsely porphyritic syenite intruded into common syenite as indicated by flow foliation. However, the fine-grained sheared zone contains matrix from both units, indicating a co-magmatic relationship.*

by pre-existing fractures in the several host rock units. Intrusive contacts against weakly porphyritic syenite are not as sharp as those against diorite. In the center of the stock, coarsely porphyritic syenite intrudes common syenite and weakly porphyritic syenite as one irregularly shaped mass and shows gradational contacts. Near the perimeter of the stock, coarsely porphyritic syenite intrudes common syenite porphyry as thin dikes, obviously filling fractures in the host syenite. However, the contacts are not sharp, and range from gradational boundaries to one-foot-wide sheared boundaries with the finer fraction of matrix showing flow structure parallel to the contact (fig. 2). These relationships suggest that common syenite experienced cohesive failure prior to solidification, as discussed later in the section on petrogenesis.

SODA SYENITE PORPHYRY

In Slickrock Swale, soda syenite intrudes coarsely porphyritic syenite, whereas on the proximal end of the Dark Canyon laccolith, the contact is so gradational that neither can be said to intrude the other. Soda syenite occurs in one large mass occupying over 70% of the eastern one-half of the central stock and is the predominant rock type found in the mantle of boulders in upper Corral Canyon.

Soda syenite is distinguished in hand sample by abundant (55%) oval-shaped feldspar phenocrysts and euhedral clinopyroxene phenocrysts in a light gray-green, aphanitic matrix. Feldspar phenocrysts are locally aligned. Sharp contacts between local masses showing discordant foliation are common, suggesting turbulent flow within the crystal-rich magma as it was emplaced.

Large mafic inclusions were not observed in soda syenite outcrops, but minor amounts of small polygranular clots were noted in thin section. This unit contains approximately 1% xenoliths of slightly metamorphosed Jurassic and Cretaceous sandstone and shale. The xenoliths average 0.3 m diameter and occur randomly and in clusters. On the west side of Slickrock Swale several clusters, up to 4 meters in diameter, are embedded in a matrix of altered igneous material (fig. 3). The enclosing matrix material displays a relatively sharp contact with the host soda syenite and appears similar to granite porphyry. The matrix material might have resulted from alteration of the host by volatiles lost during the slight metamorphism of sedimentary xenoliths, but is of uncertain origin.

GRANITE PORPHYRY

Granite porphyry is clearly the last intrusive unit. It displays sharp contacts against all previous units and occurs almost exclusively in one outcrop on the south side of

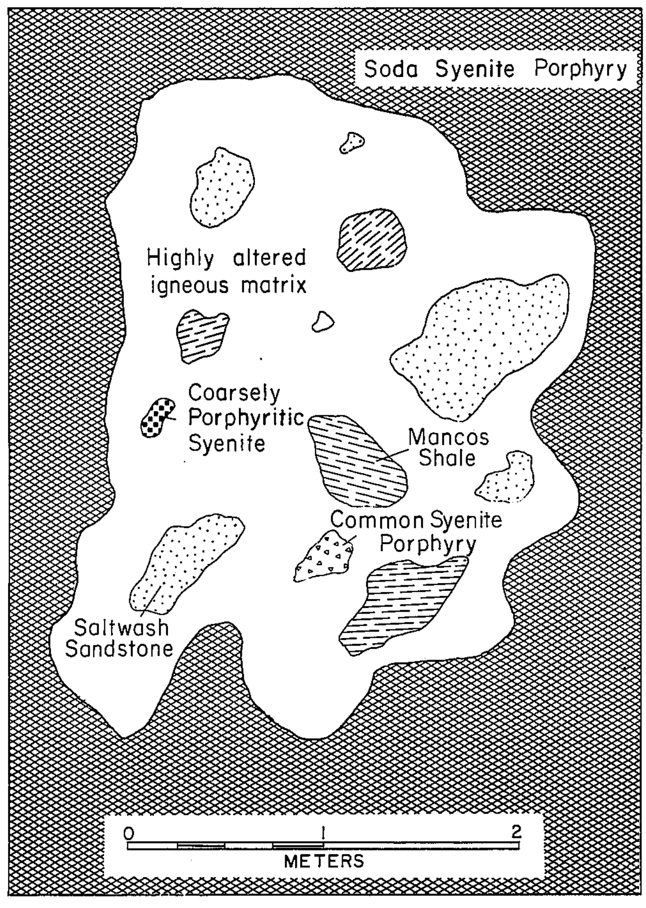


FIGURE 3.—*Cluster of sedimentary xenoliths and igneous inclusions from intrusive units. The enclosing igneous matrix is altered and appears similar to granite porphyry, but is of uncertain origin.*

East Pennell Peak, where it fingers upward into weakly porphyritic syenite and soda syenite forming well-developed plug dikes (fig. 4). Several small plug dikes also occur on Prospect Point and South Coyote Ridge.

In hand sample, this unit is characterized by iron-stained miarolitic cavities in the shape of elongate ellipsoids, the alignment of which defines a lineation. Anhedral feldspars are the only phenocrysts in a greenish somewhat altered aphanitic matrix. Mafic inclusions were not observed in this unit, but small (0.5 cm) fragments of every earlier intrusive unit, together with sedimentary xenoliths of similar size, are an integral part of the rock. Inclusions make up as much as 10% of dikes, but are less abundant in the main outcrop.

OTHER ROCKS

Thin, microcrystalline felsic dikes, generally 2 to 3 cm wide, intrude all units except granite porphyry, and contacts are sharp. The majority of dikes are found at higher topographic elevations near the mountain peak. One unusually large dike, approximately 1 m wide, occurs on Prospect Point adjacent and parallel to a distinct fracture that is oriented radially to the peak.

Exotic blocks, as much as 30 m across, of recrystallized common syenite and coarsely porphyritic syenite, entirely surrounded by soda syenite, occur in Slickrock Swale (plate 1). The contact is a blurred, gradational zone averaging 3 m wide. Other outcrops shown as weakly porphyritic syenite on plate 1 may be exotic blocks, but field evidence is not compelling.

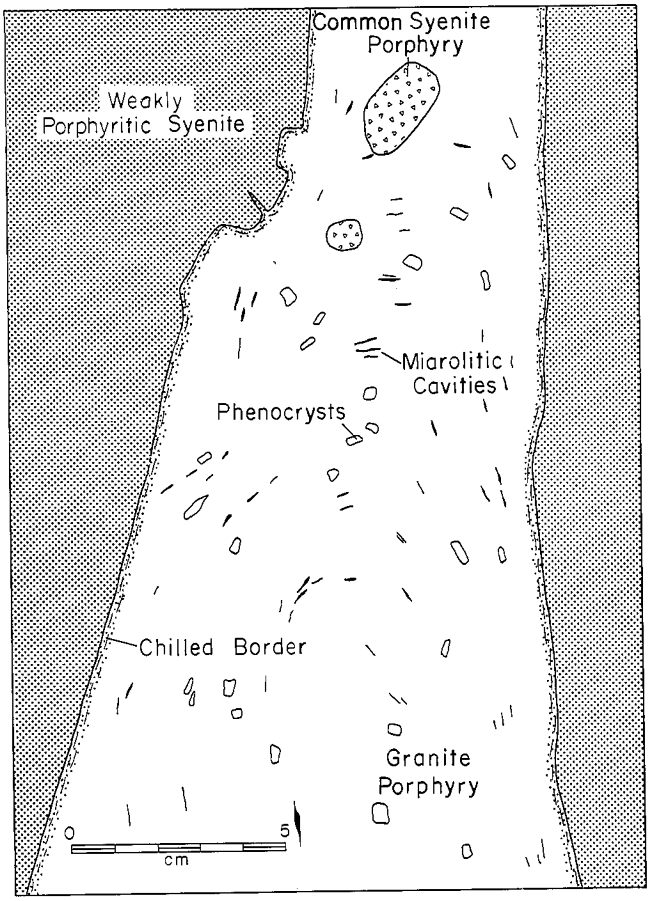


FIGURE 4.—*Typical plug dike of granite porphyry intruded into weakly porphyritic syenite, displaying flow foliation parallel to contact. Contact is sharp and apparently fracture controlled.*

PETROGRAPHY

Detailed petrographic descriptions of two rock units from Mt. Pennell have been published by Hunt and others (1953) and Engel (1959). In the present study, 52 thin sections were examined and microprobe analysis of 4 sections were made; average modes are summarized at the end of this section on figure 19A.

DIORITE PORPHYRIES

In thin section, diorite from Mt. Pennell is characterized by euhedral to subhedral, equant plagioclase phenocrysts averaging 3 mm in diameter residing in a microcrystalline matrix (fig. 5). Plagioclase phenocrysts average An 50, display three types of twinning—albite, percline, and carlsbad—and have as many as ten oscillatory zones. Hornblende occurs as prismatic phenocrysts and glomeroporphyritic masses. Thin rims of opaque minerals have developed around many of the hornblende phenocrysts. A few small euhedral sphene and apatite microphenocrysts together with anhedral opaque grains are also present. Only a small amount of potassium feldspar occurs in the matrix. Quartz diorite porphyry is essentially identical to diorite, except for the presence of approximately 7% slightly resorbed bipyramidal phenocrysts of alpha quartz pseudomorhs after beta quartz (fig. 6).

WEAKLY PORPHYRITIC SYENITE

Weakly porphyritic syenite has euhedral to subhedral plagioclase phenocrysts, averaging An 25, in a microcrystalline felsic matrix. These phenocrysts are the largest in the rock, averaging 2 mm diameter, and display percline and albite twinning. Many of the phenocrysts are jacketed by potassium feldspar, giving two distinct compositional zones. Both of the major zones have thin minor oscillatory zones (fig. 7). A few phenocrysts of pleochroic green clinopyroxene, sphene, and hornblende rimmed with opaques are present. Staining reveals abundant potassium feldspar in the matrix.

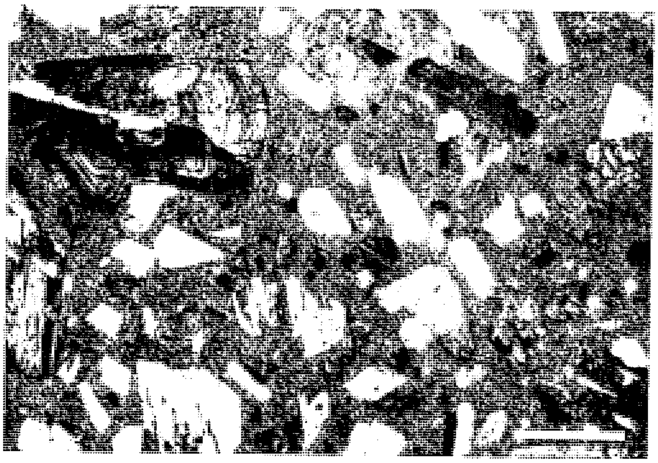


FIGURE 5.—*Diorite porphyry. Large subhedral plagioclase with oscillatory zonation and faint albite and carlsbad twinning, upper left; and subhedral plagioclase displaying strong albite twinning, left center. Bar scale is 10 mm.*

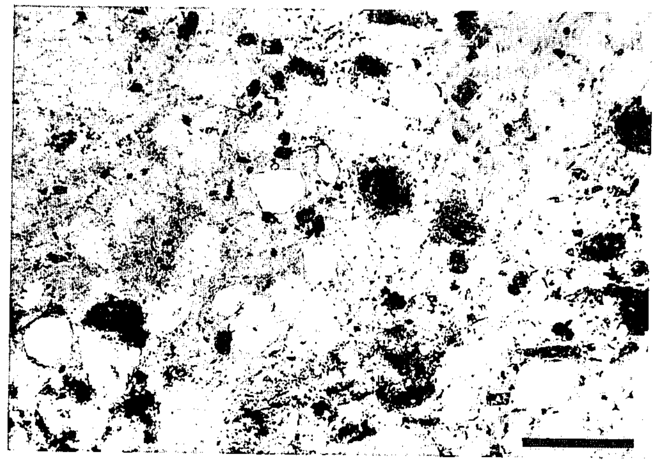


FIGURE 6.—*Quartz diorite porphyry. Clear, embayed, bipyramidal phenocrysts of quartz, and dark phenocrysts of hornblende partially replaced with Ti-Fe oxides. Bar scale is 10 mm.*

COMMON SYENITE PORPHYRY

Common syenite is characterized by tabular and locally equant, subhedral, alkali-feldspar phenocrysts, averaging 8 mm in length, in a microcrystalline trachitic matrix (fig. 8). This matrix plus the aligned phenocrystic feldspars define a flow foliation.

Feldspar phenocrysts typically have two zones and display three types of twinning—albite, percline, and carlsbad. Phenocrysts of hornblende (averaging 5 mm in length) and clinopyroxene (averaging 3 mm in length) are also present, together with minor amounts of apatite and sphene microphenocrysts, and opaques in the felsic matrix. Hornblende phenocrysts display an inner and outer zone and are replaced to varying degrees by green clinopyroxene and opaques (fig. 9). The average amount of replacement is greater than that observed in hornblende in the diorite porphyry.

COARSELY PORPHYRITIC SYENITE

Coarsely porphyritic syenite has two types of alkali-feldspar phenocrysts in a microcrystalline trachitic matrix (fig. 10). Euhedral, tabular, potassum-rich phenocrysts average 16 mm, but reach 80 mm in length. They average Or 58 Ab 40 An 2 and display faint oscillatory zonation. Smaller Na-rich feldspars contain two major zones: inner Or 9 Ab 64 An 27, and outer Or 10 Ab 72 An 18. The outer zone contains several minor oscillatroy zones. Phenocrysts of hornblende and green clinopyroxene are also present with minor amounts of sphene and apatite microphenocrysts and anhedral opaque grains in the matrix. Hornblende phenocrysts are replaced by green clinopyroxene and opaques to approximately the same degree as hornblendes in common syenite porphyry. The matrix is foliated parallel to the oriented tabular phenocrysts. This flow fabric is similar to that in common syenite.

SODA SYENITE

Soda syenite has sodic feldspar phenocrysts averaging 3 mm in length enclosed in a felsic microcrystalline matrix (fig. 11). The cause of the unusual ellipsoidal shape of the phenocrysts is not known with certainty, but appears to be a product of mechanical deformation. A rhomb form is evident in some inner compositional zones, and most phenocrysts are strained, as manifest by intense mosaic extinction, and some appear to have been ruptured. All have two major compositional zones and many display three, none of which show minor oscillatory zonation (fig. 12). Compositions are complex and variable but average Or 9 Ab 82 An 9 in the inner zone and Or 22 Ab 72 An 6 in the middle zone and Or 11 Ab 81 An 8 for the outer zone.

Green clinopyroxene, locally with penetration twins, occurs as euhedral phenocrysts and as minute grains in the matrix. A minor amount of microphenocrystic sphene is also present. Staining reveals the matrix to be predominantly potassium-rich feldspar.

GRANITE PORPHYRY

Granite porphyry is characterized by irregular, elongated miarolitic cavities and feldspar phenocrysts averaging 2 mm in diameter in a greenish matrix (fig. 13). Igneous inclusions and sedimentary xenoliths are about 3 mm in diameter and, although amounts vary locally, generally constitute about 6% and 1%, respectively. The feldspar phenocrysts occur as three optically different types, each jacketed with K-rich feldspar. One type has four distinct recognizable zones. From inner to outer,

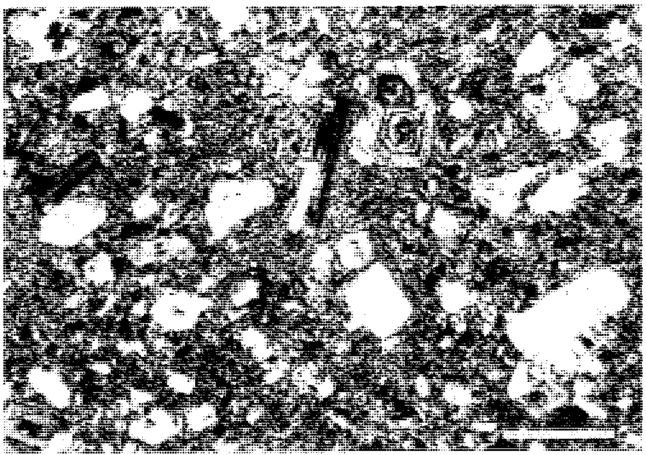


FIGURE 7.—*Weakly porphyritic syenite. Double plagioclase phenocryst displaying oscillatory zoning with two major zones, upper right of center. Bar scale is 10 mm.*

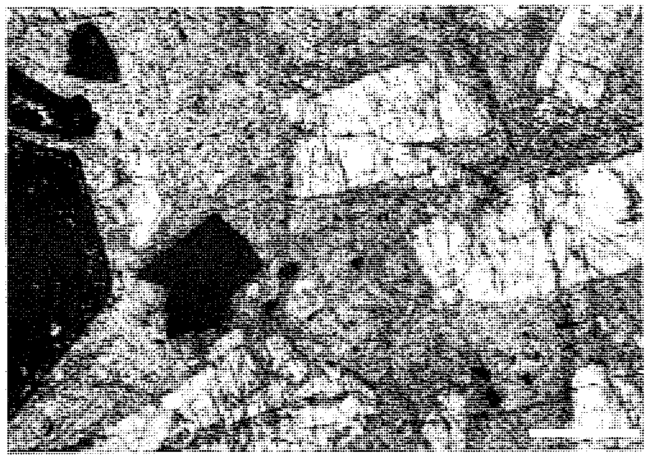


FIGURE 8.—*Common syenite porphyry. Large hornblende phenocryst, far left, is partly replaced by opaques. Green clinopyroxene phenocryst center left. Alkali feldspar phenocrysts are fractured. Bar scale is 10 mm.*

these zones are: (1) Or 9 Ab 74 An 17, (2) Or 54 Ab 44 An 2, (3) Or 21 Ab 77 An 2, (4) Or 58 Ab 41.5 An 0.5 (fig. 14). A second type consists of oval feldspar phenocrysts that appear very similar to those in soda syenite porphyry (fig. 15). The third type comprises anhedral plagioclase phenocrysts that display oscillatory zonation and albite twinning, similar to plagioclase in diorite porphyry (fig. 16). Sphene and a trace of apatite and biotite occur as microphenocrysts. The matrix is composed of opaque grains, anhedral, rather fragmental-appearing green clinopyroxene, and K-rich feldspar.

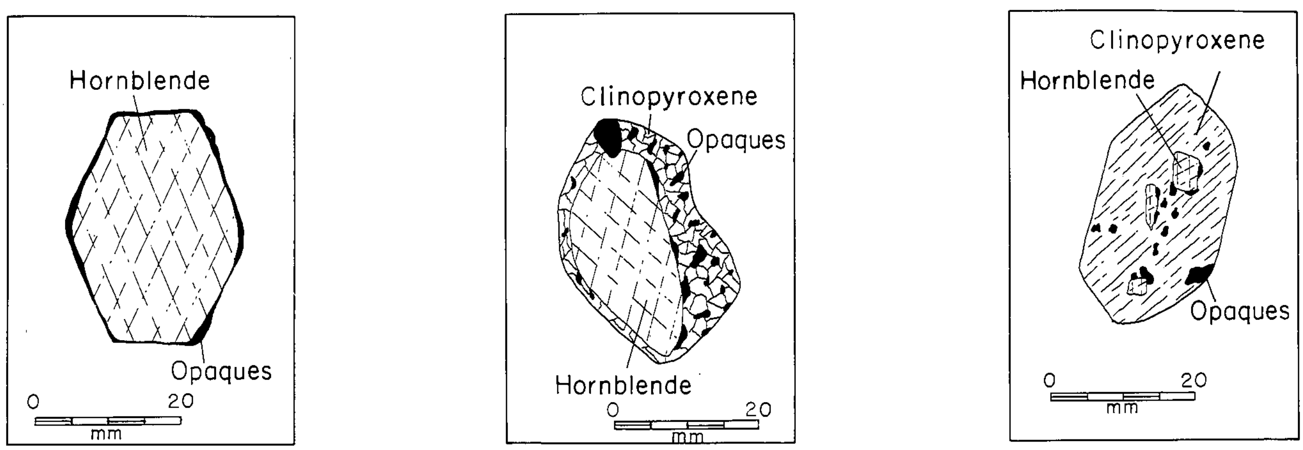
OTHER ROCKS

In thin section, microcrystalline felsic dikes are allotriomorphic (fig. 17). Staining indicates that only sparse amounts of K-rich feldspar are present. Most of the microcrystalline feldspar is apparently sodic. Minor amounts of indistinguishable dark minerals are ubiquitous.

Exotic blocks are granoblastic and contain aggregates of small garnets that outline recrystallized feldspar phenocrysts (fig. 18). Judging from the size of the relict feldspars, a block in Slickrock Swale could have formed from coarsely porphyritic syenite. Other blocks of coarsely porphyritic syenite and common syenite porphyry are less recrystallized, thus preserving their original identity.

MAFIC INCLUSIONS

Mafic inclusions display a variety of textures from massive xenomorphic to gneissic, with foliation defined by alternate layers rich in hornblende and feldspar, or by oriented hornblende crystals only. Hornblende is the



A B C

FIGURE 9.—*Hornblende is rimmed with opaques in diorite (a), approximately one-half replaced by green clinopyroxene and opaques in common syenite (b), almost entirely replaced with green clinopyroxene and opaques in soda syenite (c).*

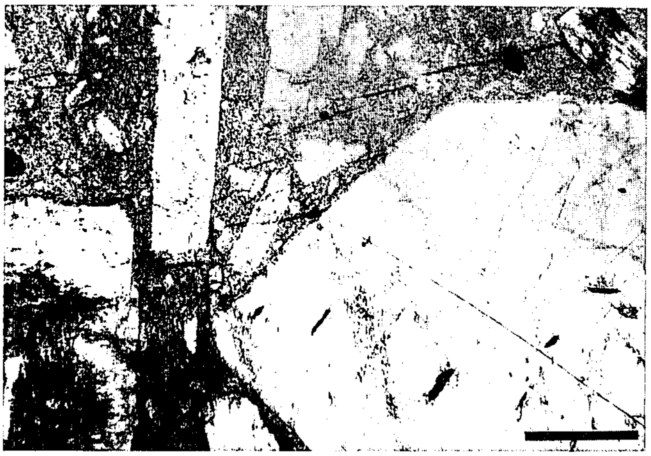


FIGURE 10.—*Coarsely porphyritic syenite. Lath-shaped phenocryst, upper left is Na-rich alkali feldspar. Lower right is approximately one quarter of a large, euhedral K-rich alkali-feldspar phenocryst. Bar scale is 10 mm.*

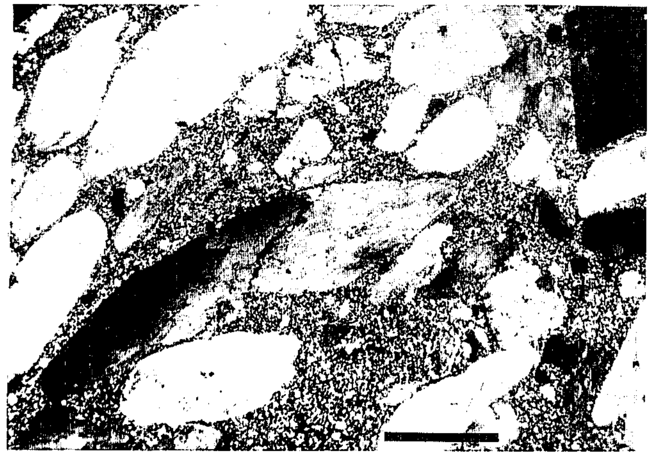


FIGURE 11.—*Soda syenite porphyry. Deformed oval feldspar phenocrysts are flow oriented. Clinopyroxene phenocryst in upper right. Bar scale is 10 mm.*

major constituent, but as much as 50% feldspar occurs in some gneissic inclusions (Hunt and others 1953, p. 160). Small amounts of Fe-Ti oxides are present in most inclusions and consititute approximately 15% in a few. Mafic inclusions from Mt. Pennell fall roughly into two chemical groups (table 3). Gneissic inclusions show greatest compositional variation but have an average Mg/Fe ratio of approximately 0.3, whereas massive inclusions have a Mg/Fe ratio of approximately 0.5. Engel (1959) reports that most inclusions from Mt. Ellen, northernmost of the Henry Mountains, have an average Mg/Fe ratio of 0.5 with a few reaching 0.8. Those from Mt. Ellen do not have as much Fe as the high Fe variety from Mt. Pennell. Gneissic inclusions probably are unfused pieces from the metamorphic basement, whereas inclusions with higher Mg/Fe ratio and higher Cr and Ni values may be remnants of an early-formed mafic hood or crystal segregation from the parent magma (Engel 1959).

CHEMICAL ANALYSIS

PROCEDURE

Twenty-one of the least-altered samples were analyzed in duplicate by X-ray fluorescence spectrometry; the method of Norrish and Hutton (1969) was used for major elements and pressed pulverized rock was analyzed for Rb, Sr, and Ba. Relative error between the duplicate samples was less than 1%. Standards included AGV–1 and G–2. Compositions of feldspar zones in samples from the youngest three intrusive units were determined by electron microprobe at the University of Utah using Bence-Albee corrections. Cu, Mo, Pb, Zn, Co, Ni, Cr, and V were analyzed by atomic absorption at Chemical and Mineralogical Services, Salt Lake City, Utah.

The low weight percent totals for analysis in table 3 reflect the presence of volatiles in secondary phyllosilicate, carbonate, and epidote minerals.

MAJOR ELEMENTS

With only slight exceptions, compositions of the eight mappable rock units fall into four chemical groups: diorite, syenite, soda syenite, and granite (table 1). Compositions of syenite porphyries are somewhat variable, but common syenite porphyry and coarsely porphyrytic syenite are similar to one another (table 3). Major elements except Si and Al vary continuously through the older intrusive units, but show a reversal in trend in the youngest intrusive unit (fig. 19B).

The rocks of Mt. Pennell contain more than 70% feldspar; therefore, a plot of the normative minerals on a ternary feldspar diagram represents them to a good approximation (fig. 20). This diagram clearly groups rock units and shows a sequential decrease in the normative An value with respect to order of intrusion. The diagram shows data from four other laccolithic complexes on the Colorado Plateau. The earliest intrusive rock type in the Ute Mountains was a microgabbro. This rock was followed by a suite of sequentially more felsic rocks that follow a rather smooth trend. Ekren and Houser (1965) favored a differentiation mechanism to account for this trend in the Ute Mountains. Only two rock types are reported from the La Plata Mountains, diorite porphyry and monzonite porphyry (Eckel 1937). Mt. Pennell sample 6 and its matrix 6-M lie on the trend line between diorite and monzonite of the La Plata Mountains. Whatever mechanisms were responsible for diversification of magma in the La Plata Mountains apparently produced

Table 3. Composition of Mt. Pennell rock units.

SAMPLE	1	2	3	4	5	6	7	8	9	10	11	12
SI02	61.00	65.20	64.90	59.50	60.70	60.30	64.40	63.70	68.20	68.80	32.90	42.70
TI02	0.45	0.34	0.24	0.34	0.34	0.38	0.25	0.19	0.32	0.30	1.93	0.90
AL203	17.80	17.50	18.60	19.40	19.50	19.30	18.70	18.60	14.80	12.90	9.50	17.20
FE203	3.80	2.70	2.40	3.20	3.10	3.30	2.10	3.20	2.50	2.20	25.60	13.70
MNO	0.02	0.02	0.10	0.10	0.09	0.20	0.09	0.03	0.13	0.02	0.40	0.40
MGO	0.60	0.30	0.20	0.70	0.30	0.30	0.10	0.00	0.70	0.40	9.10	3.90
CAO	5.30	4.27	2.75	3.70	3.57	3.18	1.18	1.26	1.89	2.11	12.86	10.30
NA20	5.00	4.90	6.40	6.30	6.00	5.90	7.70	7.80	6.10	5.50	1.10	4.60
K20	2.26	2.56	3.78	4.85	4.45	4.72	4.26	4.26	4.47	4.43	0.92	1.10
P205	0.21	0.16	0.08	0.16	0.13	0.13	0.05	0.06	0.11	0.10	0.80	0.40
TOTAL	96.40	98.00	99.50	98.30	98.20	97.70	98.80	99.10	99.20	96.80	95.10	95.20
CIPW NORMS	Fe203/Fe0 ratio: 0.5 (Assigned arbitrarily)											
Q	11.96	17.72	6.91	0.00	0.56	0.69	0.00	0.00	12.19	18.76	0.00	0.00
OR	13.88	15.47	22.50	29.39	28.66	26.83	25.49	25.51	26.70	27.11	0.00	7.05
AB	44.04	42.41	54.54	46.82	51.30	51.98	66.84	65.18	51.64	43.28	0.00	14.29
AN	20.15	18.61	10.94	10.60	12.58	13.37	3.47	3.23	0.00	0.00	19.69	25.00
LC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.60	0.00
NE	0.00	0.00	0.00	3.71	0.00	0.00	0.00	0.68	0.00	0.00	4.75	13.22
AC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	2.08	0.00	0.00
NS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.49	0.00	0.00
DI	4.70	1.69	1.96	5.99	2.37	3.30	1.87	2.42	7.28	6.30	19.76	22.93
WO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.14	0.00	0.00
HY	2.09	1.80	1.41	2.36	1.94	1.44	0.67	0.00	0.09	0.00	0.00	0.00
OL	0.00	0.00	0.00	0.97	0.00	0.00	0.10	1.02	0.00	0.00	26.76	7.93
CS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.03	0.00
MT	1.79	1.24	1.09	1.48	1.53	1.41	0.96	1.46	1.06	0.00	12.42	6.69
IL	0.88	0.66	0.46	0.66	0.74	0.66	0.48	0.37	0.61	0.59	3.95	1.85
AP	0.51	0.39	0.19	0.39	0.32	0.31	0.12	0.14	0.26	0.25	2.04	1.03
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1. Diorite porphyry, South Coyote Ridge (S-102).
2. Quartz diorite porphyry, South Coyote Ridge (S-73).
3. Weakly porphyritic syenite, West Pennell Peak (S-20).
4. Common syenite porphyry, Straight Deer Ridge (S-1).
5. Coarsely porphyritic syenite, Straight Deer Ridge (S-6).
6. Coarsely porphyritic syenite matrix, Straight Deer Ridge (S-6-M).
7. Soda syenite porphyry, approximately 100 m east of East Pennell Peak (S-56).
8. Soda syenite porphyry, East Pennell Peak (S-17).
9. Granite porphyry, 2 m wide dike on Prospect Point (S-125).
10. Granite porphyry, south side of East Pennell Peak (S-21).
11. Mafic inclusion, Pennell stock, average of massive high Fe (S-36, S-64).
12. Mafic inclusion, Pennell stock, average of gneissic (S-10, S-127).

the same effect as separating phenocrysts from matrix of syenite from Mt. Pennell.

Seven intrusive rock types were described from the La Sal Mountains by Hunt and Waters (1958). The earliest intrusive unit is diorite porphyry having a composition near that of diorite porphyry in the La Plata Mountains, but subsequent diversification produced divergent trends. The trend from diorite to soda syenite parallels the Ute Mountains differentiation curve, but is offset toward Ab. From this point, the trend swings sharply toward Or. Hunt and Waters (1958) indicated the shift toward Or occurred during a volcanic cycle in the closing phases of igneous activity in the North La Sal stock.

On Mt. Pennell, diorite porphyry is the first intrusive unit and is very similar to diorite porphyry in the Ute Mountains. From diorite, the diversification trend follows that of the Ute and Abajo rocks, then moves toward Ab before swinging in the late stage toward Or as do all the other intrusive complexes except Abajo.

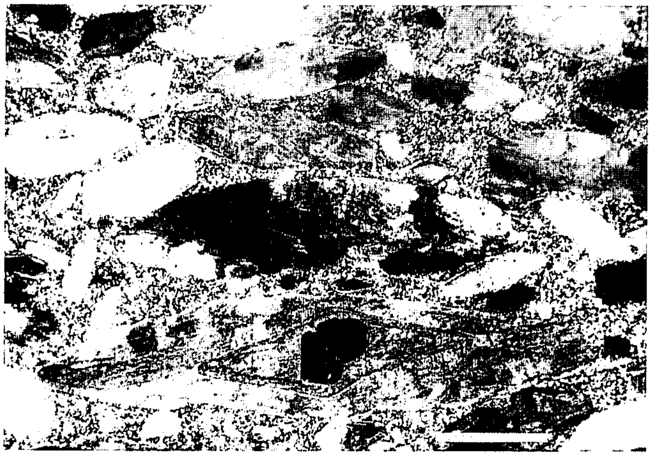


FIGURE 12.—*Soda syenite porphyry. Feldspar phenocryst in lower center has three distinct zones, an inner zone An 10 and an outer zone of sodic alkali-feldspar. Bar scale is 10 mm.*

FIGURE 14.—*High magnification view of alkali-feldspar phenocryst with four major zones, in granite porphyry. Bar scale is 4 mm.*

TRACE ELEMENTS

Many of the trace elements show systematic variations (fig. 19C). Either an increase or decrease occurs between diorite and syenite, then a steady change from syenite to granite. Concentrations of Sr and Ba are low in diorite but increase to their highest levels in common syenite then decrease steadily to their lowest concentrations in granite. The sharp increase in Sr and Ba in common syenite coincides with the appearance of K-rich feldspar. Analyses of coarsely porphyritic syenite (sample 6 and 6-M), also indicate that Sr partitioned into the K-rich feldspar. Ba, however, is higher in the whole rock sample while Rb values are highest in the matrix. Concentrations of Co appear to correlate with occurrence of clinopyroxene phenocrysts.

SUMMARY OF SIGNIFICANT DATA

Any model of petrogenesis for the intrusive rocks in Mt. Pennell has to explain and account for the following:

Field Relationships

1. Intrusive sequence proceeded sequentially from diorite through syenite to granite.
2. Majority of contacts between rock units are gradational and blurred.
3. Intrusive units are crudely zoned from youngest in the center of the central stock to oldest in peripheral laccoliths.
4. Common syenite and soda syenite display local discordant changes in internal foliation, sharp intrusive con-

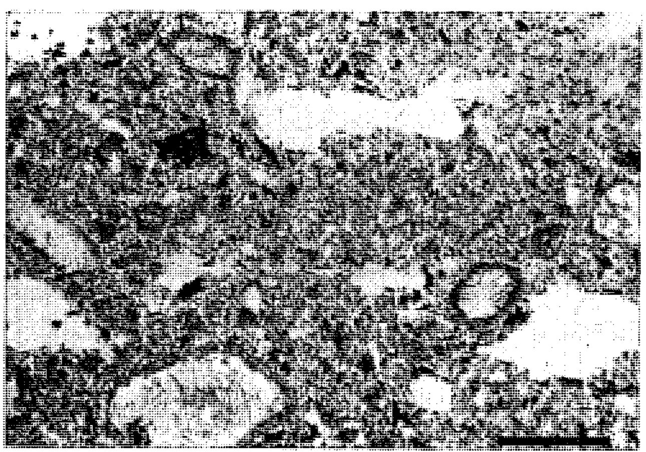


FIGURE 13.—*Granite porphyry. Irregular miarolitic cavities and anhedral feldspars with K-rich rims. Bar scale is 10 mm.*

FIGURE 15.—*High magnification view of elongate oval feldspar in granite porphyry. Note mosaic extinction within and distinct K-rich feldspar rim. Bar scale is 4 mm.*

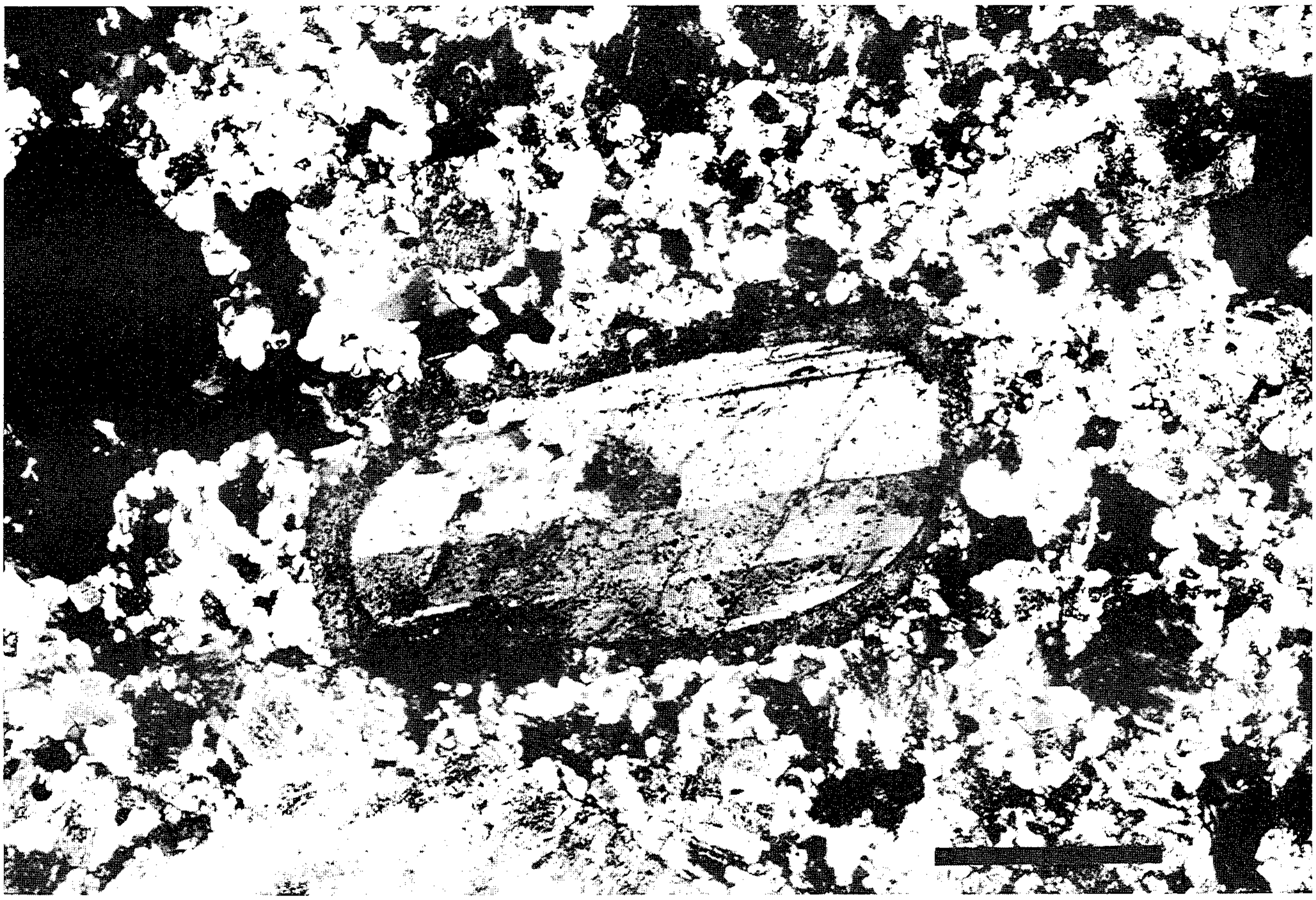


FIGURE 16.—*High magnification view of anhedral plagioclase phenocryst displaying albite twinning and faint carlsbad twinning, rimmed with K-rich feldspar. Dark areas are miarolitic cavities. Bar scale is 4 mm.*

tacts at the boundary of the changes, and small slickensides on some of the boundaries.

5. Major portions of coarsely porphyritic syenite and granite occur in fracture-controlled dikes and have phenocrysts aligned parallel to contacts, forming a pronounced flow foliation.

6. Large mafic inclusions are common only in diorite and syenite.

7. Sedimentary xenoliths occur almost exclusively in soda syenite and granite.

Petrography

1. Feldspars are distinctly zoned.

a. Plagioclase in diorite averages An 50 but shows oscillatory zonation.

b. Plagioclase in weakly porphyritic syenite contains oscillatory zones and two major zones, outer zone is more K-rich.

c. Plagioclase in common syenite contains two distinct zones. Oscillatory zones are rare.

d. Coarsely porphyritic syenite contains two alkali feld-spars; the Na-rich alkali feldspar has two distinct zones, the outer shows oscillatory zonation.

e. Soda syenite contains sodic alkali feldspar with three major zones, none show oscillatory zonation. K-rich feldspar phenocrysts are also present.

f. Granite contains three types of feldspar, all are rimmed with K-rich feldspar, none have oscillatory zones. One has at least four major zones, another is probably the same alkali feldspar as in soda syenite. Another displays albite twinning and appears very similar to plagioclase in diorite.

2. Hornblende is rimmed by opaques in diorite, by opaques and clinopyroxene in syenite, and replaced almost entirely by clinopyroxene in soda syenite.

3. Coarsely porphyritic syenite is virtually identical in composition to common syenite but has large euhedral K-rich alkali-feldspar phenocrysts, oscillatory zones in outermost major zone, and does not contain mafic inclusions.

4. Granite contains miarolitic cavities.

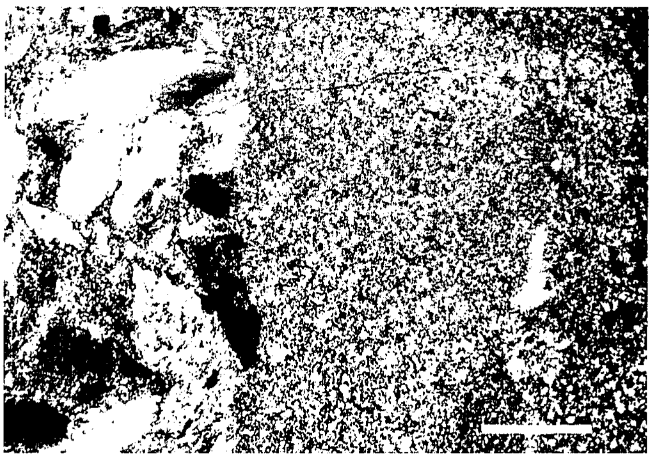


FIGURE 17.—*Contact between soda syenite, left, and microcrystalline felsic dike. Bar scale is 10 mm.*

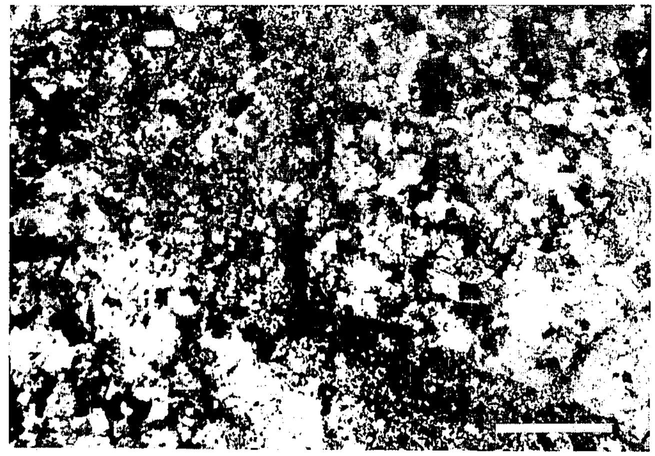


FIGURE 18.—*Exotic block. Note relict feldspar phenocryst with the corner outlined by dark garnet grains, center to right. Bar scale is 10 mm.*

Compositional Variations

1. By far the most significant variation is a progressive enrichment in normative alkali feldspar in younger intrusive units. This trend also prevails in all other Colorado Plateau laccolithic complexes where more than one rock type is present.
2. Four of the five complexes from which analyses are available show a late-stage enrichment in normative Or.
3. The youngest intrusive unit, granite porphyry, shows higher Mg, Ti, Ca, and Mg/Fe than immediately older soda syenite, and reverses the diminishing values in these elements in the sequence from diorite to syenite. A similar trend is reported in the Rico Mountains (Cross and Spencer 1900, McKnight 1974), where the magmatic sequence became progressively more felsic and terminated in lamprophyre magma. This sequence was likely true also of the Ute Mountains (fig. 21), but field relationships are not compelling (Ekren and Houser, 1965).
4. Ba and Sr first increase then decrease through the intrusive sequence.
5. Co and especially Rb show higher values with decreasing age of the units, whereas Cr decreases with age of the unit through the sequence.

POSSIBLE MODELS OF PETROGENESIS

Hunt and Waters (1958) proposed anatexis of amphibolitic basement rock to produce the sequence of La Sal Mountains' magmas. Their model, however, fails to explain the late alkali-feldspar enrichment in that complex as well as others in the Colorado Plateau. Ekren and Houser (1965) suggested that rock types in the Ute Mountains formed by differentiation of a mafic parent magma but did not explain how the differentiated magma chamber was emptied sequentially to supply intermediate magmas in the early intrusions and increasingly more felsic magmas in the later intrusions.

Wilcox (1954) suggested that at Parícutin, Mexico, a zoned magma chamber was evacuated bottom first via a fissure that fortuitously intersected the lowermost and least felsic part. It is tempting to adapt this mechanism to explain compositional changes in Mt. Pennell and the other laccolithic complexes of the Colorado Plateau. In doing so, however, it implies that in all of the laccolithic mountains, fortuitous fractures first intersected each chamber at the level of diorite. This does not seem a likely possibility.

Other mechanisms that might be considered to explain the sequence of intrusive rocks on Mt. Pennell and other Colorado Plateau laccolithic complexes include a variation of anatexis where partial melting advances upward into increasingly more felsic lower crustal source rocks. This mechanism is not favored because it appears unlikely that such a source region would be layered everywhere in just the right manner to produce the observed trend. Mixing of dissimilar magmas may also be proposed, but this mechanism does not explain the sequential zoning of feldspar phenocrysts nor, if diorite and granite were the end members, does it account for the intermediate syenites (fig. 19B).

McBirney (1980) presented a model and experimental analog to show how a single magma chamber might differentiate into stable, nonconvecting, chemical zones growing from the top of a chamber downward, eliminating a lower nonzoned convecting portion of the magma body. Magma differentiates as residual melts buoy up from the walls of the chamber as crystals grow there. No evacuation mechanism is proposed.

The model of petrogenesis preferred to explain the observed sequence of intrusive rocks on Mt. Pennell involves a feldspar-rich magma body within the crust that differentiated into zones from diorite composition near the base to syenite and granite toward the top. Elucidation of the exact mechanism by which this compositional zoning developed is beyond the scope of this study. One mechanism or a combination of several mechanisms, including double diffusive convection (Hildreth 1979, also McBirney 1980), may have formed the zones. The presence of oscillatory compositional zones in feldspars of the earliest intrusive units and the absence of these zones in feldspars in the later units may be interpreted to suggest the lower zone of differentiated magma was convecting and the upper zones were not. The differentiation mechanism of McBirney (1980) accounts for this interpretation and is favored. Also unsolved is how batches of magma were extracted sequentially from base upward, which is the reverse of the evacuation sequence observed in many calc-alkaline and silicic ash flow tuff magma systems.

Evidence that injection of mantle-derived basaltic magma into the base of a high crustal level silicic magma chamber can trigger explosive eruptions has been presented by Sparks and Sigurdsson (1977). Hot basaltic magma causes local superheating and increased volatile pressure in the silicic magma body, causing the roof of the chamber to crack, allowing quick volatile release to the surface and evacuation of the chamber from top downward.

It appears theoretically possible that injection of hot mafic magma into the bottom of a crystal-laden, highly viscous, zoned, intermediate composition magma chamber might cause volatile presssure to increase sufficiently to crack the roof of the chamber but not sufficient to extend the cracks to the surface. This being the case, quick pressure release should not occur and the magma might not evacuate from the top downward. Instead, the lowermost heated zone, because of rapid decreases in viscosity and density, might move upward and escape through the overlying colder and more viscous magma zones by simply buoying upward or through "cracks" that may have developed in the nearly congealed overlying zones. This proposal raises many questions for which there are no answers because of an absence of experimental data. However, noting that intrusive bodies have been described where partially molten rock has apparently behaved simultaneously plastically and in a brittle manner (Shaw 1980) and the very high phenocryst content and apparent high viscosity of magmas that formed syenites in Mt. Pennell, makes the model more appealing.

While not shedding light on the mechanisms by which zoned magma managed to evacuate the chamber bottom first, integration of data strongly suggests close genetic relations between several of the younger intrusive units. These relations are used together with the basic differentiation trend to conceive a working hypothesis for the later intrusive units.

A small portion of magma that formed common syenite apparently remained in the chamber, was heated by underplating mafic magma, and became less viscous. It experienced a phase re-equilibration that caused large, oscillatory zoned K-rich alkali feldspars to grow along with oscillatory zones over previous zones in the other alkali feldspars. It then was intruded into fractures to form coarsely porphyritic syenite. A significant amount of volatiles apparently escaped from the chamber with this evacuation, causing another re-equilibration. The following unit, soda syenite, contains clinopyroxene instead of hornblende, although small amounts of hornblende remained as poikilitic inclusions inside crystals of clinopyroxene, where replacement was not complete. This re-equilibration also caused feldspar growth to shift toward Ab as recorded within the feldspars in soda syenite.

Soda syenite magma apparently evacuated from the storage chamber as a dry viscous crystalline mush. Alkali-feldspar phenocrysts were deformed and ruptured. Large K-rich alkali-feldspar phenocrysts, which presumably were once euhedral, became deformed and broken. Wall rock was plucked and became incorporated as xenoliths; blocks of common and coarsely porphyritic syenite were also incorporated and became exotic blocks. Soda syenite magma remained in one large cohesive body and did not form dikes.

A small portion of the differentiated magma that remained in the chamber following emplacement of soda syenite became enriched in components that partitioned into the melt, notably Or constituents and Rb. Re-equilibration apparently occurred once again, causing the remaining feldspar phenocrysts, which included remnants from several earlier units, to be rimmed with K-rich feldspar. Previously emplaced magma bodies had time to become more or less completely solidified while granite magma was being chemically contaminated by the underplating mafic magma. Granite magma was emplaced at shallow depth and gained a miarolitic texture by exsolution of volatiles from the top of the chamber.

ALTERATION AND MINERALIZATION

Hydrothermal fluids that accompanied and followed the intrusion of granite porphyry magma disseminated outward through the concentric fracture zone and into radial fractures, creating an aureole of alteration immediately adjacent to the stock. Precious metals were deposited in fissure veins as these fluids cooled upon reaching outlying regions of the intrusive complex (plate 1).

Diorite of the laccoliths is altered near the stock, and in concentric bands lying outward from the stock. Effects of

PETROGRAPHIC DATA, MT. PENNELL INTRUSIVE PORPHYRIES
(From visual estimates)

Intrusive sequence		oldest			youngest
Average modal %		Diorite	Syenite	Soda Syenite	Granite
Matrix		50	40 coarsely porphyritic 48 others	35	55
PHENOCRYSTS	Plagioclase	30	30 coarsely porphyritic 35 others	55	16
	K Spar		15 coarsely porphyritic 5 others	2	6
	Hornblende	14	3 coarsely porphyritic 7 others	<1	
	Clinopyroxene		5	6	
	Apatite	1	<1		
	Sphene	<1	1	<1	<1
	Opaques	3	4	1	1
Sedimentary xenoliths				1	1
Inclusions		2% mafic	2% mafic		6% igneous
Average An		50	25	12	25
Comments		Two varieties, quartz diorite has 7 % quartz as bipyramidal phenocrysts, both varieties have oscillatory zoned feldspars.	Four textures, all feldspars have two zones. Weakly and coarsely porphyritic syenites have oscillatory zoned feldspars. Flow foliation in coarsely porphyritic syenite.	One texture, oval shaped strained and ruptured feldspars with three zones, no oscillatory zones.	One texture, 15% miarolitic cavities. Feldspars have four zones. Abundant K-spar in matrix.
Number of samples		4	8	5	3

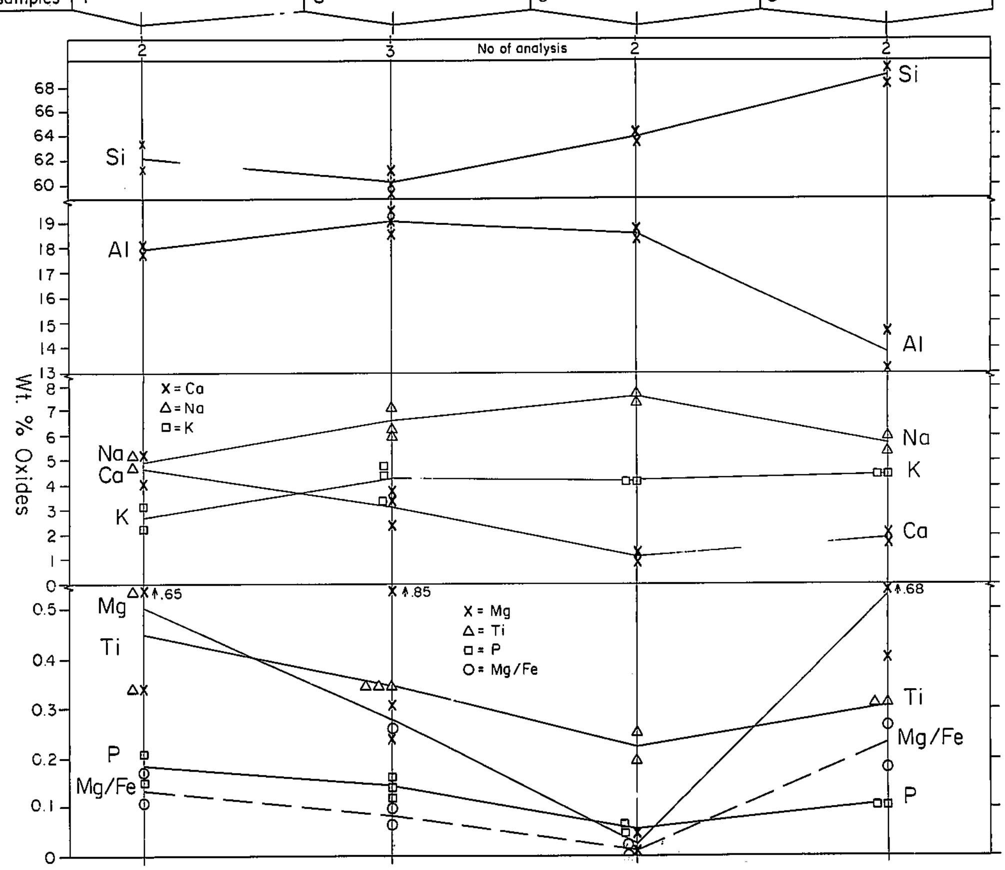


FIGURE 19.—*Major element variation diagram. (Data point symbols are offset to the left when values overprint.)*

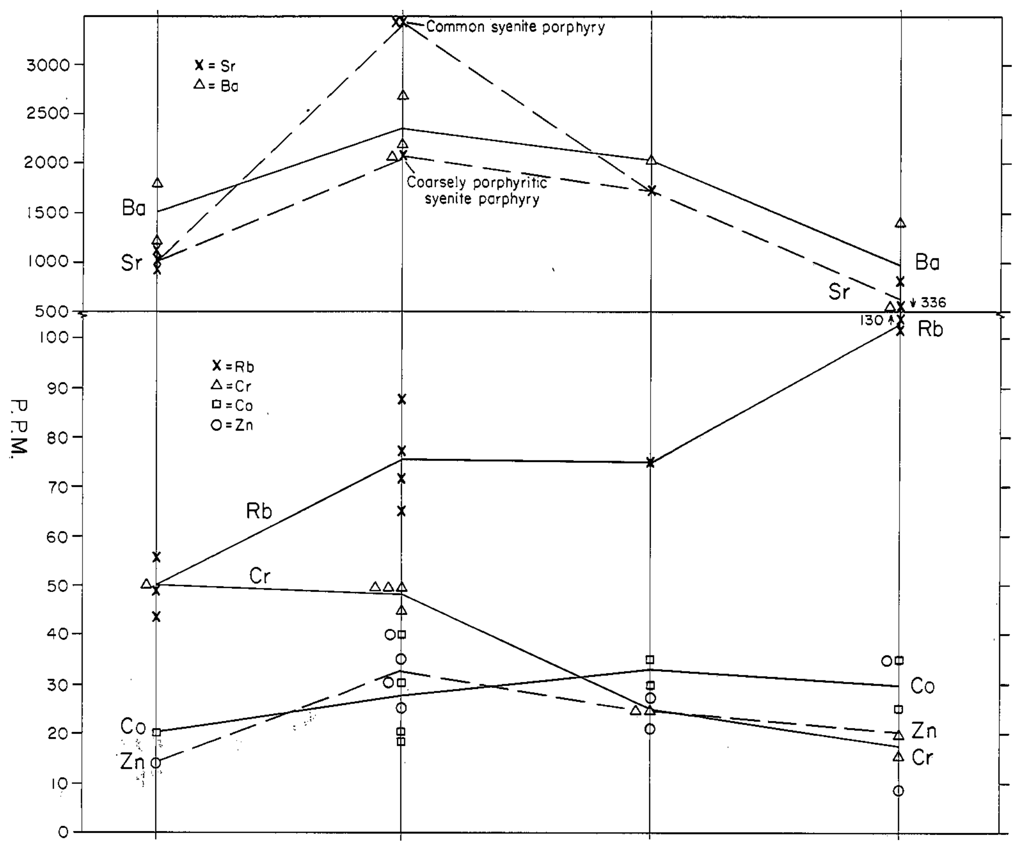


FIGURE 19. continued—*Trace element variation diagram. (Data point symbols are offset to the left when values overprint.)*

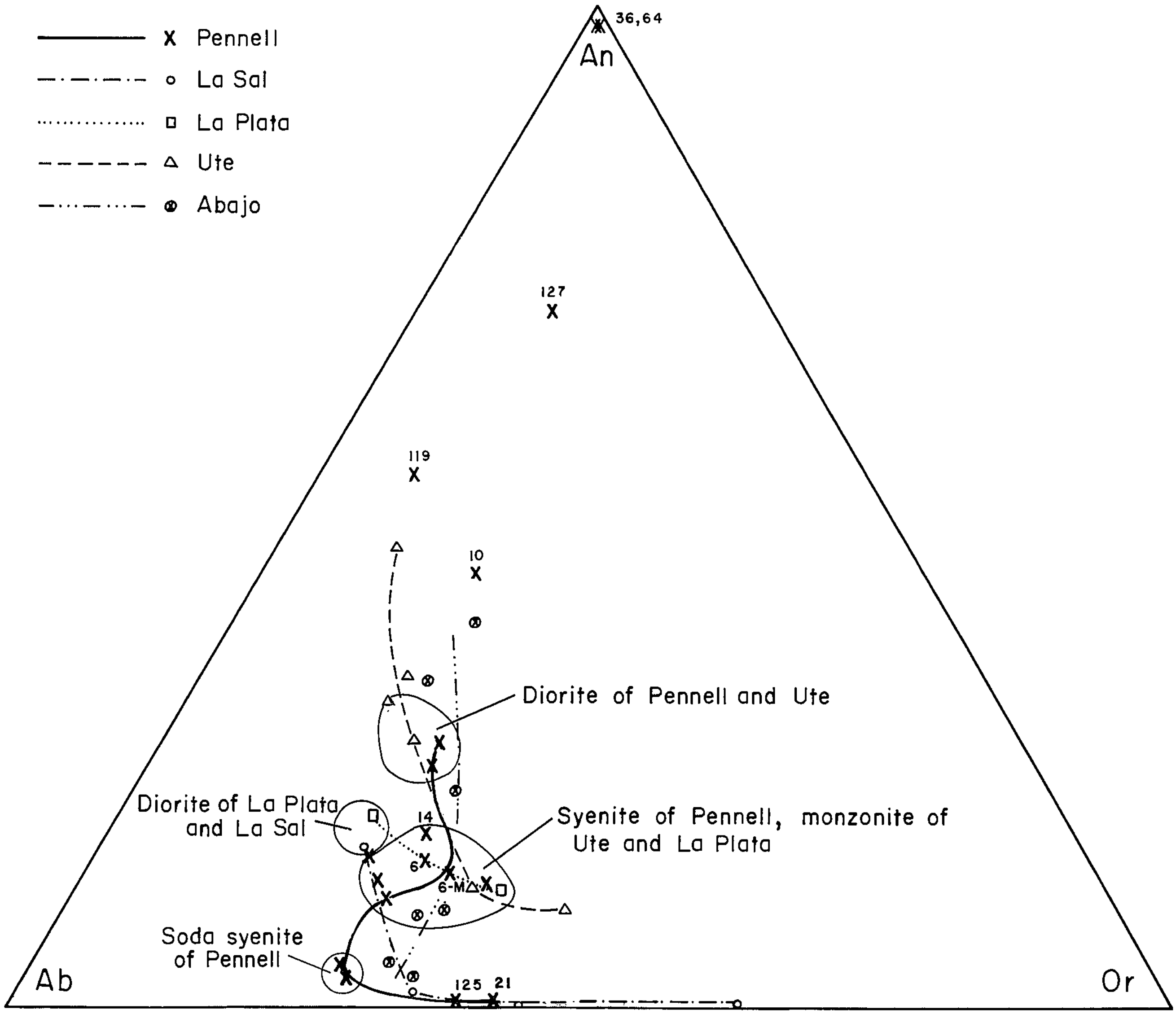


FIGURE 20.—*Normative Feldspar Diagram. La Sal, Hunt and Waters (1958); La Plata, Eckel (1937); Ute, Ekren and Houser (1965); Abajo, Witkind (1964). 14: Weakly porphyritic syenite, Pennell; 21, 125: Granite porphyry, Pennell; 10, 119, 127: Gneissic mafic inclusions, Pennell; 36, 64: Massive high Fe maffic inclusions, Pennell.*

alteration die out irregularly within one mile from the perimeter of the stock. The alteration aureole is easily recognized by limonite formed by decomposition of pyrite deposited during alteration. Samples of diorite porphyry collected from the alteration zone (plate 1) also show effects of propylitic alteration. Hornblende is replaced by chlorite, calcite, magnetite, and epidote. Feldspars are replaced by minor amounts of sericite. Radial fractures in the alteration aureole are actually fissure veins filled with a laterally zoned assemblage of hydrothermal minerals. Limonite plus calcite and quartz are found within the stock, whereas limonite plus quartz is found as far as one-quarter mile beyond the stock. Only limonite is found beyond that. Native gold and silver together with copper carbonates are also present in most of the fissure veins. These metals also display a crude zonation. All three are found within the central stock, and are particularly abundant at the copper prospect in upper Straight Creek where copper occurs as bornite and chalcopyrite. Molybdenite is present in trace amounts and increases at depth, according to drill core assays (Smith 1973). This indicates that molybdenum, and perhaps other metals, are zoned vertically as well as laterally.

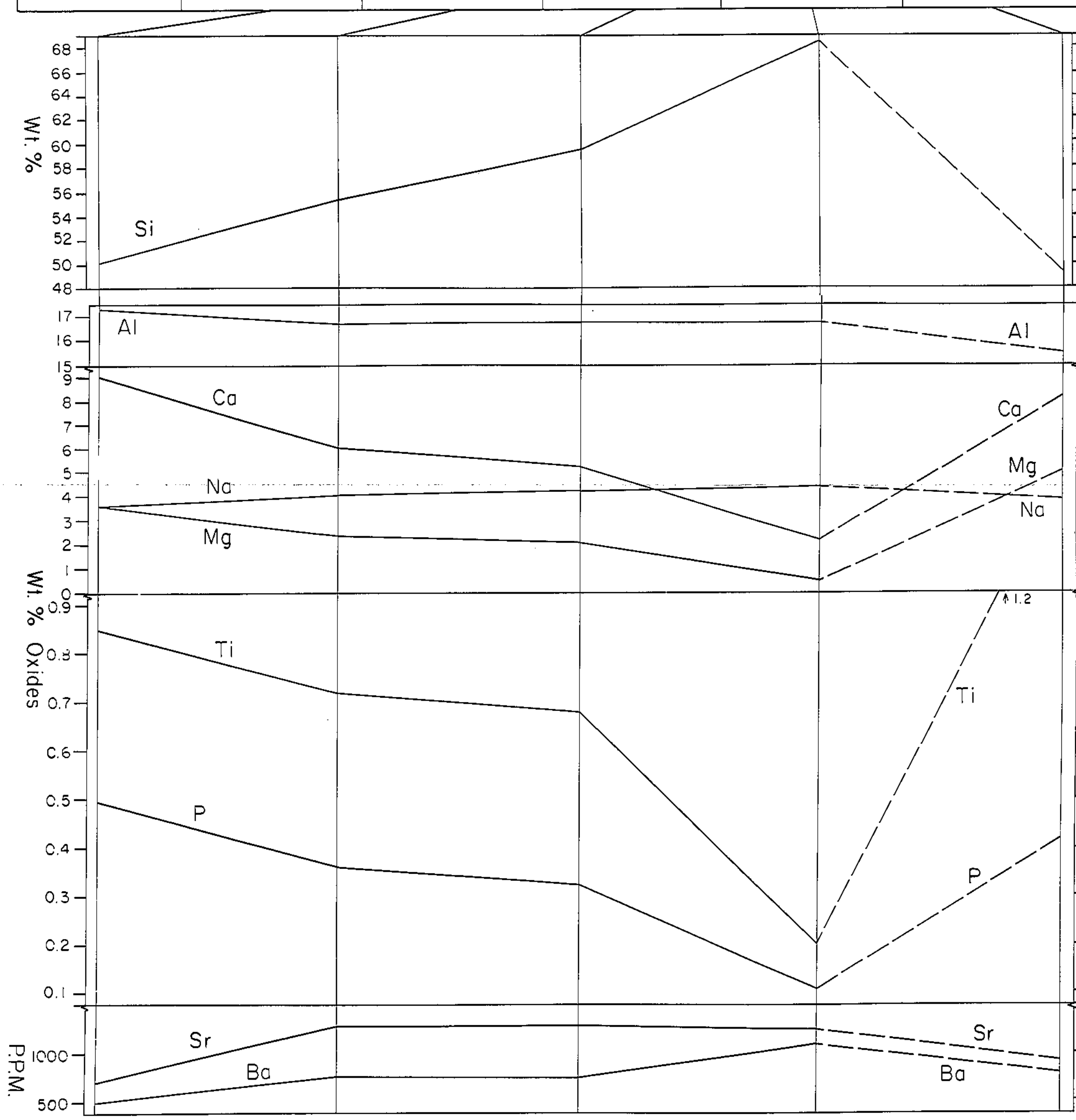
FIGURE 21

PETROGRAPHIC DATA AND CHEMICAL VARIATION DIAGRAMS, UTE MOUNTAINS INTRUSIVE PORPHYRIES

Data from Ekren & Houser (1965)
(Note, position of Lamprophyre in intrusive sequence is not well established)

Intrusive sequence — oldest … youngest

Representative modal %	Gabbro	Diorite	Granodiorite	Qtz. Monzonite	Lamprophyre
Plagioclase	59	38	34	31	43
K-Spar		3			1
Hornblende	10	5	9		3
Augite	3	8	trace		17
Quartz	4		4	7	
Comments	Zoned plagioclase Max. An≈65, Average An = 55	Plagioclase zoned from ≈An65 to ≈An30	Zoned plagioclase ≈An40, K-spar in matrix.	Zoned plagioclase cores ≈An50, outer zones ≈An30	Zoned plagioclase Average An40



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