University of Montana

ScholarWorks at University of Montana

Graduate Student Theses, Dissertations, & Professional Papers

Graduate School

1985

Differentiation of a shoshonitic magma at Snake Butte Blaine County Montana

Dave E. Leppert
The University of Montana

Follow this and additional works at: https://scholarworks.umt.edu/etd

Let us know how access to this document benefits you.

Recommended Citation

Leppert, Dave E., "Differentiation of a shoshonitic magma at Snake Butte Blaine County Montana" (1985). *Graduate Student Theses, Dissertations, & Professional Papers*. 7437.
https://scholarworks.umt.edu/etd/7437

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.

COPYRIGHT ACT OF 1976

THIS IS AN UNPUBLISHED MANUSCRIPT IN WHICH COPYRIGHT SUBSISTS. ANY FURTHER REPRINTING OF ITS CONTENTS MUST BE APPROVED BY THE AUTHOR.

MANSFIELD LIBRARY
UNIVERSITY OF MONTANA
DATE: 1985

Differentiation of a Shoshonitic Magma at

Snake Butte, Blaine County, Montana

By

Dave E. Leppert

B.S. Utah State University, 1978

Presented in partial fulfillment of the requirements for the degree of

Master of Science

University of Montana

1985

Approved by: DW Hyndman

Chairman, Board of Examiners

Dean, Graduate School

------May 16, 1985------
Date

UMI Number: EP38238

All rights reserved

INFORMATION TO ALL USERS
The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript
and there are missing pages, these will be noted. Also, if material had to be removed,
a note will indicate the deletion.

UMI
Dissertation Publishing

UMI EP38238
Published by ProQuest LLC (2013). Copyright in the Dissertation held by the Author.
Microform Edition © ProQuest LLC.
All rights reserved. This work is protected against
unauthorized copying under Title 17, United States Code

ProQuest

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346

Leppert, Dave E. M.S., June 1985 Geology

Differentiation of a Shoshonitic Magma at Snake Butte,

Blaine County, Montana (121 pp.)

Director: Dr. Donald W. Hyndman

Snake Butte, a sill-like laccolith on the eastern flank of the Bearpaw Mountains provides an excellent example of magmatic differentiation dominantly occurring prior to intrusion. Unlike other alkalic laccoliths of central Montana, excellent exposures, in part due to a large quarry, allowed access to the lower and upper chill zones and feeder dike in addition to the interior portions of the laccolith.

A vertical section through the intrusion consists of: lower felsic chill zone, felsic shonkinite, mafic shonkinite, syenite pegmatite, syenite, and upper chill zone. Except for the syenite pegmatite, this sequence also roughly corresponds to a section across the feeder dike.

Geochemical and petrographic evidence indicates that crystal fractionation dominated pre-intrusion differentiation. Contrasts in phenocryst content and geochemistry between the lower and upper chill zones are consistent with a model of pre-intrusive crystal settling. A tie line on the AFM diagram projects to a Mg:Fe ration of 85:15, corresponding to the observed ratio within the olivine.

The origin of syenite globules within the mafic shonkinite remains enigmatic. Similar studies of alkalic laccoliths propose an origin via silicate liquid immiscibility, but segregation of fluids flowing through the crystal matrix remains as an alternative explanation of the globules.

Residual fluids formed pegmatites during late stages of crystallization. The formation of joints apparently stimulated the migration of residual fluids.

Acknowledgements

Thanks to my parents for moral and financial support. Don Fiesinger stimulated my interest in mineralogy and igneous rocks. Jack Wehrenberg provided excellent technical advice and suggested studying Snake Butte. Thanks also to Don Hyndman and Dave Alt for insights into the formation of alkaline rocks, Keith Osterheld for serving as an advisor, the geology department staff, my friends at the University of Montana, and my mountaineering buddies for peace of mind.

Table of Contents

List of Illustrations

INTRODUCTION

Snake Butte, a sill-like laccolith of shoshonitic affinity on the eastern flank of the Bearpaw Mountains, Montana, provides an excellent opportunity to further test theories of magmatic differentiation in alkalic rocks. Edmond (1980), Kendricks (1980), Kuhn (1983) and Liptak (1984) invoked silicate liquid immiscibility as the dominant process responsible for differentiation of similar laccoliths in central Montana. However, silicate liquid immiscibility apparently played an insignificant role in the differentiation at Snake Butte. Crystal fractionation dominated the differentiation at Snake Butte with volatile transport probably contributing significantly. Much of the differentiation occurred prior to intrusion.

Many factors influenced the choice of Snake Butte, initially suggested by Dr. J.P. Wehrenberg, over numerous other differentiated alkalic intrusions in Montana. These include:

1. Good accessibility with roads part way around and on top of the butte;
2. Excellent exposure, partially due to a large quarry on the north side which provided rock for construction of the Fort Peck dam;
3. Relative intactness, with exposure of the upper and lower contacts;
4. Relatively simple intrusion, isolated from the main eruptive centers of the Bearpaw Mountains with only one apparent feeder dike and;

5. Extensive zeolitization; this fascinating group of minerals may provide clues to the water content of the magma.

Various analytical methods supplemented field observations and geologic mapping. Whole rock densities successfully allowed quantitative comparison of many samples rapidly and for a minimal cost. Whole rock geochemistry permitted the essential quantitative evaluation of composition to help determine the dominant processes of magmatic differentiation. Thin section petrography supplied critical mineralogical and petrological information, and x-ray diffraction aided in the identification of minerals when petrographic methods proved insufficient.

LOCATION AND ACCESS

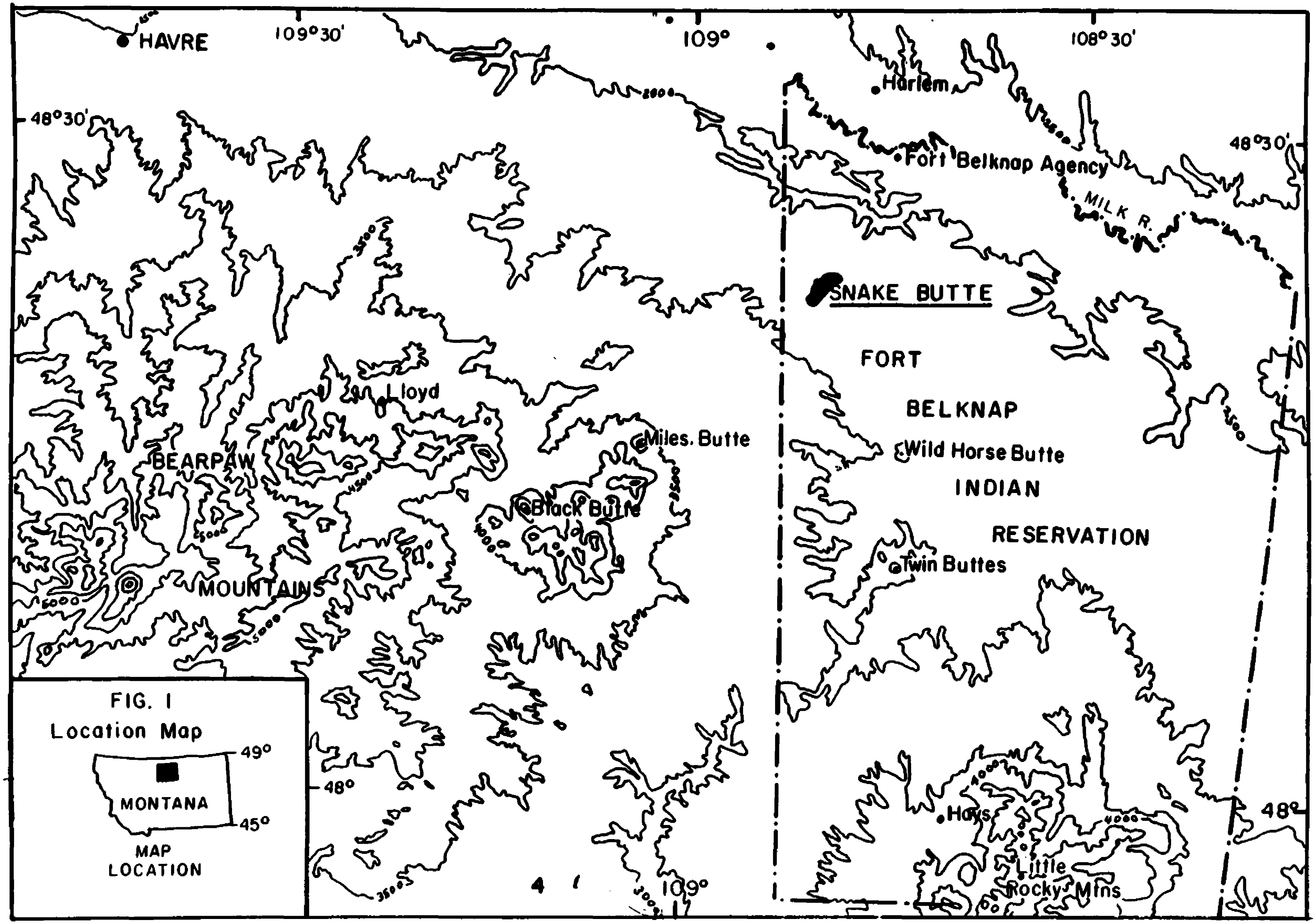
Snake Butte lies on the eastern fringe of the Bearpaw Mountains within the Fort Belknap Indian Reservation at longitude 108 50' West and latitude 48 23' North (Fig. 1). Six miles of improved dirt road provides access from state highway 66, with unimproved dirt roads allowing access to the top and southeast side of the butte.

An inhospitable climate prevails with extremes of temperature during winter and summer, though some days are pleasant. Prevailing westerly winds make the cold bite and camping difficult. Unfortunately, the winds tend to cease during the heat of the day when they could provide some relief. Thunderstorms frequently pass through the area during the summer. Of course, the butte attracts lightning which may add some excitement to your day.

Although a few small trees grow in the quarry, grasses dominate the vegetation. The lack of tall plants aids geologic study of the area considerably.

As the name implies, rattlesnakes abound. In particular, the broken rock around the quarry provides cozy homes for them. The feeder dike should be approached cautiously since the prairie to the southeast of Snake Butte supports a herd of bison.

Anyone wishing to visit Snake Butte or other intrusives on the Fort Belknap Reservation should contact the tribal chairman at the Fort Belknap Agency.


HAVRE
109°30'
109°
108°30'
48°30'
48°30'
Harlem
Fort Belknap Agency
MILK R.
SNAKE BUTTE
FORT
BELKNAP
INDIAN
RESERVATION
Lloyd
Miles Butte
Wild Horse Butte
BEARPAW
MOUNTAINS
Black Butte
Twin Buttes
48°
48°
Hays
Little
Rocky Mtns
109°
Location Map
49°
45°
MONTANA
MAP
LOCATION
FIG. I

HISTORICAL BACKGROUND AND GENERAL GEOLOGY OF THE BEARPAW MOUNTAINS

The Bearpaw Mountains, one of the larger alkalic complexes in Montana, cover parts of Hill, Choteau, and Blaine counties southeast of Havre, Montana. The igneous complex consists of a wide variety of mid-Eocene extrusive and intrusive rocks. These include trachyte, shonkinite, syenite, pyroxenite, alkalic monzonite, carbonatitic dikes and other igneous rocks in addition to Cretaceous to Recent sediments. Hearn (1976) provides a relatively recent geologic map of the region, including a summary of the geologic history and structure. Snake Butte lies approximately 12 km east of the eastern boundary of this map.

The earliest reference to the igneous rocks of the Bearpaw Mountains consists of an analysis by Lindgren and Melville (1896). Weed and Pirrson (1896b) completed a general geologic reconaissance of the area, including a map, but failed to mention the outlying intrusion at Snake Butte. A few interesting observations by them include the occurrence of "globulitic material" and their difficulty in explaining the high water content of the fresh, unaltered appearing rock. They concluded that the abundant analcite in the rock may represent a primary phase. Also, they invoked "liquation" (liquid immiscibility) as a possible differentiation process and noted numerous similarities with the Highwood Mountains.

Cathcart (1922?) first described the petrography of Snake Butte as quoted by Knechtel (1942). In his description of the glacial geology of the region, Knechtel noted glacial striae and exotic cobbles on Snake Butte.

Reeves (1924) mapped much of the area surrounding the Bearpaw Mountains. His studies concentrated on the associated folding and faulting and he mapped a series of concentric thrust faults and folds around the igneous complex. Snake Butte, Twin Buttes and Wild Horse Butte lie in a concentric arc on trend with the mapped faults, though due to glacial cover no faults appear on Reeves' map in this area. He surmized that the localized tectonic activity resulted from the load imposed by the massive volcanic pile. This idea seems reasonable and gains support from a series of gelatin experiments performed by Hyndman and Alt (1983). Reeves cited evidence that the faulting occurred after emplacement of the intrusions.

The gelatin experiments also suggest that the laccoliths should form around the long axis of the igneous complex. They note a similar relationship with intrusions in a concentric arc north of the Adel Mountains, Montana. The long axis of the Bearpaw Mountains obviously runs approximately east-west, in line with the laccoliths (Fig. 2). A horst along this axis exposes intrusive rocks while volcanic rocks remain north and south of the horst. Fisher (1946) speculated that deep-seated basement faults control the location of the east-west trend of the Bearpaw Mountains and associated laccoliths. Alverson (1965) stated that Twin Buttes and Wild Horse Butte originated from the little Rocky Mountains. However, he provided no evidence for this.

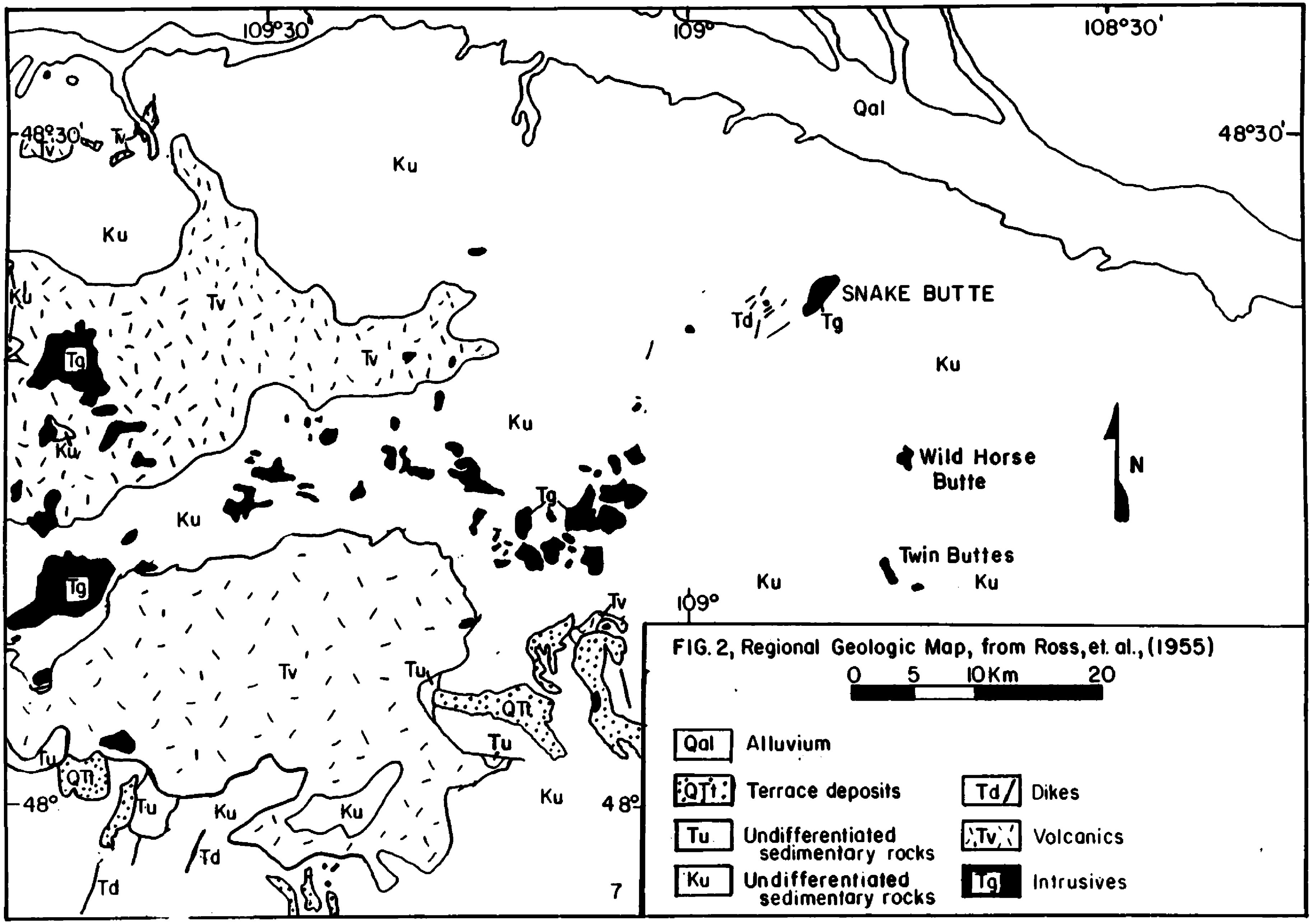


FIG. 2, Regional Geologic Map, from Ross, et. al., (1955) Fisher (1946) described a series of trachytes which erupted before emplacement of shonkinites. The early volcanic series possibly produced minor folding which provided the locus for later emplacement of the three intrusions along an arc on the eastern flank of the Bearpaw Mountains. He also examined a series of analcime-bearing phonolites and concluded on the basis of similar chemical composition and age that they were the extrusive equivalents of the shonkinitic intrusions. Numerous shonkinitic intrusions within the Bearpaws are differentiated (Fisher, 1946).

Fisher's study of Snake Butte furnishes the most extensive information about the laccolith before this report. He measured whole-rock densities and mafic mineral content from core holes drilled in conjunction with development of the quarry during the late 1930's. Fisher's (1946) data reveal a low density zone near the base of the intrusion, with increasing density upward. His density data did not extend to the syenites on top of Snake Butte.

Fisher (1946) concluded that crystal fractionation explained the major differentiation at Snake Butte with possible minor effects of assimilation and volatile transport. He explained the vertical pegmatitic dikes as a result of collapse of the roof and squeezing of the still liquid fraction downward into previously formed fractures. He accounted for the lower felsic zone by rapid cooling which hindered crystal settling above the lower contact. However, as explained later in this report, additional evidence modifies Fisher's conclusions.

The U.S. Geological Survey published a series of six Geological Survey Bulletins and accompanying maps on quadrangles in the Bearpaw Mountains in the 1950's and 1960's. These studies noted differentiation within various intrusives, but did not include detailed work on any single intrusive (Bryant, et. al., 1960; Hearn, et. al, 1964; Kerr, et. al, 1957; Pecora, et. al, 1957; Schmidt, et.al., 1961, 1964; Stewart, et. al., 1957)

Other laccolith studies (Edmond, 1980) in central Montana recognize a low density zone near the base and invoke silicate liquid immiscibility as the explanation for the low density zone. According to this hypothesis, cooling inhibited complete separation of the immiscible magmas.

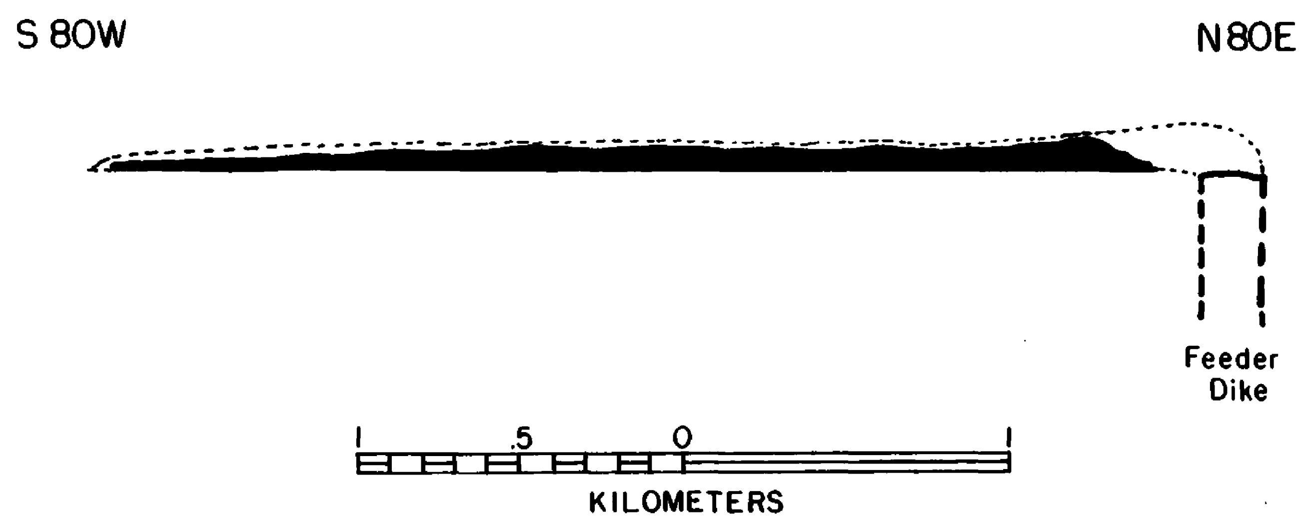
FIELD RELATIONS

Snake Butte is a wedge-shaped, predominantly concordant intrusion four kilometers long and two kilometers wide (Fig. 1). A 217-meter-wide (as measured by pacing) feeder dike enters the laccolith from the south, tangential to the eastern margin (Fig. 4). Note that the width of the dike greatly exceeds the 100m thickness of the laccolith (Fig. 2). The tangential relationship between the feeder dike and the laccolith coincides with the results of gelatin experiments by Hyndman and Alt (1983). The magma apparently rose within the dike and "flipped over" as the lithostatic load decreased below some critical value. The presence of a relatively competent bed above the laccolith possibly influenced the precise level of emplacement.

From a maximum thickness of approximately 100 m adjacent to the feeder dike, the laccolith tapers northwest and west. The upper surface slopes away from the high point adjacent to the feeder dike, but the lower surface remains relatively horizontal (Fig. 3).

Sharp contacts separate the laccolith from the country rock, the Cretaceous Bearpaw Shale (Alverson, 1965). A zone of hard, tan baked shale extends approximately 3 m from the contact. The shale interfingers with the intrusion near the margins. In the quarry, shonkinite surrounds beds of shale (Fig. 6). Silty beds above the upper contact possibly acted as a competent layer to influence the level of emplacement.

FIGURE 3
SNAKE BUTTE
TRUE-SCALE CROSS SECTION



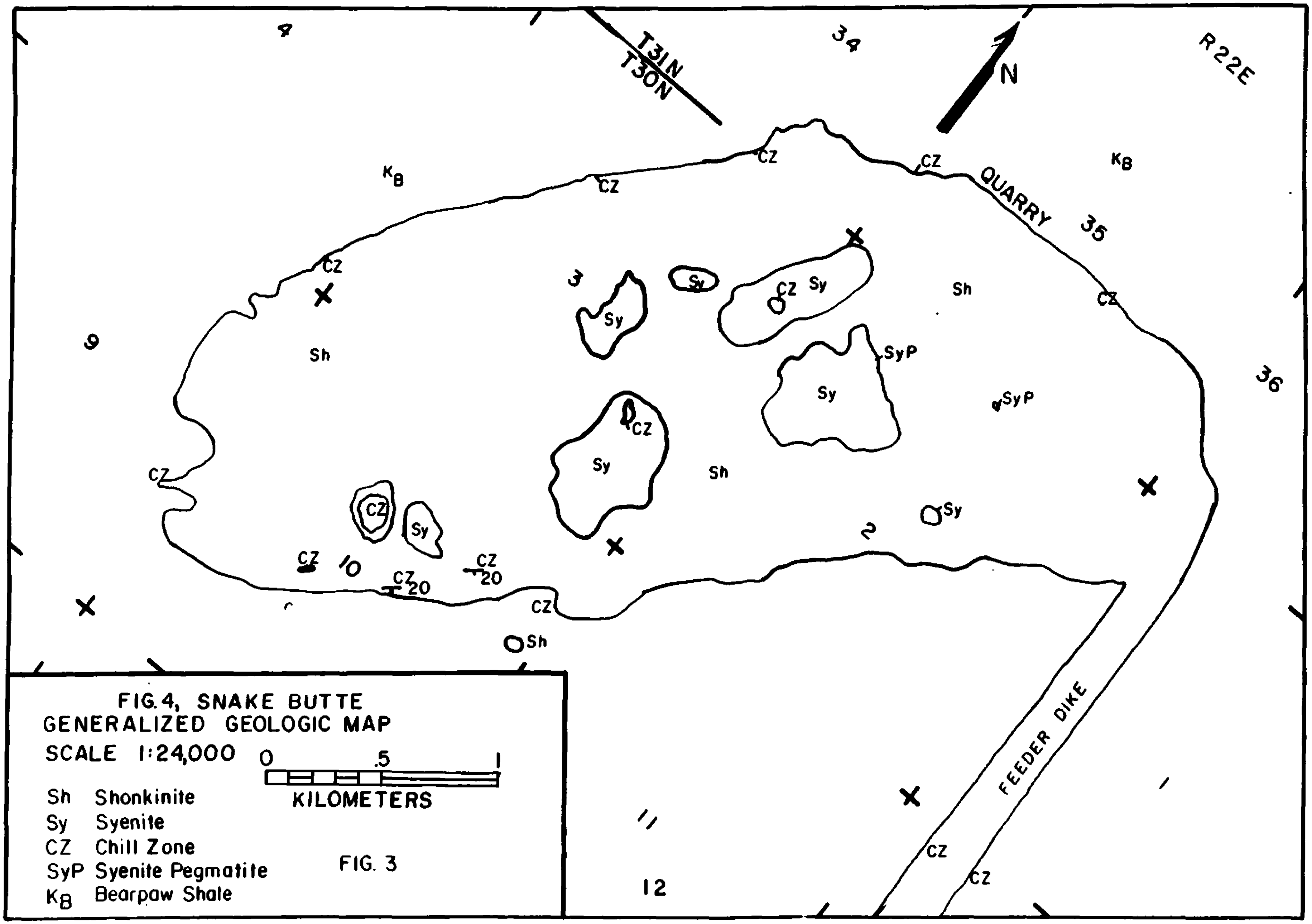
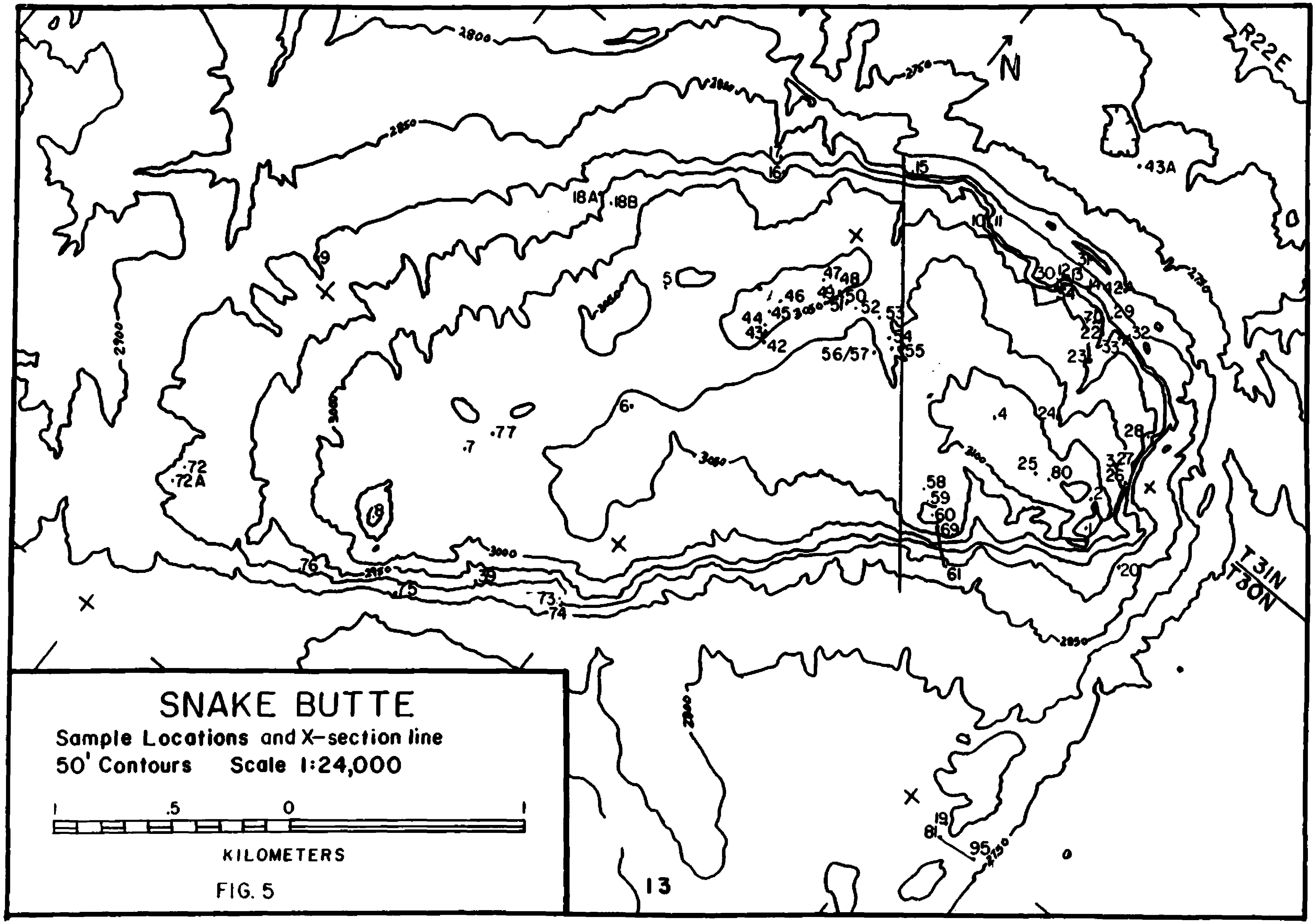


FIG.4, SNAKE BUTTE
GENERALIZED GEOLOGIC MAP



SNAKE BUTTE

Sample Locations and X–section line
50' Contours Scale 1:24,000

FIG. 5

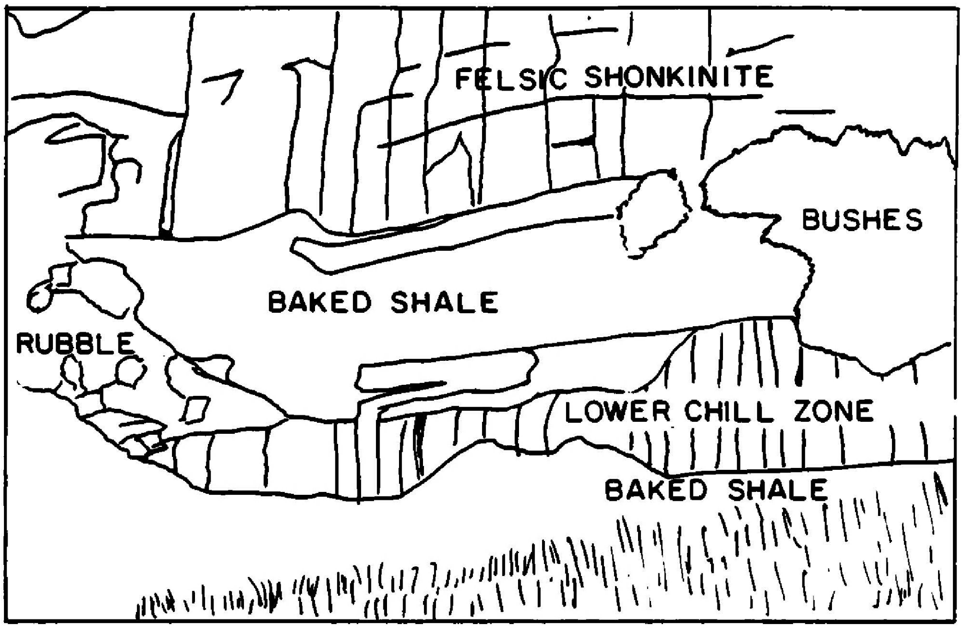


FIG. 6, Photo and sketch showing interfingering relationships in the quarry, near the margin of the laccolith.

Large-scale features of the laccolith become obvious when viewed from a distance. Benches separate cliffs on the southeast side of the butte and reveal distinctive layering within the intrusion. The layers undulate slightly and one of the major drainages follows a small synclinal fold (Fig. 7). Views from the north reveal the overall tapering away from the feeder dike and tilt of the upper surface which merges with the prairie to the southwest.

In order to evaluate Snake Butte within the framework of the central Montana alkalic province, I visited Round Butte, Shaw Butte, the Sweetgrass Hills, Shonkin Sag laccolith, and various parts of the Bearpaw Mountains. Numerous similarities with the extensively studied Shonkin Sag laccolith (Barksdale, 1937; Nash and Wilkinson, 1970; Edmond,1980; and numerous others, see Edmond) provoke comparison. Obvious differences between the intrusions also exist.

Briefly, various authors attributed the differentiation at Shonkin Sag laccolith to processes ranging from multiple injection (Barksdale, 1937), to in situ crystal fractionation (Hurlbut, 1939), and most recently to silicate liquid immiscibility (Edmond, 1980). Knowledge acquired from study of Snake Butte will aid in interpretation of this classic petrologic puzzle.

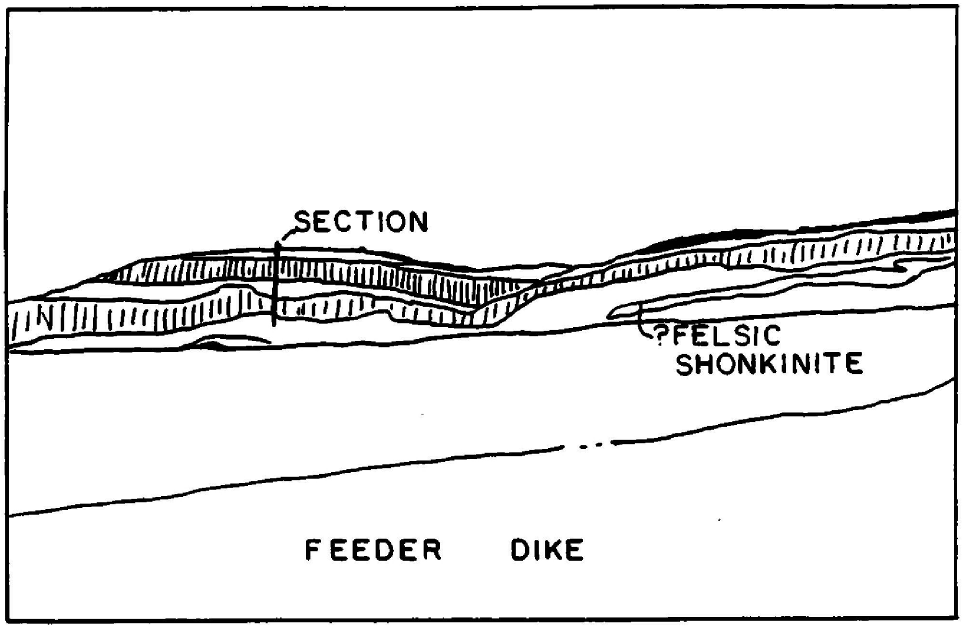
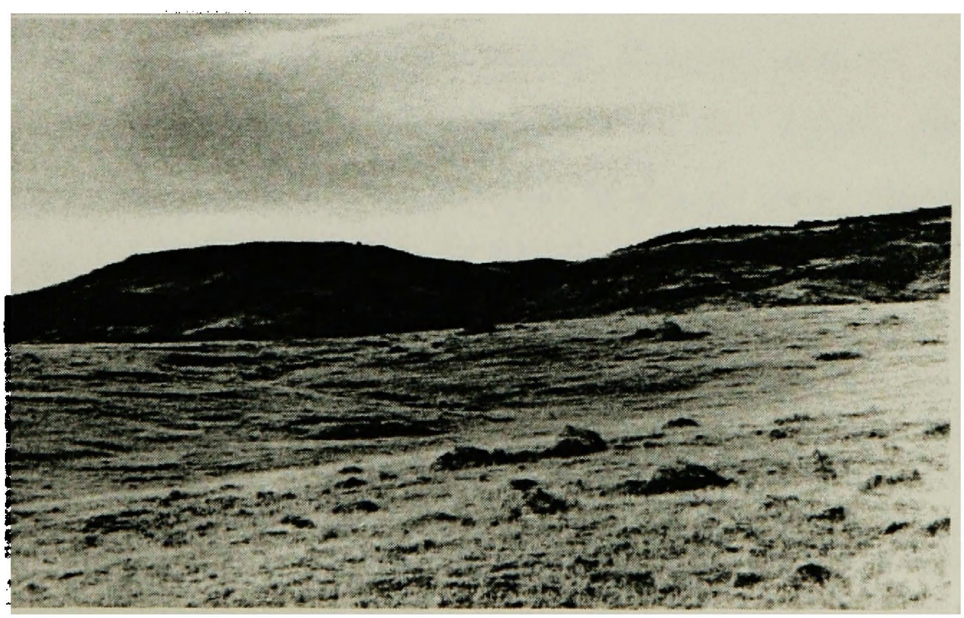


FIG.7, PHOTO AND SKETCH SHOWING LAYERING ON THE SOUTH SIDE OF SNAKE BUTTE, FROM THE FEEDER DIKE. THE GENTLE TILT TO THE WEST, UNDULATING LAYERING, AND ALTERNATING CLIFFS AND BENCHES ARE EVIDENT FROM THIS VIEW. SECTION OF SAMPLES 61-69 INDICATED



Units within the laccolith

The laccolith consists of six distinct units: the lower chill zone, felsic shonkinite, main shonkinite, syenite pegmatite, syenite, and the upper chill zone (Fig. 8). Minor features include felsic sheets, pegmatitic dikes, syenitic globules, and the upper shonkinite. This sequence roughly coincides with the rock units observed at Shonkin Sag laccolith (Edmond, 1980; Barksdale, 1937).

Lower Chill Zone

The best exposure of the lower chill zone at Snake Butte occurs in the quarry. A few poor exposures exist along the northwest margin of the laccolith and another excellent exposure is on the south side. At the contact (Fig. 9A) the dark gray aphanitic rock contains only small number of phenocrysts less than 2 mm across. Away from the contact the grain size gradually increases and the lower chill zone merges gradationally with the overlying felsic shonkinite.

White sheets, less than 1 cm thick, parallel the lower contact within the lower chill zone (Fig. 10). They are composed of natrolite, alkali feldspar and aegirine. Some studies of other alkalic laccoliths in Montana refer to similar features as "ribbons" (Kuhn, 1983). They apparently represent residual fluids which migrated into joints formed parallel to the contact.

FIG.8, COMPOSITE STRATIGRAPHIC COLUMN

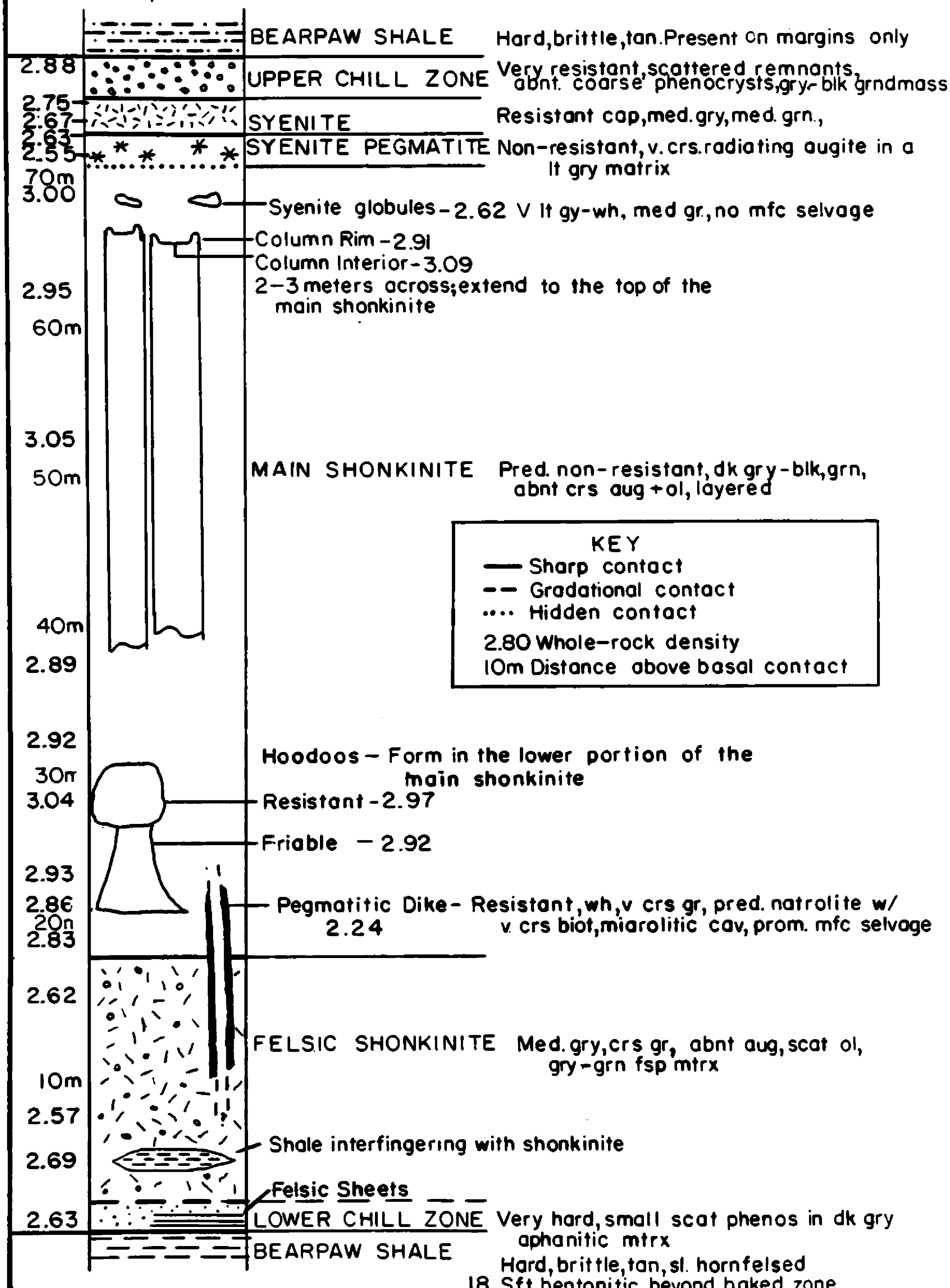


FIG. 9 HAND SPECIMENS

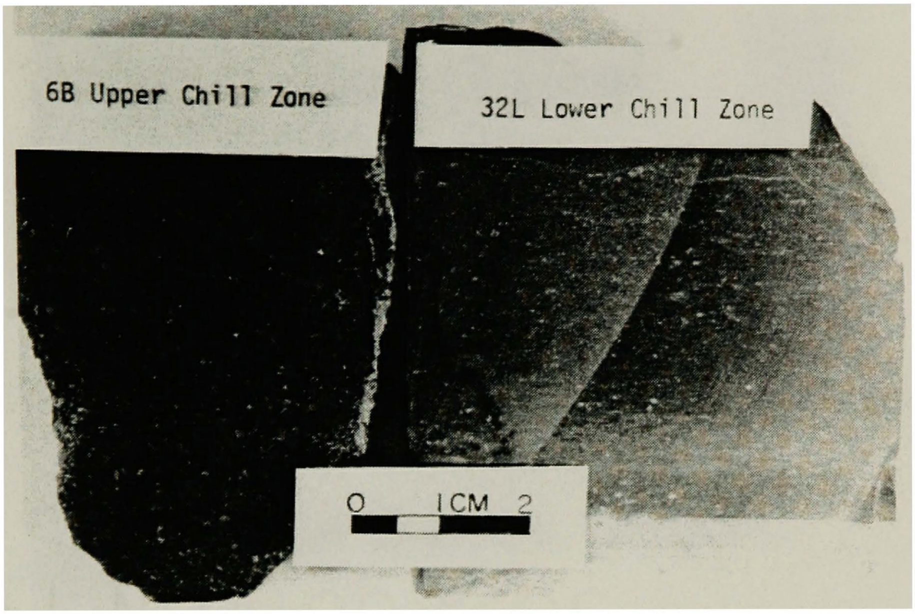


FIG. 9A, Upper chill zone and lower chill zone.

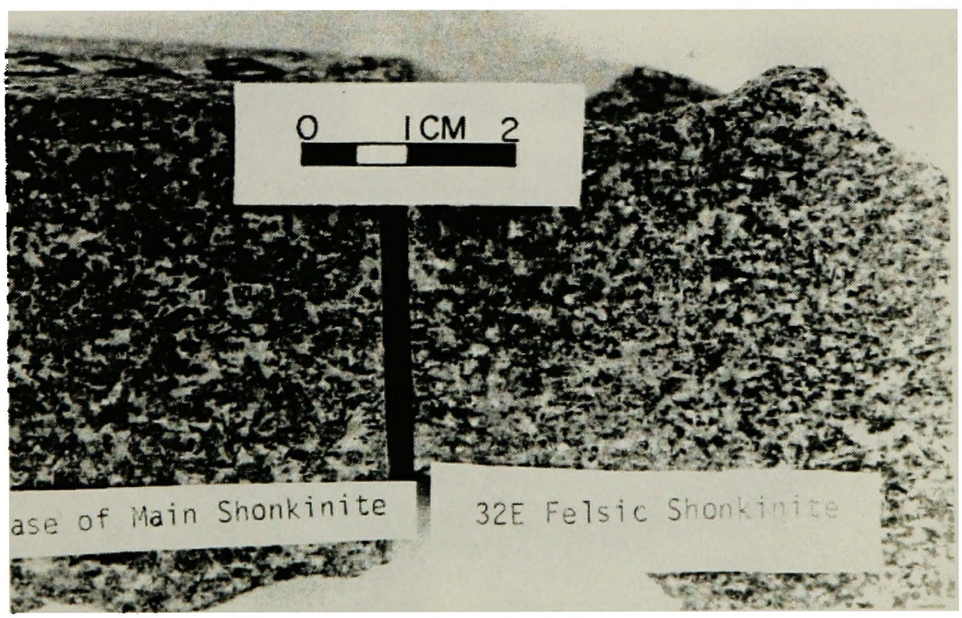


FIG 9B, Main shonkinite and felsic shonkinite

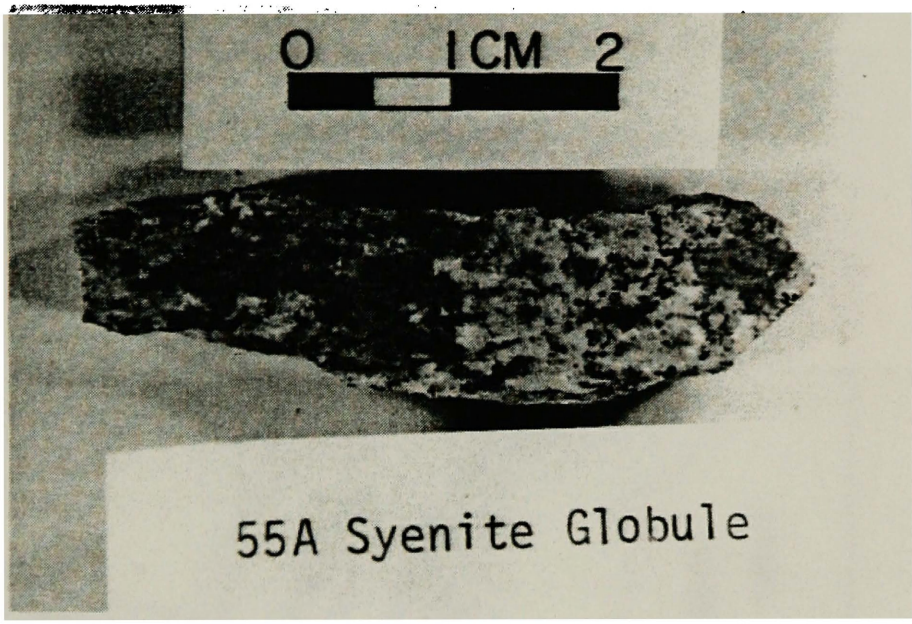


FIG. 9C, Syenite globule

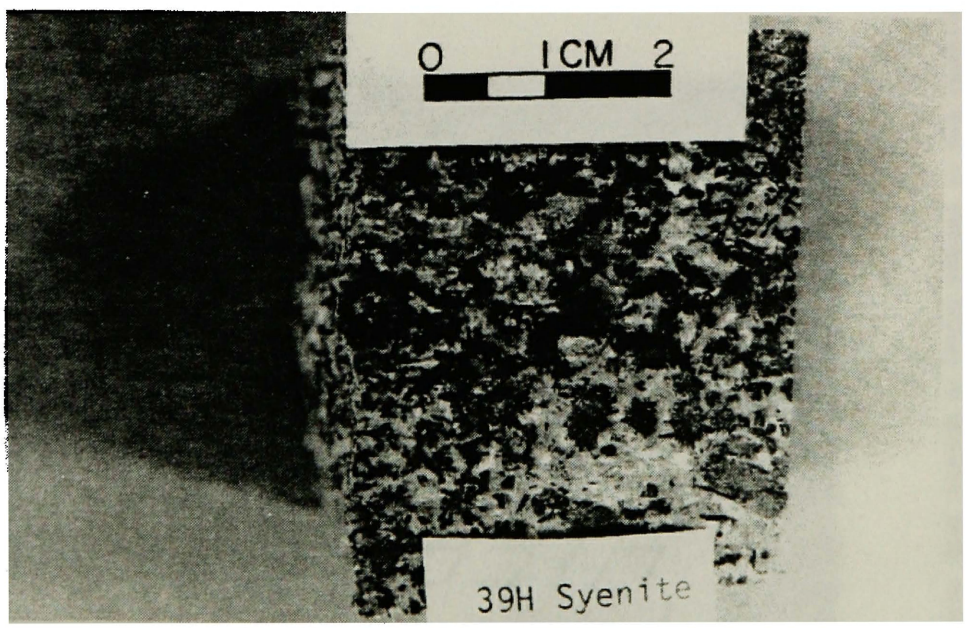
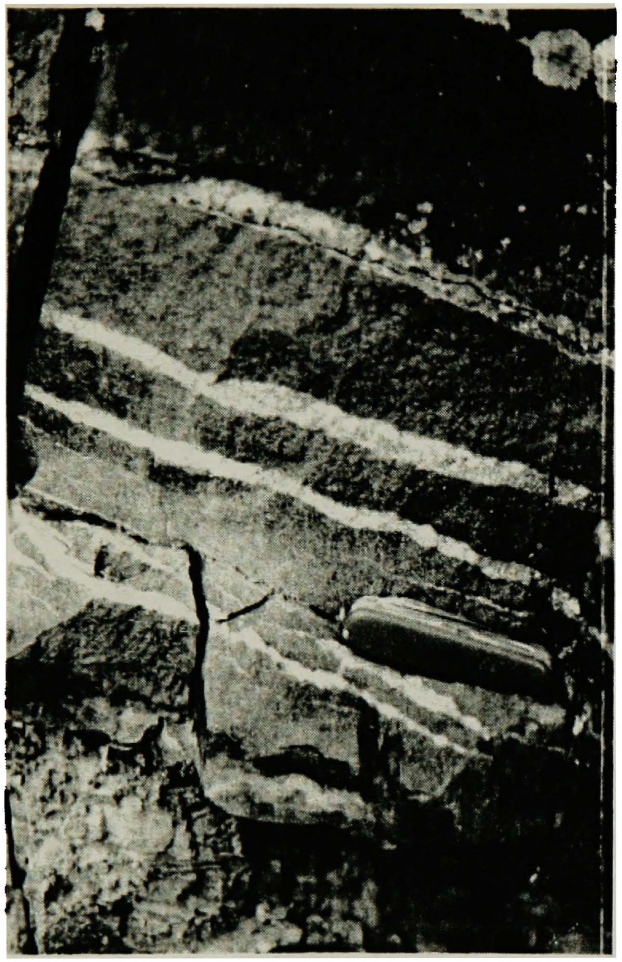


FIG 9D, Syenite from marginal dike



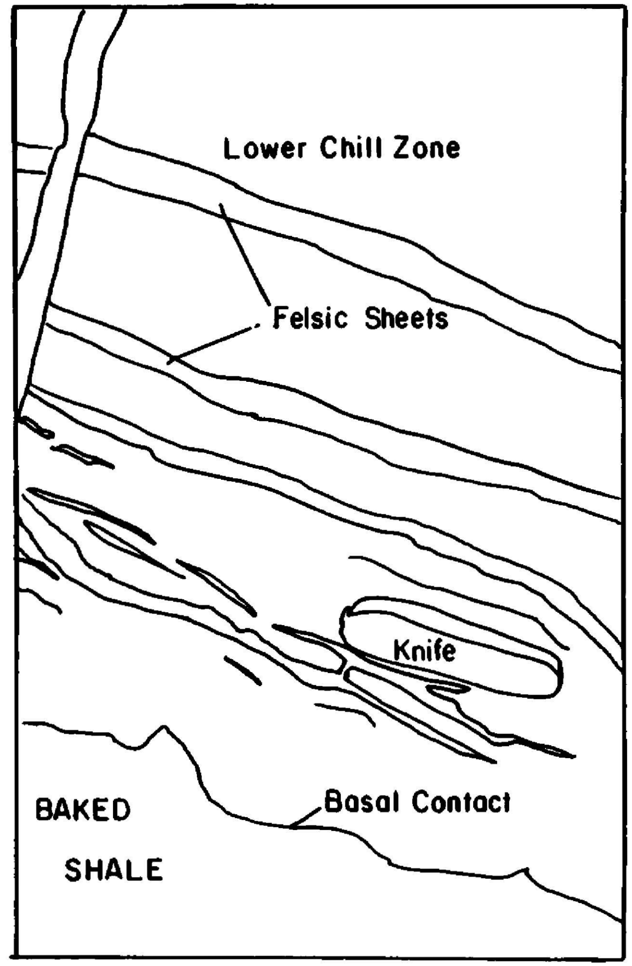


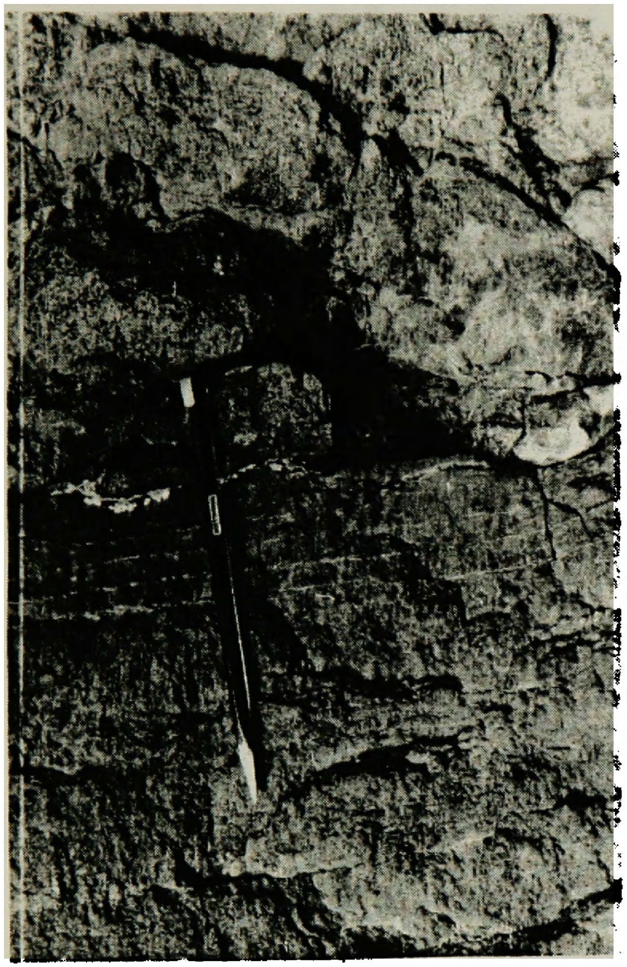
FIG.10, Photo and sketch of felsic sheets in the lower chill zone. Knife is 9 cm.

On the south side of the laccolith at sample location 74, coarse grained, friable shonkinite surrounds ripped up fragments of the lower chill zone (Fig. 11). This indicates some movement of magma after formation of the chill zone and felsic sheets. Apparently, the laccolith intruded in distinct pulses. The lower chill zone cooled at least long enough to develop jointing and felsic sheets prior to being engulfed by later magma.

Felsic Shonkinite

The only sampled exposures of the felsic shonkinite are in the quarry, although nalong the steep northeast face of the laccolith.te, beolow loche quarry. On the northeast margin of the butte, below location 28 where numerous hoodoos exist, a resistant cliff forming unit underlies the easily eroded shonkinite which forms the base of the hoodoos. The same type of distinctive change marks the transition from the felsic shonkinite to the base of the main shonkinite above the quarry. Similarly, a zone of hoodoos low on the south side probably marks the same horizon.

With cursory examination the felsic shonkinite appears similar to the main shonkinite. Closer inspection and comparison with the mafic shonkinites reveals the overall lighter color, lack of large olivine phenocrysts, and scattered white patches of presumably zeolitic material (Fig. 9B). The strong contrast in density confirms the differences quantitatively. Though not actually sampled on the southeast side due to poor exposure, a topographic break (Fig. 12) may mark the boundary between it and the overlying main shonkinite there. A sharp contact



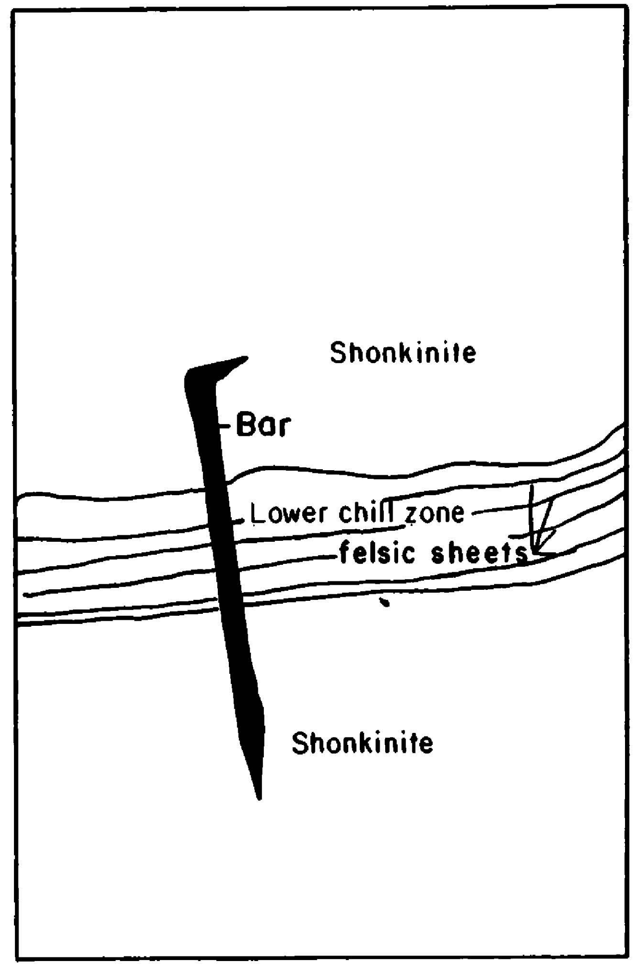
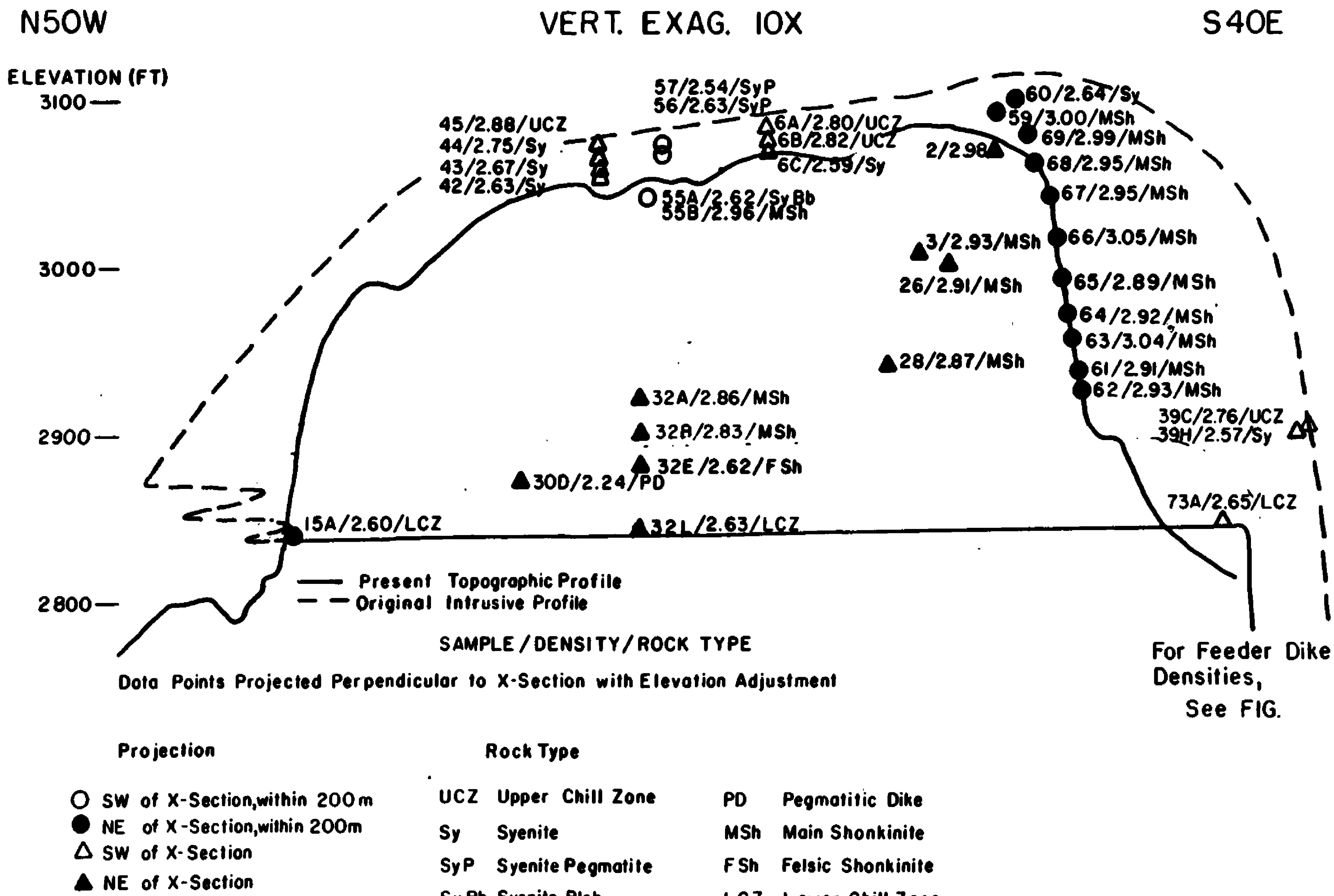


FIG.11, Photo and sketch of ripped up lower chill zone. Bar is 45 cm. Location 74.

FIG. 12, SNAKE BUTTE CROSS SECTION



separates the felsic shonkinite from the overlying main shonkinite.

Pegmatite Dikes

Vertical pegmatitic dikes cut the felsic shonkinite and extend up into the lower portion of the main shonkinite. These dikes, from 10 to 30 cm wide, consist largely of natrolite, as confirmed by x-ray diffraction. They extend for considerable distances horizontally, 10 meters or more in places, disappearing due to lack of exposure. Orientations vary considerably. They apparently follow early formed, widely spaced master joints within the intrusion. They formed after crystallization of the main shonkinite but their horizontal extent indicates that they formed prior to jointing of the laccolith into columns.

A very dark, somewhat friable, mafic selvage occurs on either side of the dikes. Large flakes of biotite parallel the sharp but somewhat irregular contact. Augite also mainly occurs near the contact, partly forming "fingerprint" textures. Natrolite predominates in the main mass of the dike and euhedral natrolite crystals line the abundant miarolitic cavities. The presence of miarolitic cavities indicates a shallow level of emplacement.

Within the cavities, natrolite grew in two distinct crystal habits. In most of the cavities, natrolite needles up to one centimeter long line the pockets and radiate inward (Fig. 13A). In one cavity, flat lying crystals of natrolite cover balls of tightly packed radiating natrolite. The natrolite balls attain a maximum diameter of one cm (Fig. 13B). Presumably, some difference in the conditions of formation, such as temperature or pH influenced the habit (Walker, 1951; Wise, 1978).

Main Shonkinite

The main shonkinite is the thickest unit in the laccolith. As measured in the quarry (location 32; Fig. 5), it begins approximately 17 m above the basal contact and extends approximately 55 m up to the base of the syenite pegmatite. Considerable variation and distinct layering (Fig. 7) characterize this unit, but further subdivision seems unwarranted. Density data (samples 58-69; Fig. 12 and Appendix 1) delineate some of the variation within the main shonkinite.

Hoodoos commonly form within the lower portion of the main shonkinite. They consist of a tough, resistant shonkinite (D=2.97) overlying a friable, easily weathered shonkinite (D=2.92; Fig. 14). Apparently, the layering within the main shonkinite controls the location of the hoodoos. Hoodoos exist on the north, west and southern margin of the laccolith, within a layer directly above the felsic shonkinite.

The upper portion of the main shonkinite forms resistant outcrops of high density (D=2.99) along the southeast face of the butte which appear relatively light colored from a distance. The lack of lichen on these outcrops and concentration of the mafic components into exceptionally large phenocrysts, up to 1 cm across, accounts for this apparent anomaly.

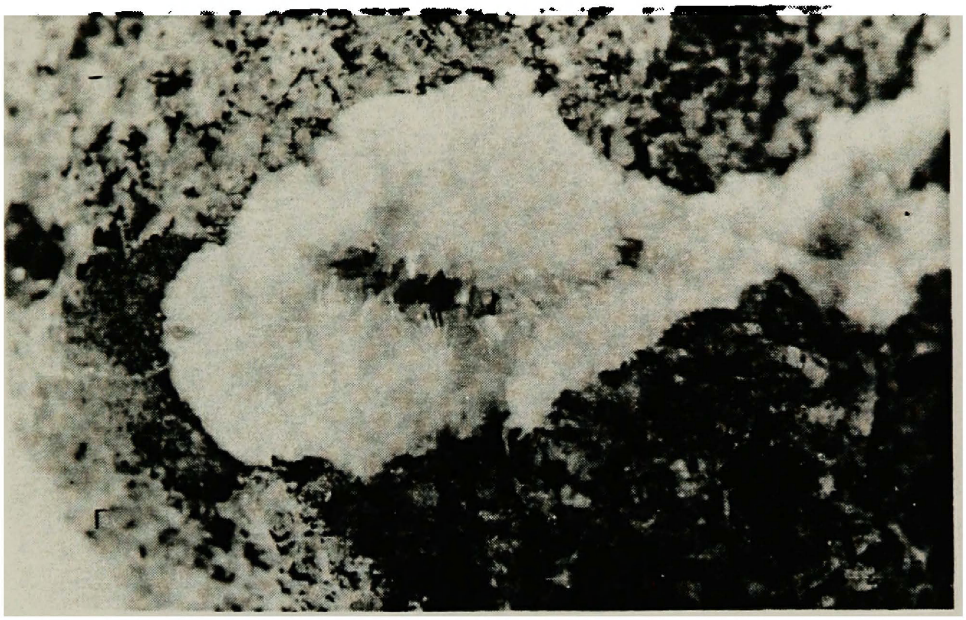


FIG. 13A, Radiating habit of natrolite, pegmatitic dike, sample 30

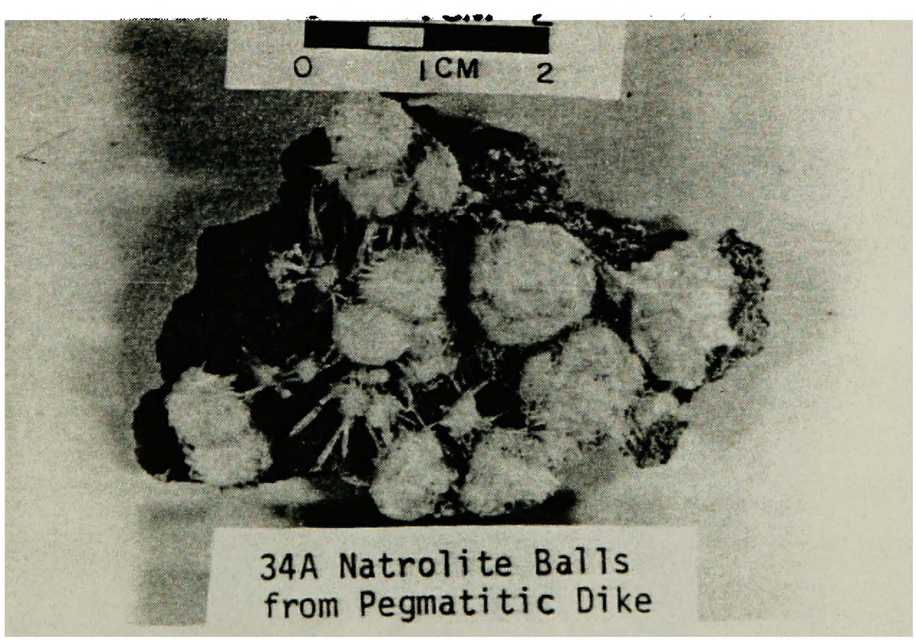
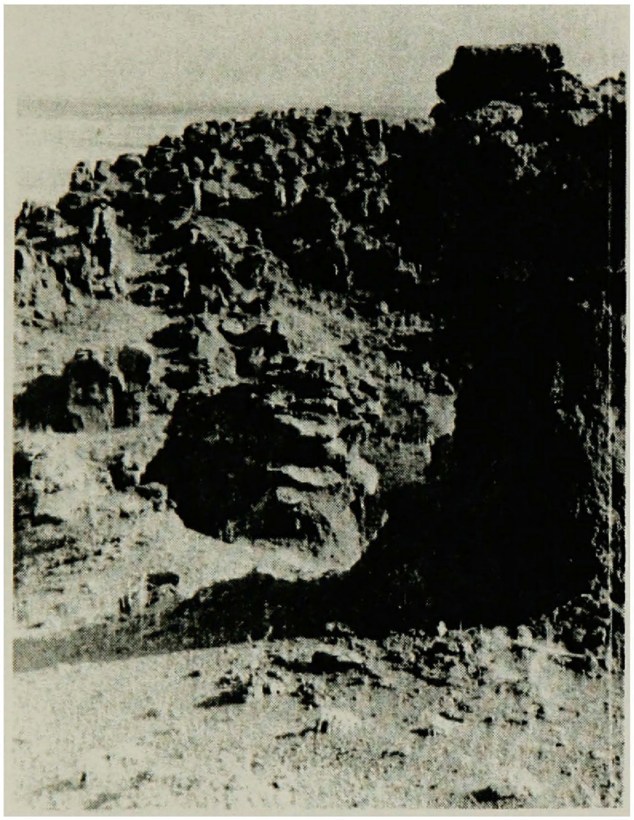


FIG. 13B, Ball habit of natrolite, pegmatitic dike, sample 34A



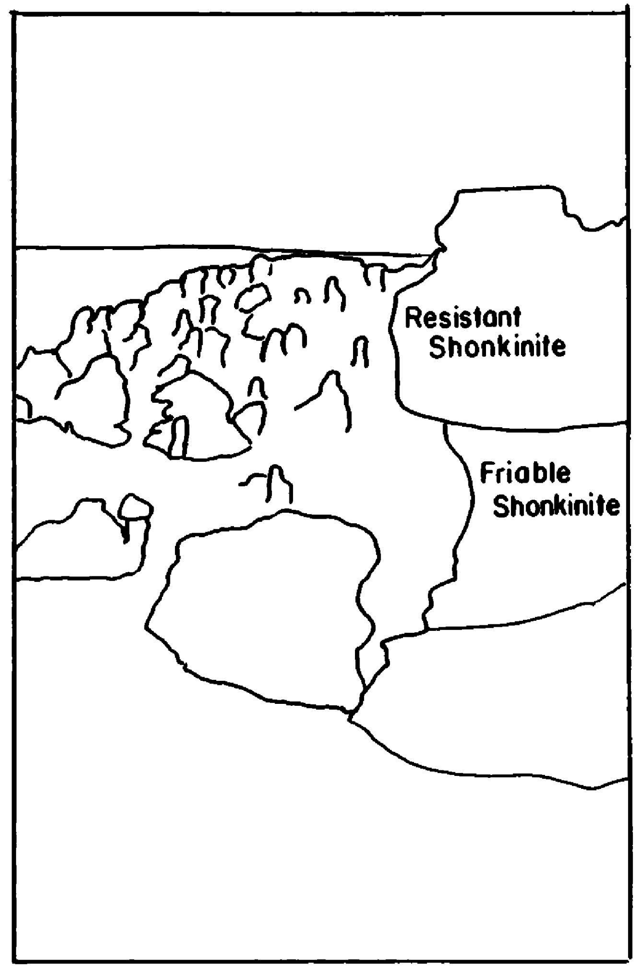


FIG.14, Photo and sketch of hoodoo layer near the base of the main shonkinite, directly above the quarry. Hoodoo in foreground is about 2 meters tall.

A spectacular example of columnar jointing forms the eastern face of Snake Butte and jointing extends throughout the laccolith. The columns measure two to three meters across. On top of the butte, the edges of the columns resist erosion better than the column centers and differential weathering leaves distinct rims around the columns (Fig. 15). Density differences quantify the obvious compositional differences between the very dense column centers (D=3.09) and the less mafic rims (D=2.91; Fig. 16).

Syenite Globules

Several syenite segregations (Fig. 9C and 17), similar to "blobs" or "globules" that other studies attributed to silicate liquid immiscibility (Edmond, 1980; Kuhn, 1983; Liptak, 1983) outcrop in the upper portion of the main shonkinite (location 55; Fig.XOX). Sharp contacts separate the globules from the enclosing shonkinite and they contain swirls of mafic minerals. In the field, I recognized no mafic selvage adjacent to them, but examination of photos suggests that a diffuse selvage may exist (Fig. 17). Density measurements on sample 55B, directly adjacent to the globule, gives slightly higher values than other nearby shonkinites. A distinct discontinuity within the shonkinite adjacent to the globule may provide a clue to their origin.

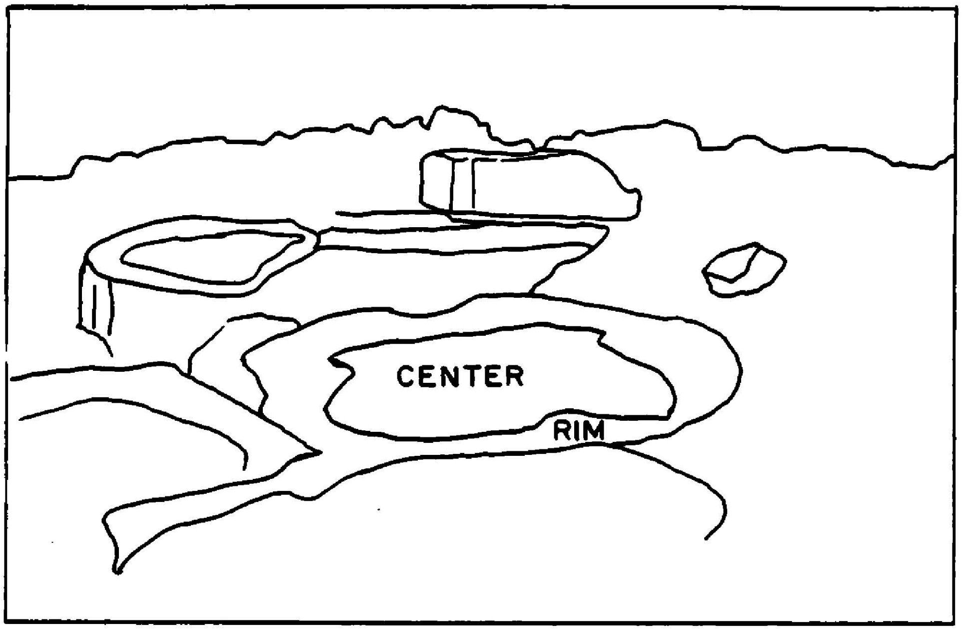


FIG. 15, Photo and sketch of resistant rims on columns. The relatively felsic rims apparently formed due to migration of residual fluids. Column in center approximately two meters across.

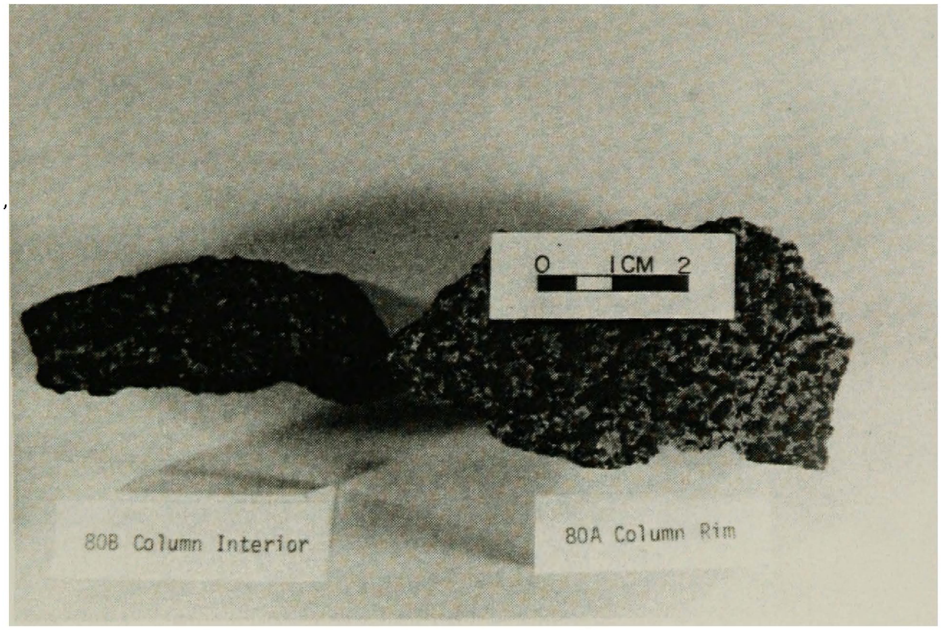


FIG. 16, Column interior (D=3.09) and rim (D=2.91)

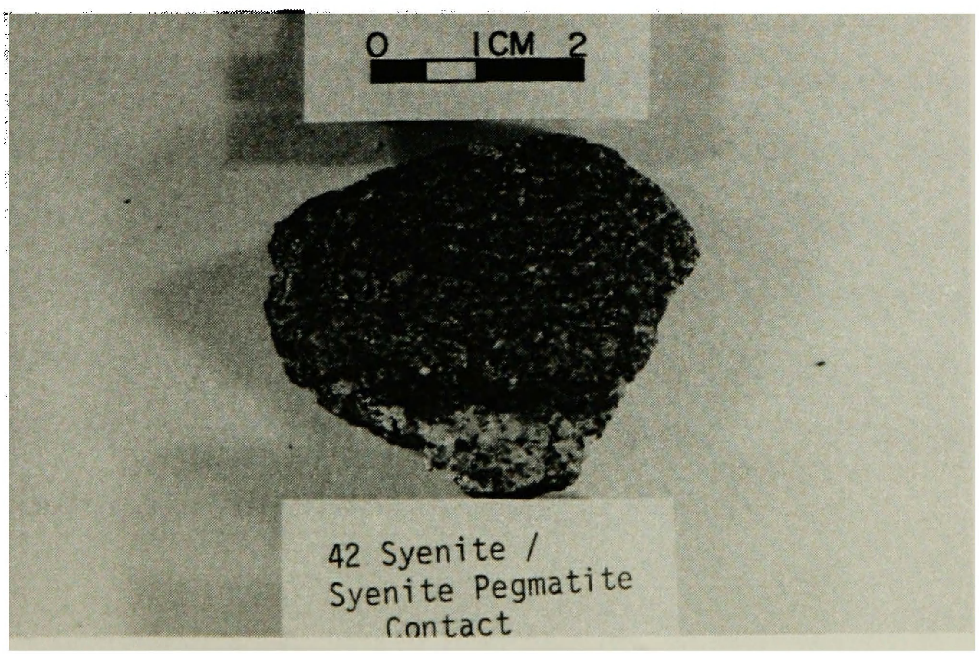


FIG. 18, Syenite/syenite pegmatite contact, Note the mafic selvage.

Syenite Pegmatite

Only three small outcrops expose a thin syenite pegmatite which forms a layer between the main shonkinite and the syenite. The light gray rock contains large radiating clusters of augite crystals and "fingerprint" augite crystals within a matrix of sanidine and zeolites. It closely resembles the pegmatite present at Shonkin Sag laccolith (personal observation). At Snake Butte the true thickness of the pegmatite remains uncertain due to poor exposure, but cannot be more than a about two m thick. The pegmatite weathers back so that the overlying syenite forms a protruding ledge above it at one of the outcrops.

Syenite

Three main masses of syenite form a cap on much of Snake Butte and a few minor outcrops of syenite also remain on top of the laccolith. Although a thin unit, the syenite resists weathering well. Density within the syenite increases slightly upward. Observations reveal no exposure of the contact with the upper chill zone, but their proximity indicates a sharp contact. A thin, but distinct mafic selvage marks the sharp boundary with the underlying syenite pegmatite (Fig. 18). Presumably, the syenite covered much of the butte prior to glaciation. Columnar jointing is absent from the syenite. This may mean that the syenite and the syenite pegmatite remained largely molten during joint formation in the main shonkinite (Jaeger, 1968).

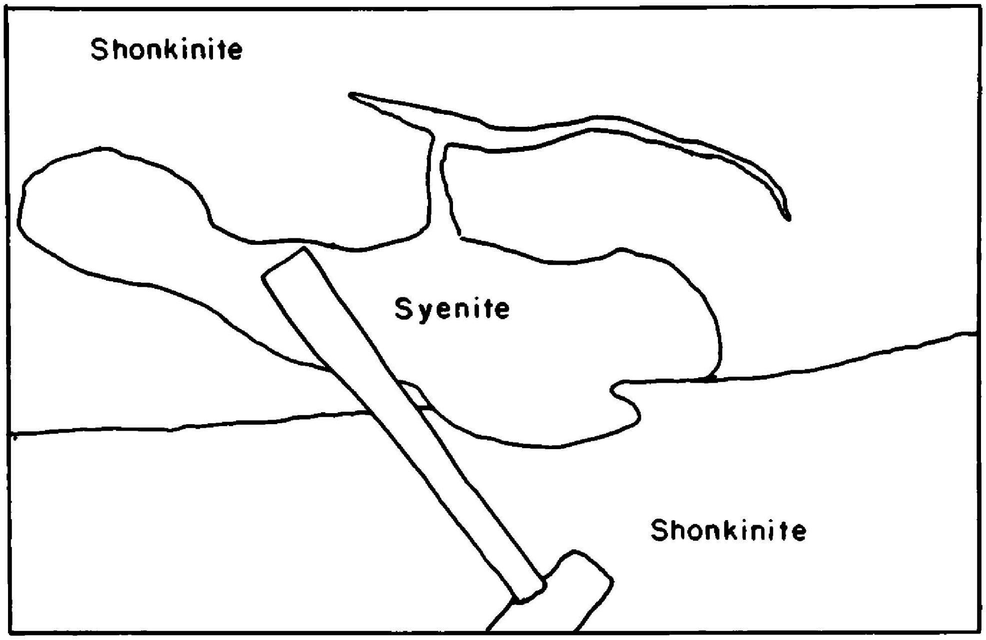
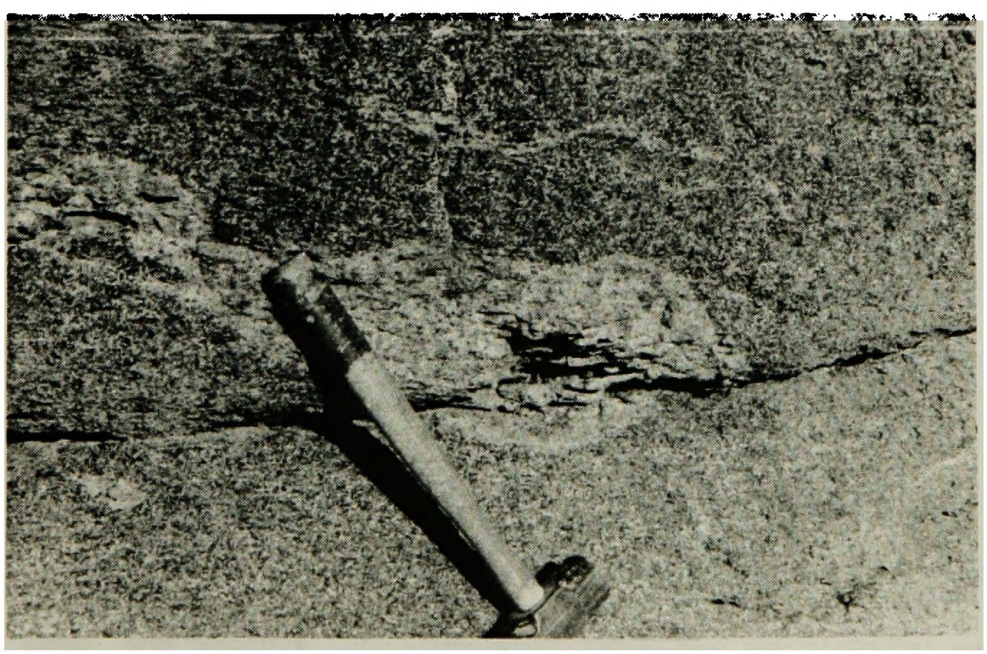


FIG.17, Photo and sketch of a syenite globule, 55A.
Hammer is 40 cm.

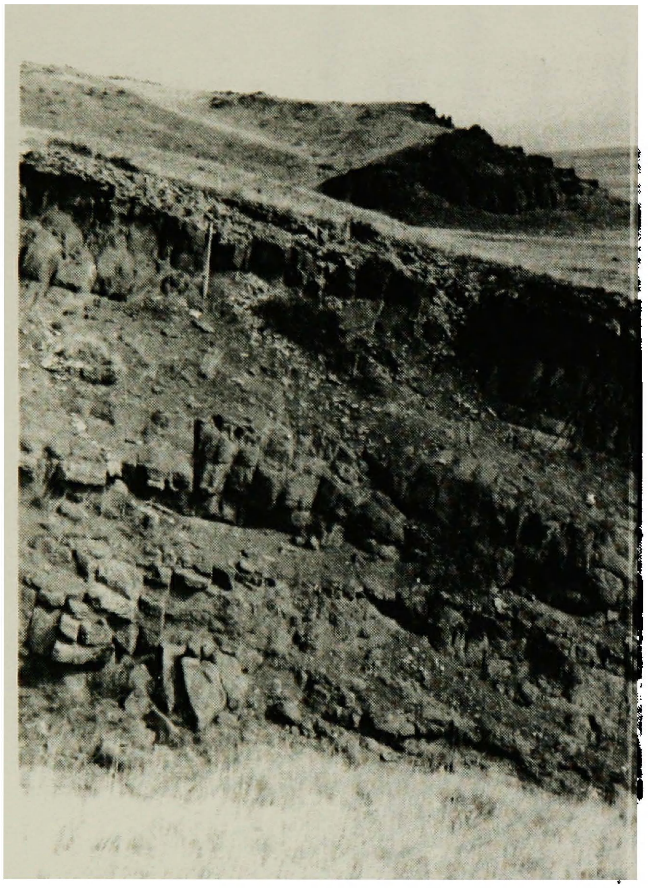


Upper Chill Zone

A few scattered remnants of the upper chill zone remain on top of Snake Butte. Though most of the upper chill zone occurs as flat outcrops, one outcrop reveals that the original thickness approached two meters. The high phenocryst content, larger size of phenocrysts, and greater whole-rock density contrasts strongly with specimens from the lower chill zone.

The upper contact exposed along the margin of the intrusion differs considerably from the exposures on top of the butte (Fig. 19). At the edge of the laccolith, the actual chill zone only attains a thickness of about 0.2 m. Below this, 5.3 m of shonkinite separates the chill zone from the syenite, analagous to the "upper shonkinite" in other central Montana laccoliths (Liptak, 1983; Barksdale, 1937). The syenite (Fig. 9D) forms at least two dike-like bodies approximately 0.5 m thick with no lower exposure, which roughly parallel the 20 degree dip of the contact. The elevation at this point indicates close proximity to the base of the laccolith. Small calcite veinlets cut the chill zone and die out in the upper shonkinite.

Syenite forms the base of a prominent knob on the western portion of the intrusion with chilled shonkinite forming the upper part of the knob. The knob apparently represents a large irregularity in the shape of the intrusion. Below this hill on the southeast face of the butte, abundant calcite veins cut the shonkinite and euhedral calcite crystals up to one cm line cavities in the shonkinite. The presence of calcite and lack of zeolitic veinlets in this area remains a mystery but suggests some difference in chemistry between the eastern and western



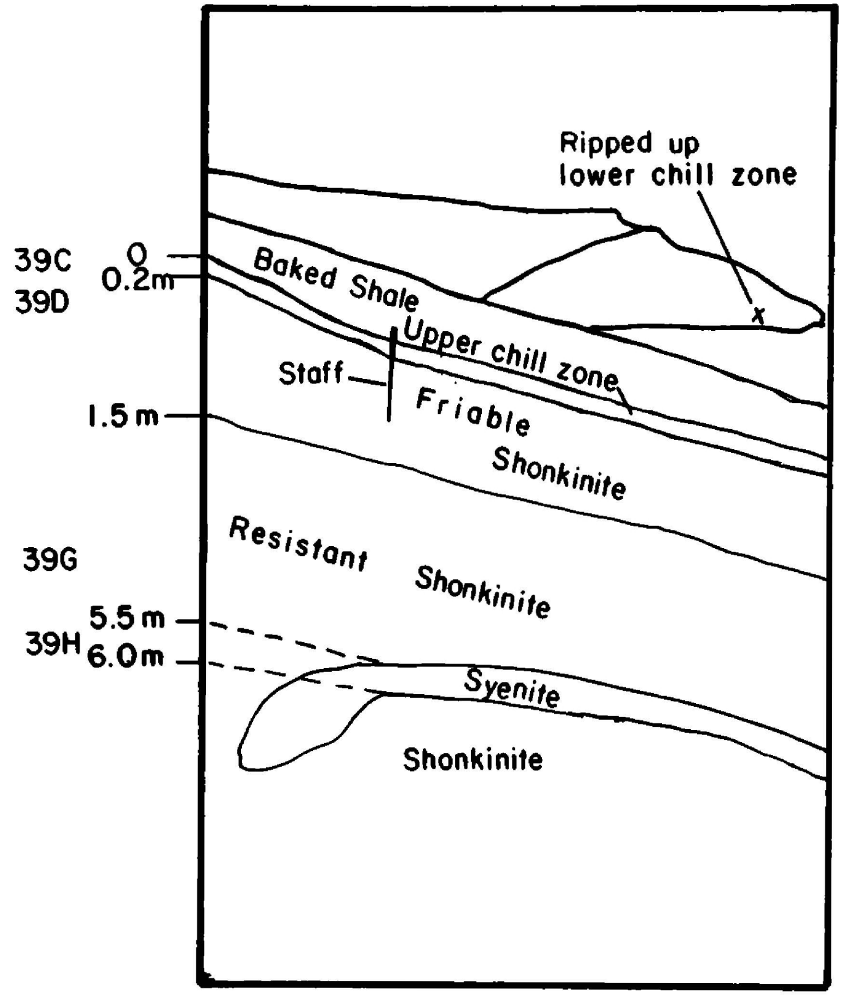


FIG.19, Photo and sketch of outcrop on the southern margin of Snake Butte.
Staff is 1.7 meters.

portions of the butte. Perhaps, a difference in the carbon dioxide and water content of the magma within the butte or differences in the percolating groundwater could account for this contrast in fissure filling minerals.

Feeder Dike

The 217 m-wide feeder dike provides critical clues to the genesis of Snake Butte. Rock densities across the feeder dike (Fig. 20) emphasize the inhomogeneity within the dike. Unreliable exposures due to glaciation inhibited sampling of the eastern portion of the dike. The western chill zone contains only a small percentage of phenocrysts, less than 2 mm across. The western chill zone contrasts strongly with the eastern chill zone. The higher density, greater amount of phenocrysts and larger size of phenocrysts mimic the differences observed between the lower and upper chill zones, respectively, within the laccolith. Immediately adjacent to the eastern chill zone, the chilled shonkinite (sample 94) resembles the western chill zone. The low density and geochemical data support the hand specimen comparison. Major differences in density from west to east across the dike (Fig. 20) roughly correspond to the changes in density from the base to the top of the laccolith (Fig. 12).

Many samples from the feeder dike contain small gas cavities. The presence of natrolite within the cavities indicates the magma contained some water prior to solidification, although carbon dioxide probably formed a significant portion of the volatile content (Hyndman, 1985, p. 407).

Comparison of Snake Butte with Shonkin Sag laccolith reveals many interesting similarities and contrasts. The lower chill zone at Shonkin Sag contains abundant augite and leucite phenocrysts, larger and more abundant than the phenocrysts in the lower chill zone at Snake Butte. Within the Shonkin Sag shonkinite, in an exposure adjacent to the Buck Ranch, an obvious discontinuity exists in the lowest exposure of the shonkinite. Above this the shonkinite appears similar to the main shonkinite at Snake Butte. Within the upper portion of the shonkinite, numerous pipe-like syenitic segregations occur in the shonkinite. No features similar to these were observed at Snake Butte. The thick pegmatite at Shonkin Sag outcrops prominently below an overhanging ledge of syenite. The pegmatite, with large radiating clusters of augite crystals, appears similar to the limited exposures of pegmatite at Snake Butte. An aplitic dike runs through the pegmatite at Shonkin Sag laccolith. Unfortunately, no exposures of the upper chill zone were seen. Only one small, deeply weathered, dike was observed cutting up into the base of the laccolith.

The proportionately greater thickness of the pegmatite at Shonkin Sag laccolith, compared to the pegmatite at Snake Butte, indicates a significant quantitative difference between the intrusions. The thick pegmatite at Shonkin Sag laccolith suggests that the magma contained proportionately greater amounts of water after intrusion. The intrusion of Shonkin Sag laccolith into the porous Eagle sandstone could account for this apparent difference in water content. The high water content could significantly affect the course of differentiation.

DENSITY MEASUREMENTS

Density measurements utilized a simple homemade beam balance and provided a means of evaluating a large number of samples quantitatively, quickly, and inexpensively. Appendix 1 lists all the density measurements. Measurements omitted many samples taken early in the study due to insufficient amount of sample or inappropriate sample material.

Multiple weighings of numerous samples demonstrated the precision to be within 0.03 and generally within 0.01. A large quartz crystal used as a reference showed that the accuracy was within the limits of precision. Density measurements helped delineate variations within the laccolith with a minimal number of chemical analyses.

GEOCHEMISTRY

The geochemical data allow a quantitative evaluation of differentiation processes at Snake Butte. Detailed examination of the geochemistry, coupled with field, petrographic and other data, inexorably led to the conclusion that crystal fractionation exerted the primary control on the course of differentiation. Volatiles probably played an important role during the migration of residual fluids during late stages of differentiation.

Background

Crystal Fractionation

Crystal fractionation requires little explanation and the general principles outlined by Bowen (1928) remain valid. Basically, as minerals crystallize from a melt, elements which do not fit into the crystal structure of the early formed minerals become enriched in the residual liquids. Final crystallization products depend upon whether or not early formed minerals separate from the magma, the timing of separation, and the degree of equilibrium reached between early formed crystals and the evolving magma if they do not physically separate.

For example, some minerals which crystallize early, such as forsteritic olivine, contain relatively large amounts of Mg and a relatively small proportion of silica. Therefore, early crystallization and removal of forsterite from the melt causes a depletion of the residual melt in Mg and relative enrichment in Si. Similarly, crystallization of apatite controls the partitioning of P. In general, P, Ti and other "incompatible elements" become enriched in residual liquids with processes of crystal fractionation (Hyndman, 1985, p. 115).

Silicate Liquid Immiscibility

Numerous other laccolith studies in the Montana alkalic province emphasize silicate liquid immiscibility and consider the process in greater detail (Edmond, 1980; Kendricks, 1980; Kuhn, 1983; Liptak, 1984). Like some other reviews of silicate liquid immiscibility (Hess, 1980) this interpretation emphasizes the structural aspects of the silicate melt.

Understanding the factors which govern whether or not immiscible separation of the melt can occur requires knowledge about the silicate melt, one of the least understood phases in igneous petrology. Fortunately, numerous recent studies emphasize the properties and structures of silicate glasses. Mysen (1981) showed that the structure of glasses closely approximates the structure of the corresponding melts. This enables studies of glasses, which are supercooled liquids, to closely approximate information obtainable only through much more difficult, high temperature experiments on actual melts.

Above its liquidus, a magma contains an assortment of polymerized units, with the proportions of each largely dependent upon the composition of the magma. A felsic melt contains a greater abundance of highly polymerized three-dimensional structures, sheets and chains, whereas a mafic magma consists largely of less polymerized units such as isolated silica tetrahedra, double tetrahedra and short chains.

As discrete structural units grow in the melt, felsic domains may separate from mafic domains if sufficient structural contrast exists between them, so that liquid immiscibility occurs. This roughly corresponds to the immiscibility which occurs between oil and water. Anything wich decreases the structural contrast between coexisting structural domains in the melt should tend to suppress immiscibility. This principle of immiscibility occurring in response to structural contrasts in the melts forms the basis for evaluation of any component with regard to silicate liquid immiscibility.

Petrologists realize the great importance of water in determining the properties of magmas. Due to its low molecular weight, a minor amount of water in the magma, by weight, contains a relatively large proportion of hydrogen atoms which largely accounts for its tremendous effect on magmatic properties. Consideration of the magma structure reveals why effects such as the lowering of solidus temperatures, decrease in viscosity, and inhibition of nucleation occurs with increasing water content. Water enters the magma structure by breaking Si-O-Si bonds and creating two Si-OH units, effectively depolymerizing the melt. This directly accounts for the macroscopic effects noted above. The higher solubility of water in felsic magmas than in mafic magmas (Hyndman, 1985, p. 151) reflects the greater abundance of available sites for hydroxyl units to bond to, that is, more Si-O-Si bonds exist for the water to break.

With respect to the immiscible separation in a magma, addition of water should theoretically cause greater depolymerization in the felsic domains than in the mafic domains. This decreases the structural contrast between coexisting domains and suppresses immiscibility. However, the lower viscosity of the felsic portion of the melt would allow it to separate more easily from the mafic portion of the melt. Presumably, for any given magma, a certain concentration of water maximizes immiscible effects. Too much water decreases the contrast between the felsic and mafic domains excessively whereas too little water inhibits separation of the phases due to higher viscosities.

Similarly, understanding the role of P and Ti in silicate melts explains the enhancement of immiscibility observed in experimental systems with the addition of P or Ti (Freestone, 1978) and their strong partitioning into the mafic phase with immiscibility in experimental (Watson, 1976) and natural (Philpotts, 1982) systems. Mysen (1981) concluded that P and Ti occur as tetrahedrally coordinated cations in silicate melts which do not copolymerize with Si tetrahedra. In particular, phosphate groups tend to link into chains which, according to the concept of immiscibility based on structural contrasts within the melt, should partition into the depolymerized mafic phase, increase the contrast between structural domains in the melt and ultimately enhance immiscibility.

Qualitative evaluation based on a structural model of silicate melts thus provides a basis for understanding why immiscibility occurs and how specific components affect the immiscibility field. Quantitative evaluation of these and other factors governing immiscible separation in magmas remains beyond present knowledge.

Wood and Hess (1982) provide important data on a dry $MgO-CaO-TiO_2-Al_2O_3-SiO_2$ system. They discovered that the addition of alkalies, particularly K, stabilizes the melt, that is, suppresses immiscible separation of the melt into two phases. Unfortunately, their initial compositions did not approach natural magma compositions. However, Roedder (1979) cites other experimental data which also supports this hypothesis. According to the structural model of immiscibility outlined above, this makes sense. Potassium enters framework silicate units at tetrahedral corners, effectively depolymerizing the melt and decreasing the structural contrast with the mafic phases.

Study of immiscibility in natural systems, notably by Philpotts (1982), supports and extends the experimental data. Philpotts investigated immiscibility in volcanic rocks, utilizing microprobe data on coexisting immiscible glasses. His work emphasized numerous important factors in natural systems relevant to this study. Key factors he delineated include:

1. High oxygen fugacity as indicated by the early precipitation of magnetite and consequent lack of Fe enrichment in residual liquids retards immiscibility;

2. Partition coefficients, the abundance of an element in the mafic phase compared to its abundance in the felsic phase, for Mg, Ca, Fe and P decrease with alkaline basalts as compared to tholeiitic compositions though these elements still strongly partition into the mafic phase. He attributed this to a decrease in the contrast between the structures of coexisting magmas;

3. Although Mg widens the experimentally determined immiscibility field, a very high Mg content suppresses immiscibility. This presumably occurs due to raising of solidus temperatures above the two-liquid field (Philpotts, 1982).

Regardless of possibly ambiguous data on the effect of oxygen, water, Mg and alkalies on immiscible systems, every available study on immiscibility in experimental or natural systems indicates that P and Ti strongly partition into the mafic phase. This contrasts strongly with the general behavior of P and Ti in systems where crystal fractionation dominates. Of course, with crystal fractionation, P and Ti may eventually partition into the mafic phase as minerals containing them crystallize, thus removing P and Ti from the melt.

Volatile Transport

Volatiles probably contributed significantly to differentiation at Snake Butte. Unfortunately, little quantitative data exists on the process of volatile transport. Hyndman (1985, p. 151) notes that Na, Fe, Mn, Ti, P, Rb and other elements concentrate in the gas phase. Additionally, he notes that volatiles may drive interstitial fluids through pore spaces between earlier formed crystals. Any volatile phase tends to expand with decreasing pressure and could therefore provide an important driving force for the migration of fluids into low pressure regions.

Data

The geochemical data consists of analyses on 24 whole-rock specimens performed by X-Ray Assay Laboratory. Approximately 200 grams of each rock were sent to the lab for grinding and analysis. Appendix 2, Table 3 lists the analyses in weight percent oxides and Appendix 2, Table 4 lists the analyses after conversion to atomic proportions.

To ensure good geochemical results, sampling concentrated on obtaining relatively unweathered samples. The quarry provided excellent samples for the lower portion of the laccolith. Good accessibility to the top of the laccolith allowed collection of relatively large samples for later trimming to remove weathered material. The sample from the pegmatite dike, 30D, represents approximately 8 kilograms of rock which was coarse ground and split to obtain a fraction for analysis. Unfortunately, poor exposure of the syenite pegmatite prevented a similar treatment for it. Consistent trend lines and correlation with density measurements support the validity of the geochemical analyses.

Data Analysis

Numerous computer-generated cation-cation scatterplots and ternary diagrams aided interpretation of the data. Calculations utilized the MINITAB (Penn State, 1981) program available on the University of Montana DEC 20 system. Conversion of chemical analyses from weight percent oxides to atomic proportions facilitated comparison of elemental trends, especially when summing two or more elements prior to plotting. The program also calculated correlation coefficients for analysis of the data (Appendix 2, Tables 5,6, and 7).

Assuming that the rocks present at Snake Butte all represent differentiation products from a single primary magma, an extreme amount of differentiation occurred. Examination of the geochemical data revealed the following:

1. Mg and Ca partition strongly into the mafic rocks;
2. Si, Al, Na, K, Ti, and P partition into the felsic rocks;
3. Fe shows a very flat trend with slight enrichment in the syenites;
4. Mg differentiates more strongly than any other element;
5. The P vs. Ti diagram reveals at least two trends which represent different episodes of differentiation;
6. P correlates directly with K, and suggests two trends which correspond to the trends shown by P vs. Ti;

7. The pegmatitic dike diverges from the overall trend lines;

8. The lower chill zone and syenite globule contain the greatest amount of K;

9. Mg content correlates with whole rock density;

10. The AFM diagram strongly supports crystal fractionation dominated by Mg-rich minerals with a Mg:Fe ratio of 85:15.

11. The Ca/Na/K diagram shows a trend of strongly decreasing Ca with a nearly constant Na/K ratio and a trend of increasing Na/K ratio with slightly decreasing Ca.

Detailed examination of the geochemical data leads to the conclusion that crystal fractionation dominated differentiation at Snake Butte. Silicate liquid immiscibility cannot have played a significant role. Volatile transport probably became increasingly important during the final stages of crystallization. Contrasts between the lower and upper chill zones, composition of the lower chill zone, variation across the feeder dike, lack of Fe enrichment in mafic rocks and the partitioning of P and Ti into the felsic rocks, conclusively support a model of fractional crystallization for Snake Butte, with much of the differentiation occurring prior to intrusion.

Lower Chill Zone

The western margin of the feeder dike and the lower chill zone of the laccolith exhibit nearly identical chemical compositions, contrasting markedly with samples from the upper chill zone. The higher K, Al, Si, Na, P and Ti of the lower chill zone, combined with the obvious differences in phenocryst content between the chill zones (Fig. 9), and the strong trend observed on the AFM diagram (Fig. 21), support fractional crystallization. Assuming that the chill zones represent the composition of the magma as it intruded, much of the differentiation occurred prior to intrusion. Variations across the feeder dike reinforce this conclusion.

The extreme composition of the lower chill zone also supports this hypothesis. Examination of the lower chill zone composition reveals a very high K content and a high P content. This obviously could not represent an "average" value for a magma which differentiated in place following intrusion. The low Mg and Ca values coincide with the lack of mafic phenocrysts in the lower chill zone (Fig. 9). The high K content and recognition of pseudoleucite in the feeder dike suggests that enrichment of leucite occurred prior to intrusion, possibly via flotation. Phenocryst pseudomorphs in the lower chill zone probably were leucite prior to intrusion.

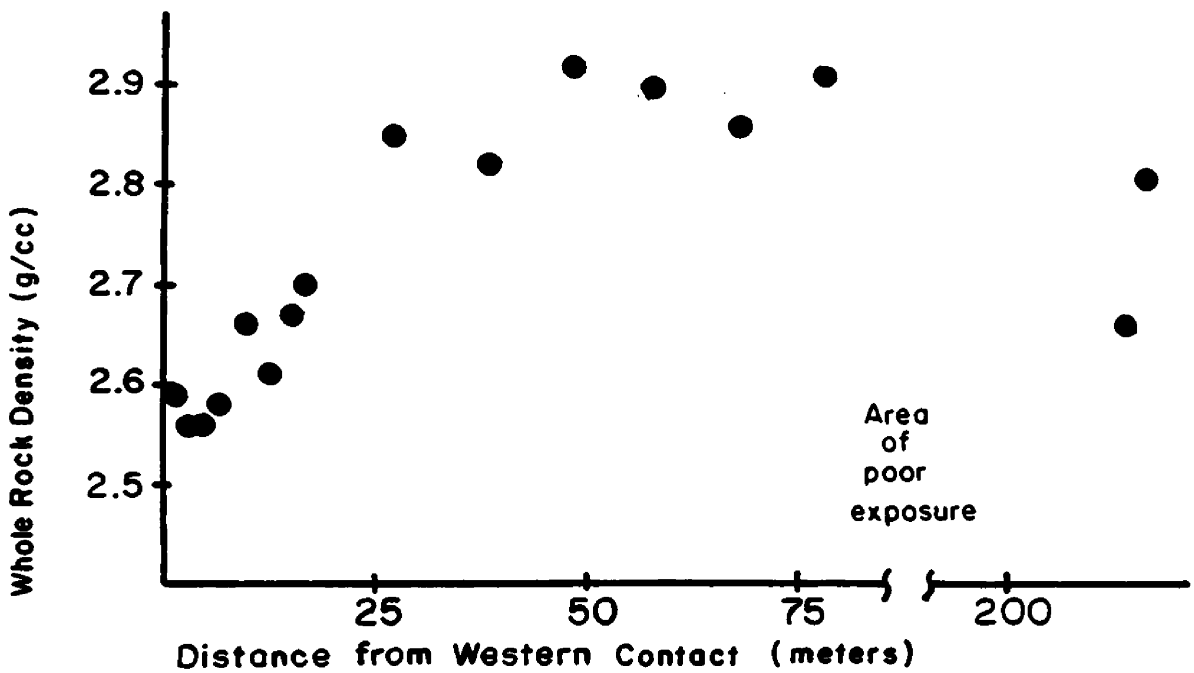


FIG.20, FEEDER DIKE DENSITY

Metasomatic effects cannot adequately explain the extreme composition of the lower chill zone. If the magma acquired significant amounts of material from the country rock during or after emplacement, progressive changes in composition of the chill zone should occur. No recognizable progressive changes in the chill zone composition exist between the feeder dike and the laccolith, and the strong geochemical trends are compatible with crystal fractionation by augite and olivine depletion and leucite enrichment of the magma prior to intrusion.

Felsic Shonkinite

The felsic shonkinite displays a composition similar to the lower chill zone. Presumably, compositions prior to injection compared closely and they may represent a single intrusive phase. However, the extremely high K of the chill zone samples suggests greater differentiation prior to intrusion for the lower chill zone. The high P content of the felsic shonkinite suggests that P continued to increase after emplacement.

Pegmatitic Dikes

The pegmatitic dikes appear to lack any genetic relationship with units other than the immediately adjacent rock. Prominent mafic selvages on the dikes prove the relationship to the felsic shonkinite and main shonkinite. The extreme depletion in P indicates they formed relatively late in the history of the laccolith, after most of the P within the felsic shonkinite had either migrated elsewhere or precipitated as apatite. Ti apparently remained mobile prior to formation of the pegmatitic dike. This correlates well with the behavior of Ti noted below for the syenitic rocks. Ti apparently remains within the fluid phase until very late stages of crystallization as also supported by petrographic evidence. Extreme enrichment of Na characterizes the pegmatitic dike as also confirmed by the presence of natrolite. Experimental formation of natrolite requires a very high Na/Ca ratio (Johnson, et.al., 1983). The presence of volatiles is indicated by the formation of zeolites and the abundance of cavities within the dikes.

Main Shonkinite

The mafic composition of the main shonkinite contrasts strongly with the composition of the felsic shonkinite, the differences reflecting the high content of mafic phenocrysts within the main shonkinite. Though only a few analyses exist for the main shonkinite, the density differences indicate a wide range of mafic compositions. The obvious layering within the laccolith (Fig. 7) coincides with changes in composition indicated by the density data.

Syenite Globule

In accord with its extremely felsic appearance, the analysis of the syenite globule reveals high Si, Al and alkali content with relatively low amounts of other elements. K is particularly high, with Fe, Mg, and Mn especially low. The globule contains a small amount of Ti and P compared to other analyzed felsic rocks, but not in comparison to the shonkinites (Fig. 24). If it formed by silicate liquid immiscibility of the shonkinite magma, the globule should contain only minimal amounts of P and Ti. Alternatively, it could represent residual fluids formed after the beginning of magnetite and apatite crystallization which would adequately account for its geochemical characteristics. However, the method by which these fluids coalesced remains enigmatic.

Syenite Pegmatite

The extreme composition of the syenite pegmatite supports the hypothesis that it formed very late in the history of the laccolith. The coarse crystal size indicates extreme volatile buildup during crystallization which inhibited nucleation (Hyndman, 1985, p. 141). The high Na, Fe, and Ti also supports the hypothesis that volatiles played an important role in the formation of the pegmatite, since volatile transport should lead to enrichment of these elements. A relative depletion in P indicates that apatite crystallized prior to the migration of fluids which formed the pegmatite. The abundance of aegirine and magnetite in the pegmatite indicates a high Fe^{+3}/Fe^{+2} ratio. Together, this combination of geochemical and petrographic characteristics illustrates the differentiation trends toward high Na, ferric Fe, and Ti.

Syenite

Two samples, 43 and 39H, represent the syenite and marginal syenitic dike respectively. Though similar in most respects, the relative depletion of the syenitic dike in Ca and P with respect to the syenite indicates some fractionation of apatite if, as field relationships suggest, they are cogenetic. The composition of the syenite closely resembles the composition of the lower chill zone and western chill zone samples from the feeder dike. However, it contains slightly higher P and Ti and lesser amounts of K relative to the chill zones. If the marginal dikes actually fed the upper syenite from the lower portion of the laccolith, the analysis may represent the last fluid expelled from the lower portion of the laccolith. Continued differentiation within the feeder dike possibly contributed to formation of the syenite but erosion of the eastern portion of the butte prevents further evaluation of this. The low P and Ca indicates apatite crystallized before the final flow of residual magma into the syenite cap. Ti apparently remained mobile as indicated by its enrichment in the syenite dike.

Alternatively, the correlation of composition of the syenite dike with the lower chill zone may indicate they formed at the same time from the same magma. Conceivably, the mafic shonkinitic magma of the main shonkinite intruded into the center of the early syenite injection. The lack of suitable outcrops, especially in the area where the feeder dike enters the laccolith, prevents definitive resolution of this question.

Upper Shonkinite

The upper shonkinite, present only on the margin of Snake Butte, exhibits a composition nearly identical to the upper chill zone. Apparently, only minimal differentiation followed intrusion.

Upper Chill Zone

The upper chill zone displays an intermediate shonkinitic composition. The composition, density and phenocryst content coincide with the chill zone from the eastern margin of the chill zone. Compared to the lower chill zone, the more mafic composition of the upper chill zone correlates with the greater abundance and size of mafic phenocrysts.

Feeder Dike

Analyses obtained from the feeder dike reinforce conclusions from density measurements which emphasized the variation across the dike. Felsic rocks from the feeder dike closely correspond in composition to felsic rocks within the laccolith. Analyses of shonkinites from the feeder dike correlate well with samples from the main shonkinite.

Geochemical Diagrams

Overall, the geochemical plots emphasize strong trends consistent with a model of crystal fractionation. Only the diagrams which show critical relationships are included here. Of particular note was the "Grieg diagram" which other studies heavily rely upon for evidence of immiscibility. For reasons noted below, the Grieg diagram is not presented here. The distribution of data points on the Grieg diagram proved insufficient to distinguish between immiscibility and crystal fractionation. The minor elements P and Ti, critical in differentiating between the processes, become insignificant when lumped together with the major elements. As expected, the upper chill zone plotted between the shonkinites and the syenites. Roedder (1979), a strong advocate of immiscibility as a significant petrogenetic process, also notes the inadequacies of the Grieg diagram.

AFM Diagram

The AFM diagram (Fig. 21) provides important evidence for crystal fractionation at Snake Butte. Most analyses plot on a line which connects the chill zone analyses and extends to the boundaries of the diagram. This tie line cuts the FM edge of the diagram at a point corresponding to a Mg:Fe ratio of approximately 85:15 which coincides with the Mg:Fe ratio measured on the olivine. The felsic shonkinites, syenites, and syenite pegmatite diverge from the trend. The syenitic rocks plot above the tie line and the felsic shonkinites below it. Conceivably, the syenites and felsic shonkinites formed from a magma with a composition very similar to the lower chill zone, which continued to differentiate after intrusion. The pegmatitic dike diverges from the main trend, showing extreme Mg depletion and alkali enrichment.

Ca/Na/K Diagram

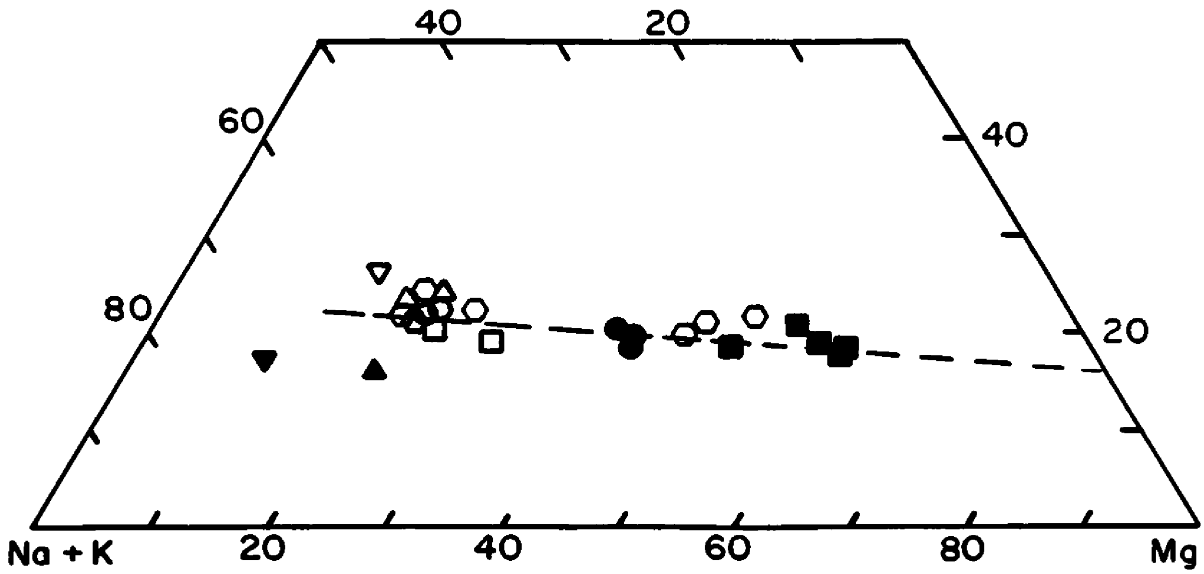
The Ca/Na/K ternary diagram (Fig. 22) illustrates the differentiation trend for these elements. Note the two contrasting trends. A strong decrease in Ca content while the proportion of Na/K remains relatively constant contrasts with the trend of Na enrichment. The trend of Ca depletion apparently represents the fractionation of augite prior to intrusion whereas the Na enrichment dominantly occurred with in situ differentiation, especially that to form the pegmatite dike. Late crystallization of apatite probably contributed to continued Ca depletion, but only to a minor extent.

P versus K Diagram

The cation-cation scatterplot of P versus K (as oxides, Fig. 23) shows a general correlation (Appendix 2, Table 5). In some respects similar to the AFM diagram, the felsic shonkinites and syenites generally plot on either side of the main trend defined by the main shonkinites and chill zone samples. The felsic shonkinites contain greater amounts of P and the syenites lesser amounts with respect to the main differentiation trend. This diagram emphasizes the distinctly high K within the lower chill zone compared to the other rocks within the laccolith, even to the felsic shonkinite directly adjacent to the chill zone. Note the minimal amount of P in the pegmatitic dike which apparently formed very late in the cooling history of the laccolith after crystallization of apatite.

FIG. 21, AFM DIAGRAM

Atomic Proportions

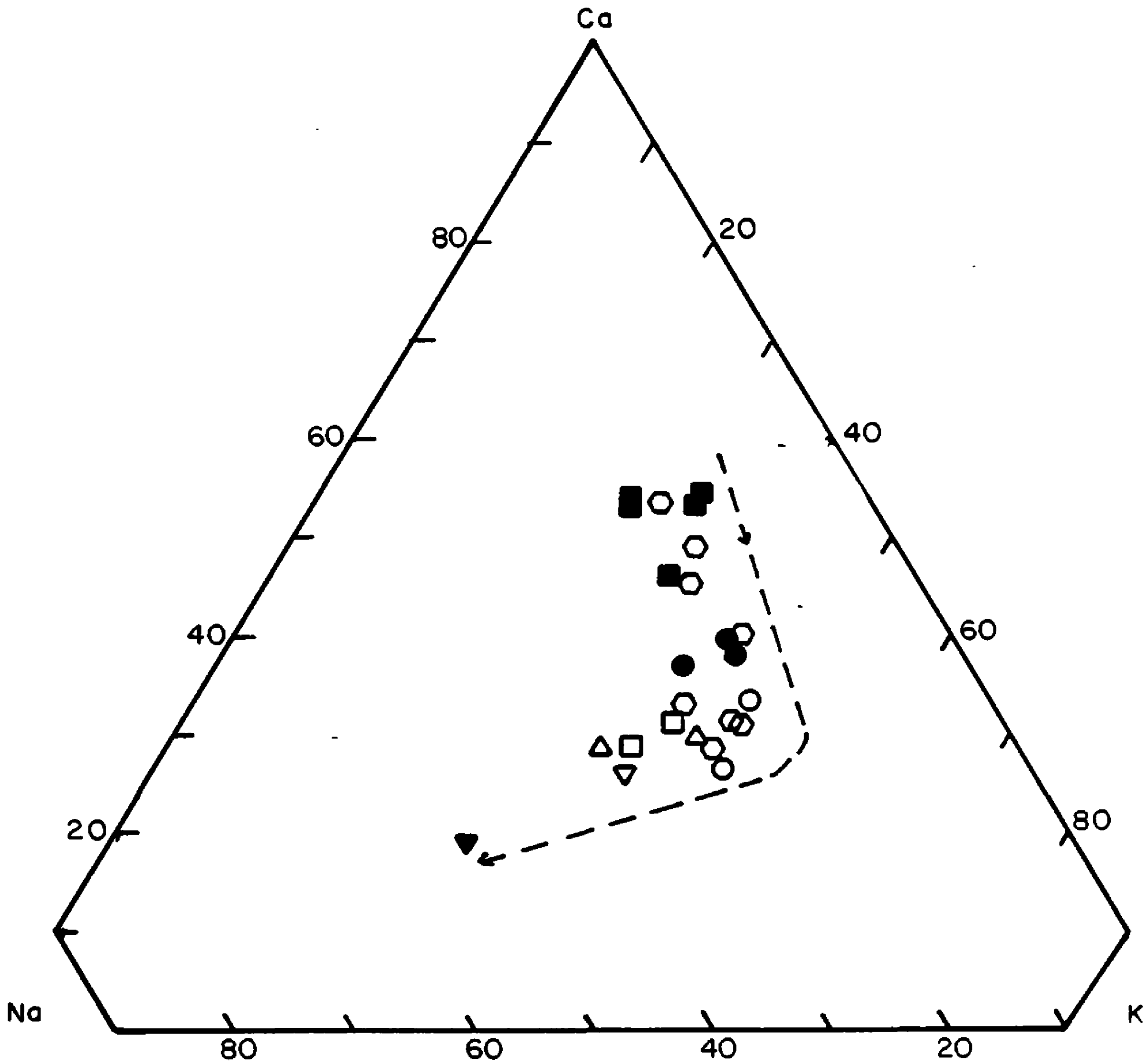


KEY

- ● Upper Chill Zone
- ○ Lower Chill Zone
- □ Felsic Shonkinite
- ■ Main Shonkinite
- △ Syenite
- ▽ Syenite Pegmatite
- ▼ Pegmatite Dike
- ▲ Syenite Globule
- ⬡ Feeder Dike

FIG.22, Ca/Na/K TERNARY DIAGRAM

Atomic Proportions



For key, see AFM diagram, Fig.

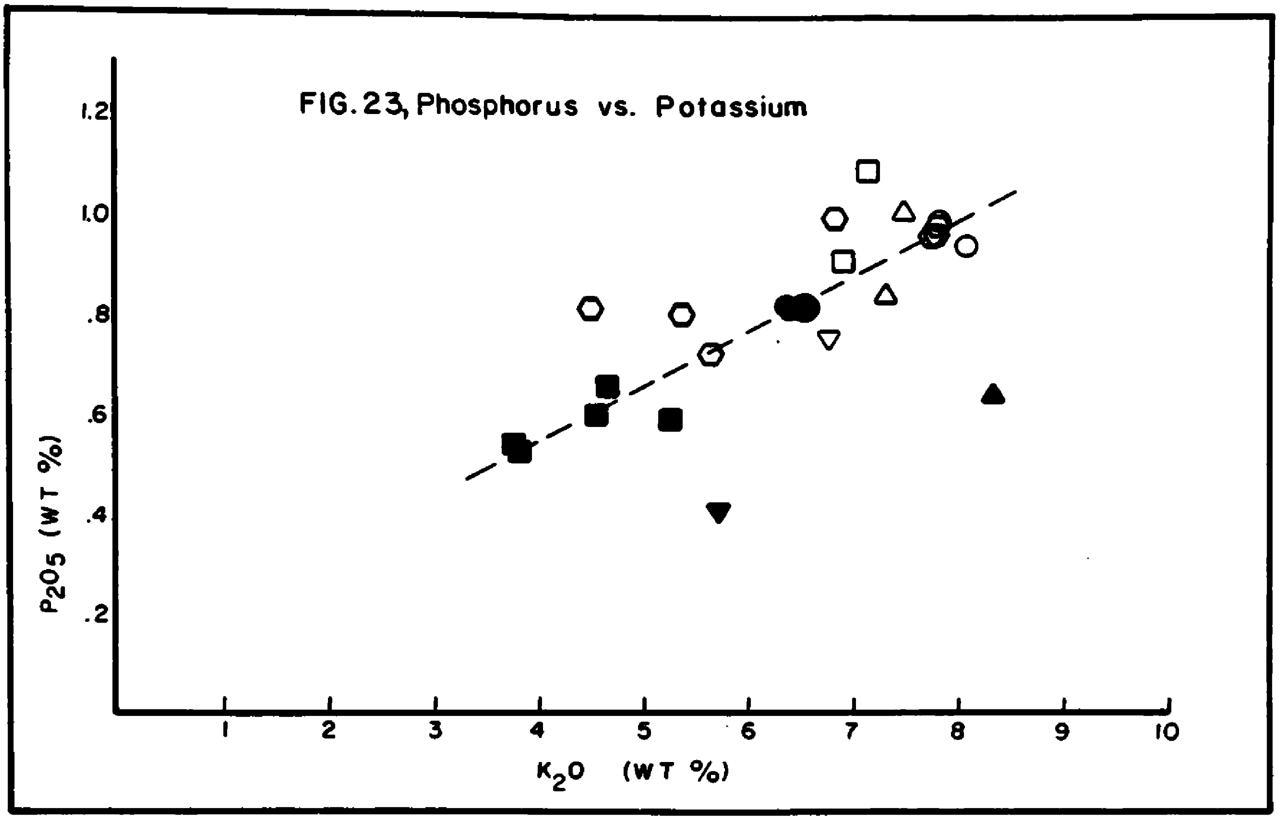


FIG. 23, Phosphorus vs. Potassium
1.2
1.0
.8
.6
.4
.2
P2O5 (WT %)
1 2 3 4 5 6 7 8 9 10
K2O (WT %)

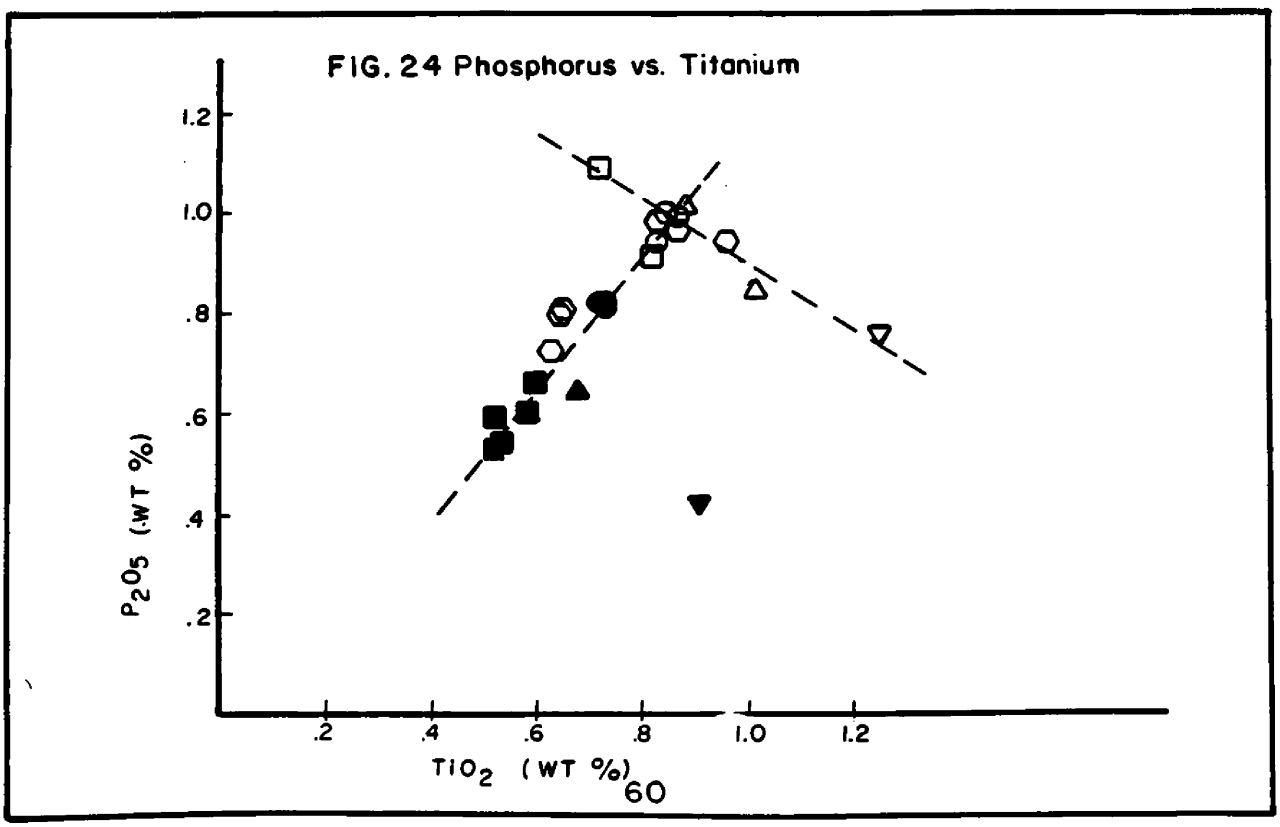


FIG. 24 Phosphorus vs. Titanium
1.2
1.0
.8
.6
.4
.2
P2O5 (WT %)
.2 .4 .6 .8 1.0 1.2
TiO2 (WT %)

P versus Ti Diagram

The P versus Ti diagram (as oxides; Fig. 24) again emphasizes the two differentiation trends within the laccolith. The trend corresponding to pre-intrusion differentiation shows a direct correlation of P and Ti, with both increasing in the more felsic rocks. This trend corresponds with normal trends of fractional crystallization. The second trend reveals an inverse correlation between P and Ti. Again, the felsic shonkinites and syenites plot on opposite sides of the first trend line, and the pegmatitic dike off by itself. This suggests that P, in the form of apatite, began to precipitate while Ti remained mobile.

Correlation Coefficients

Correlation coefficients calculated on all the samples yielded little useful information (Appendix 2, Table 5). Splitting the samples into two groups based on the interpretation of whether they best represent the pre-intrusion (Appendix 2, Table 6) or post-intrusion trends (Appendix 2, Table 7) and recalculation of correlation coefficients provided interesting results which quantitatively support the trends observed on various geochemical diagrams. Lower chill zone samples were included in both sets of data since they apparently represent an extreme differentiation product from post-intrusion differentiation and approximate the initial composition for post-intrusive differentiation formation of the syenitic rocks.

Calculations emphasize the dichotomous behavior of phosphorus. Within the group of shonkinites, which includes the lower chill zone since it did not differentiate after intrusion, phosphorus strongly correlates with Al, Ti and K. The calculations reveal a strong negative correlation for P versus Ca and P versus Mg. The behavior of P within the group of syenitic rocks, which also includes the lower chill zone analyses, contrasts sharply with its behavior in the shonkinitic group. A strong negative correlation exists for P versus Al and P versus Na with a positive correlation between P and Ca. Presumably, this indicates the influence of apatite crystallization during differentiation of the syenites.

The correlation coefficients also emphasize the strong positive relationships between the Fe/Mg ratio and numerous other cations. The strong positive correlation between the Fe/Mg ratio and Ti in both groups (Appendix 2, Tables 6 and 7) is consistent with crystal fractionation.

Geochemical Summary

Together, these diagrams offer conclusive evidence that crystal fractionation dominated the differentiation processes at Snake Butte. They delineate two major trends of differentiation. A pre-intrusion trend, dominated by strong differentiation of Mg and Ca, contrasts strongly with a post-intrusion trend. Fractionation of the incompatible elements dominates the post-intrusion trend. Augite and olivine control the pre-intrusion phase of differentiation and petrographic work further defines the minerals determining the post-intrusion differentiation.

The chemical and field relationships between the felsic shonkinite and the syenite suggest a genetic relationship, but better definition would require more detailed work including additional analyses. Both could have originated from a magma comparable, though with less K, to the lower chill zone. Crystallization of apatite in the felsic shonkinite with continued mobility of Ti adequately accounts for the lack of P in the syenites. Immiscibility theory cannot account for the contrasting behavior of P and Ti with respect to the syenites.

Nash and Wilkinson (1970) studied mineralogical and geochemical details at Shonkin Sag laccolith. Examination of their data reveals a distinct difference in composition between the lower and upper chill zones. The lower chill zone contains distinctly more Al and alkalis than the upper chill zone and a lower Ca content. Subequal Mg content indicates minimal fractionation of Mg. If immiscibility operated on a significant scale at Snake Butte, the geochemical data do not reflect it. This interpretation, of course, relies on the previously noted behavior of Ti and P in experimental and natural systems.

PETROGRAPHY

Examination of thin sections primarily serves to support and extend information available from examination of hand specimens under the binocular microscope. Mineral content of the rocks coincides with geochemical analyses. Textural relationships within the rocks provide important time relationships of mineral formation, critical to correct interpretation of the geochemical trends.

All the rocks at Snake Butte essentially consist of the same minerals, though the proportions vary greatly. Augite and sanidine comprise the bulk of most rocks with lesser amounts of olivine, pseudoleucite, biotite, magnetite, apatite, calcite, natrolite and possibly other zeolites, and locally a trace of zircon. Some of the extreme differentiates lack olivine.

The following descriptions of rock units represent a composite obtained from numerous thin sections on each unit. Petrographic studies concentrated on identifying the textural relationships between minerals. Geochemical and density studies quantify contrasts between the different rocks. All percentages of minerals in the rocks represent visual estimates.

Lower Chill Zone

Petrographic examination of numerous thin sections from the lower chill zone revealed many interesting characteristics. It confirmed the hand specimen observations of low phenocryst content. Augite and olivine dominate the distinctly recognizable phenocryst assemblage.

Abundant euhedral to rounded remains of an uncertain mineral also exist in the chill zone. I presume these represent a form of pseudoleucite though they lack the typical radiating structure of pseudoleucite (Hyndman, oral communication). Similar euhedral to rounded "grungy" minerals exist throughout the laccolith and feeder dike. Sharp boundaries separate the grungy material from the enclosing sanidine. More typical pseudoleucite radiating structure characterize the rounded patches within the feeder dike. Some of the grungy "phenocrysts" retain a euhedral crystal outline similar to leucite. The tentative x-ray identification of nepheline in sample 32I, from the felsic shonkinite, supports the identification of pseudoleucite.

Fisher (1946) identified analcime phenocrysts in phonolites he concluded were cogenetic with the shonkinite intrusions. Weed and Pirrson (1896) identified "quite well crystallized, very clear, limpid, and fresh" leucite phenocrysts from similar volcanics in the Bearpaw Mountains. Leucite readily converts to analcime through ion exchange processes (Deer et. al., 1962). Though the present mineralogical composition of the pseudoleucite remains uncertain, the original phase apparently consisted of leucite or a similar K-rich mineral. Although precise mineralogical identification of the grungy masses remains problematic, they are referred to herein as pseudoleucite.

The country rock exhibits minimal alteration other than the development of a slight hornfels texture and minor recrystallization apparent in thin section. Directly adjacent to the chill zone, the intrusive rock consists largely of a dark brown glassy material with phenocrysts. The phenocryst assemblage consists of augite, serpentinized olivine and pseudoleucite.

Numerous, very thin veinlets parallel the contact beginning approximately one cm from the contact. These veinlets contain felsic minerals and apparently represent a phenomenon similar to the felsic sheets, though on a smaller scale. The groundmass looks very irregular, with patches of glassy material surrounded by lighter minerals. Farther from the contact, olivine remains relatively intact, with an encircling ring of magnetite and serpentine alteration. Biotite becomes recognizable in the groundmass, as does magnetite.

Sample 15A displays an interesting texture (Fig. 25). Most of the alkali feldspar occurs as blocky crystals but some forms acicular crystals. The acicular feldspar may represent a "quench texture" due to rapid crystallization. Lofgren (1980) notes that in experimental systems blocky feldspars form at slow cooling rates and acicular textures develop at more rapid cooling rates. Note that in a natural system, "cooling rate" may correspond to a change in a parameter other than temperature which would affect the rate of crystallization. Similar patches of acicular feldspar occur throughout the laccolith.

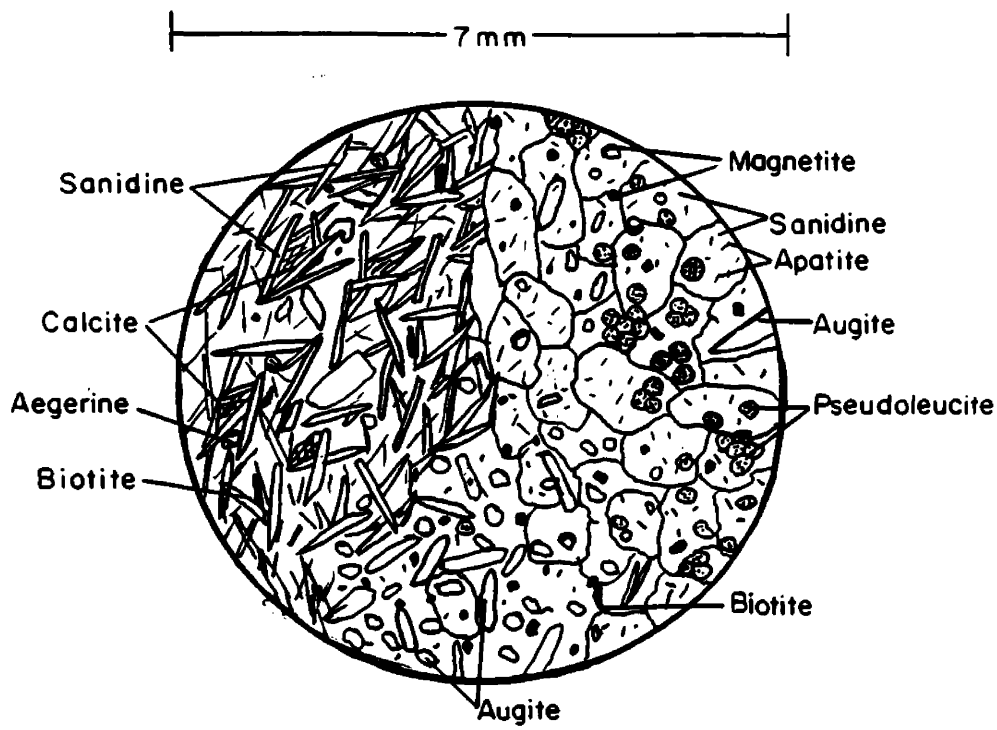


FIG. 25, Thin Section, Lower Chill Zone, Sample 15A

Primary Contrasting Characteristics

Acicular, sub-euhedral Sanidine	Blocky, an-subhedral Sanidine
Aegerine	Augite, bimodal
Minor Magnetite	Abundant Magnetite
Abundant Calcite, interstitial	Minimal Calcite
Minimal Apatite	Abundant Apatite
Minimal Pseudoleucite	Abundant Pseudoleucite

Interpretations

Acicular Sanidine – rapid crystallization, after blocky sanidine

Calcite – primary,

Apatite crystallized before blocky sanidine

Augite and Leucite present prior to intrusion

Residual fluids enriched in Na, CO_2, depleted in P

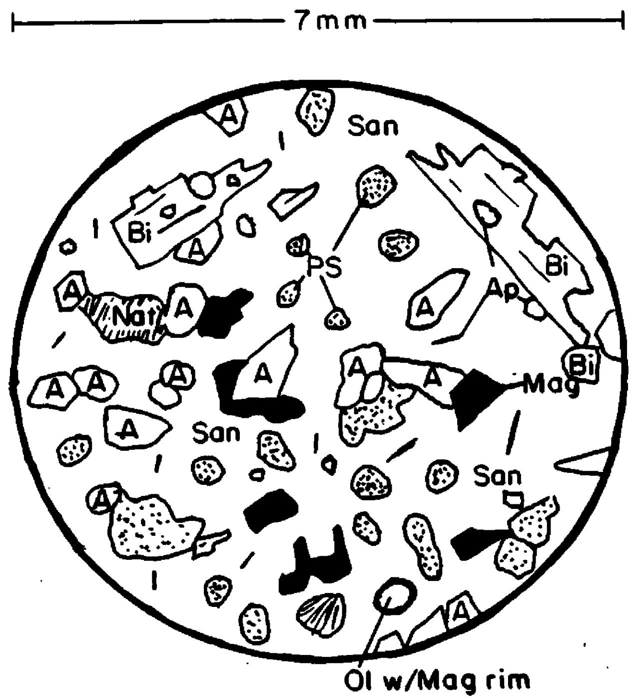


FIG.26, Thin Section, Felsic Shonkinite, sample 32E
Note: Abundance of pseudoleucite, magnetite, and apatite
Scarcity of olivine and small size of augite crystals.

A Augite
Bi Biotite
Mag Magnetite
PS Pseudoleucite
Ap Apatite
San Sanidine
Nat Natrolite

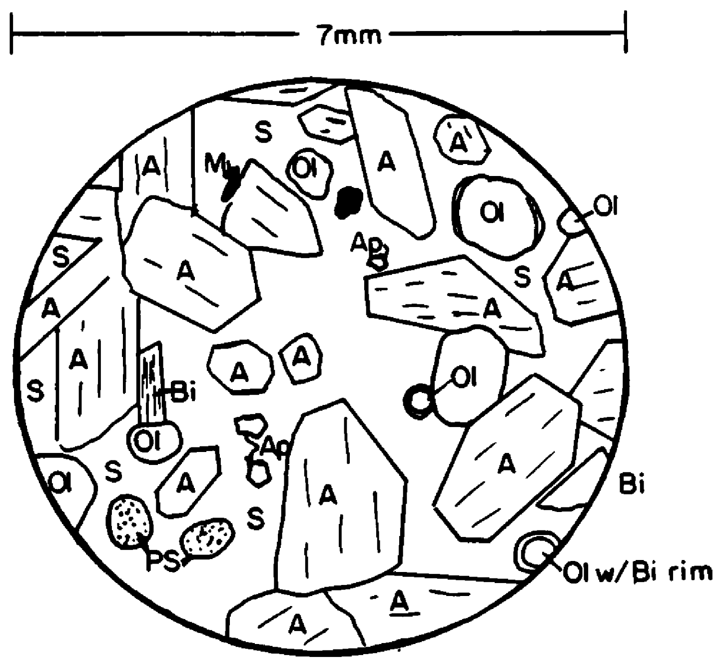


FIG. 27, Thin Section, Main Shonkinite, sample 32A

Note: Abundance of olivine and grain–grain contact;
Minimal rims of bi on ol; Apatite mostly in sanidine matrix;
and minimal amount of magnetite.

M Magnetite
Ap Apatite
PS Pseudoleucite
A Augite
Bi Biotite
S Sanidine
Ol Olivine

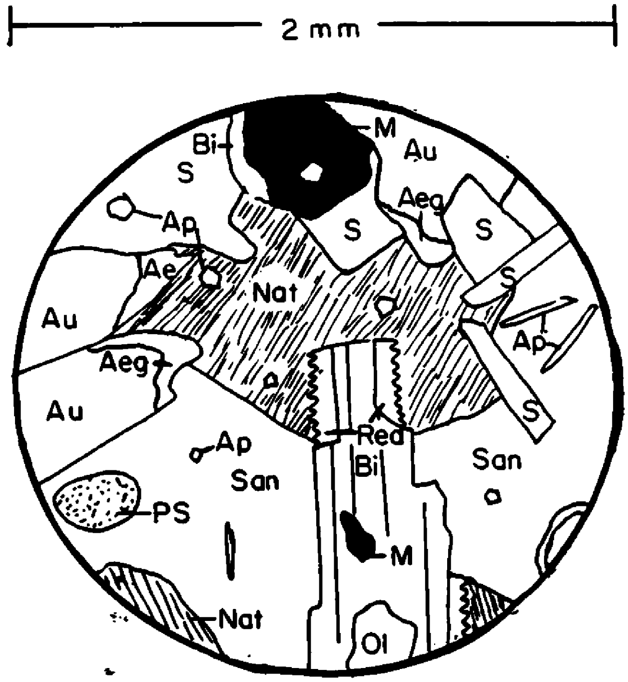


FIG.28,Thin section, Syenite, sample 43

Note: "battlement structure" on biotite adjacent to natrolite, aegerine rims predominantly adjacent to natrolite

M Magnetite
Ap Apatite
PS Pseudoleucite
Nat Natrolite
Au Augite
Aeg Aegerine
S Sanidine
Ol Olivine

Associated minerals reveal additional information about conditions which led to formation of the acicular textures. Abundant apatite accompanies the blocky feldspars but only minor amounts exist within the acicular feldspar. Apatite apparently crystallized prior to formation of the acicular texture. Abundant calcite within the acicular feldspar also indicate its late crystallization. The calcite fills interstices between feldspar crystals with no evidence of introduction through veinlets. It probably represents a primary phase. If so, the magma contained a significant amount of carbon dioxide. The noticeable lack of natrolite suggests an incompatability between natrolite and calcite, consistent with field observations.

In the felsic sheets, euhedral alkali feldspar crystals project into a formerly open space. Aegirine and natrolite fill the interstices between the feldspar crystals. Natrolite, confirmed by x-ray diffraction, apparently formed last. The comb structure of euhedral feldspar crystals lining the felsic sheets suggest they formed in open spaces, presumably cooling fractures.

Felsic Shonkinite

Away from the lower chill zone, grain size gradually increases upward into the felsic shonkinite. Observations reveal no distinct contact between the chill zone and the felsic shonkinite. Gradational variations occur in the felsic shonkinite. Density measurements and chemical analyses demonstrate that the felsic shonkinite becomes distinctly more mafic upward, which agrees with petrographic observations. This may indicate in situ differentiation of the felsic shonkinite, or merely reflect an increasingly mafic composition of the injected magma.

Augite dominates the mafic component of the rock. Green rims on some of the augite crystals indicate an aegirine component. The presence of aegirine rather than augite indicates increasing Na and ferric Fe. For the sake of simplicity, this study refers to all the distinctly green augite as aegirine though much of it probably is aegirine-augite. Precise determination was not attempted.

Biotite predominantly exhibits reddish-brown/yellow pleochroism with distinctly darker red rims. The relative amounts of Ti and ferric Fe controls the color of biotite. The red rims indicate a relatively high Ti content, whereas green biotite would indicate a high proportion of ferric Fe relative to Ti (Deer, Howie, and Zussman, 1962, p. 71).

Sparse olivine crystals in the felsic shonkinite have a 2V of 90^{o} indicating a Mg:Fe ratio of 85:15 (Deer, Howie and Zussman, 1963). Only minimal serpentinization or other alteration products exist on the forsteritic olivine. Anhedral to subhedral magnetite grains complete the mafic component of the rock.

Intergrowths of sanidine (confirmed by x-ray diffraction), pseudoleucite, apatite and natrolite comprise the dominant felsic portion of the felsic shonkinite. Other zeolites may exist in minor quantities. No attempts to identify clay minerals within the felsic shonkinite were made. Complex intergrowths of zeolites within the sanidine occur essentially as illustrated by Edmond (1980) for alkaline rocks of the Shonkin Sag laccolith. Natrolite forms distinct, felt-like masses within sanidine, often filling interstices between feldspar grains (Fig. 26). The occurrence of natrolite and the apparent lack of alteration throughout the bulk of the rock indicates that it formed as a primary, late magmatic mineral instead of as a secondary alteration product. Apatite occurs as inclusions in all minerals, though sanidine encloses most of it.

The presence of red rims on the biotite, green rims on the augite, and presence of natrolite within interstices in the feldspar indicate the trend that residual liquids follow with crystallization. Together, these minerals indicate enrichment in Ti, Na and ferric Fe during the later stages of crystallization. This coincides with the observed geochemical trends.

Main Shonkinite

The main shonkinite (Fig. 27) differs significantly from the felsic shonkinite, and a large amount of variation occurs within the main shonkinite itself. Augite dominates the mineral content within the main shonkinite and considerable amounts of olivine exist in some samples. Cumulate textures, evidenced by abundant grain to grain contacts of augite, occur throughout the main shonkinite. The mafic minerals generally lack the prominent rims prevalent on mafic minerals within the felsic shonkinite and syenitic rocks.

Many augite crystals display oscillatory zoning and at least two distinct zones of inclusions mark growth rate fluctuations. Oscillatory zoning may represent alternating rise of augite within the magma conduit with intermittent episodes of crystal settling. Alternatively, some of the oscillatory zoning could represent kinetic effects within the magma, that is, depletion of the magma adjacent to the growing crystal in specific elements as crystal growth proceeds faster than diffusion and other processes can replenish them (Lofgren, 1980). The zones of inclusions indicate a change in growth rate for some unknown reason. The augite contains only occasional traces of aegirine.

Olivine within the main shonkinite displays minimal alteration and a composition approximately the same as the olivine in the felsic shonkinite with a Mg:Fe ratio of 85:15 as determined optically and by x-ray diffraction. Biotite commonly rims olivine crystals. Olivine grains commonly contact each other without intervening biotite, indicating the biotite rim formed after crystal settling as an adcumulus phase. Much of the biotite which rims olivine displays a green pleochroism.

Of particular interest within the main shonkinite is the noticeable lack of opaque minerals. Only a minimal amount of magnetite exists within the main shonkinite. This, combined with the lack of aegirine rims on augite suggests that most of the Fe present exists in the reduced state. In turn, this suggests a relatively low oxygen fugacity and water content for the magma.

Biotite generally exhibits normal pleochroic colors. Apatite occurs as inclusions in most minerals, especially biotite and sanidine. Magnetite surrounds other minerals, indicating its late crystallization. Some of the magnetite occurs as grains within olivine. Natrolite occurs interstitially, apparently as a primary mineral, indicating the buildup of water during the latest stages of crystallization. It occurs with the acicular feldspars but not the blocky feldspar, reinforcing the previous conclusion that the acicular textures formed after the blocky textures.

Only minimal amounts of pseudoleucite exist in this portion of the laccolith. In contrast with natrolite, pseudoleucite does not coexist with acicular sanidine, but occurs with the blocky feldspar.

Syenite Pegmatite

The syenite pegmatite contrasts sharply with the underlying shonkinite. The syenite pegmatite contains large radiating augite crystals, best observed in hand specimen. Thin sections reveal very green rims on most of the slightly green augite. Extremely abundant magnetite corresponds with the high Fe content from the chemical analysis. Euhedral crystals throughout the sample and the large crystal size within the rock reflect the open space available for crystal growth and the high volatile content to inhibit nucleation.

Biotite may provide important clues to the differentiation history of Snake Butte. Within the syenite pegmatite, biotite exhibits distinct characteristics indicating different stages of growth. The centers of biotite crystals exhibit normal pleochroic colors, but are sharply bounded to distinctly red rims indicating an increased Ti content in the melt. Aegirine and magnetite within the rock indicates a relatively high proportion of ferric to ferrous Fe, consistent with the increased water content suggested by the abundance of natrolite. With a high proportion of ferric Fe, the biotite must contain a large amount of Ti to have red rims (Deer, Howie, and Zussman, 1962, p. 71). Numerous crystals are broken. Slender, projecting growths of biotite on biotite, similar to the "battlement" structures illustrated by Edmond (1980), represent the final stage of biotite growth. These "battlement" structures (Fig. 28) presumably represent a change in conditions which led to increased nucleation and rapid growth at many sites, with pre-existing biotite crystals providing a favorable substrate for nucleation. This concievably could occur due to a sudden loss of water from the magma. Hyndman (1985, p. 141) suggests a similar scenario for the formation of aplitic dikes associated with pegmatites.

Prominent green aegirine-augite rims on augite and an abundance of magnetite crystals suggests a late enrichment of Na and Fe+3 in the melt. The presence of natrolite supports the trend of Na enrichment.

Within part of the syenite pegmatite, distinctive augite "fingerprints" occur. Edmond (1980) describes similar textures from Shonkin Sag laccolith. Thin sections show that they consist of many small bits of augite in optical continuity. Apparently, they represent large augite crystals which became unstable with respect to the surrounding magma and proceeded to partially dissolve.

Syenite

The syenite contains only minimal amounts of olivine and augite. Aegirine rims much of the augite. The even textured, medium-grained rock consists largely of sanidine and pseudoleucite with biotite and natrolite. Battlement structures on the biotite in the syenite differ from the battlement structures in the syenite pegmatite. They occur only adjacent to natrolite. Where the biotite contacts sanidine, no battlement structures grew. Apparently, this indicates they formed after the bulk of the sanidine but before or concurrently with the growth of natrolite.

Augite in the marginal syenite dike occurs in hand specimen as dark clots. Petrographic examination reveals corroded augite crystals with scattered remnants of the crystal in optical continuity surrounded by unidentifiable grunge. Although at first I considered the possibility that the distinctly rounded mafic patches could represent immiscible mafic droplets in the syenite, the concentration of apatite in the surrounding felsic matrix and, in particular, the disequilibrium texture of the augite refutes the original suggestion, as explained in the discussion and summary at the end of this section.

Upper Chill Zone

Upper chill zone thin sections differ significantly from those of the lower chill zone. They contain abundant augite and olivine phenocrysts up to three mm with only minor amounts of pseudoleucite. Phenocrysts comprise approximately twenty-five per cent of the rock. Bimodal augite is compatible with the interpretation that much of the augite grew prior to intrusion. Glomeroporphyritic textures and oscillatory zoning also are present. Biotite rims olivine crystals and displays normal pleochroic colors. Abundant apatite needles occur in the groundmass.

Feeder Dike

Examination of thin sections from the feeder dike reveals similar relationships. Pseudoleucite within the feeder dike differs from the that within the laccolith. In the feeder dike, it consists of rounded grungy masses similar to those within the laccolith, but graphic textures also exist. Edmond (1980) depicts similar graphic textures from Shonkin Sag.

The abundance of magnetite mimics the variation within the laccolith. Only minimal magnetite occurs in the mafic portion of the feeder dike. Apparently most of the available iron went into the augite and olivine. Abundant magnetite exists within the more felsic rocks adjacent to the western chill zone.

Corresponding to the similarities in chemical compostion, the rocks adjacent to the western chill zone display petrographic similarities to the lower chill zone and felsic shonkinite of the laccolith. Sample 84 contains a bimodal distribution of augite grains, with a maximum grain size of approximately 1.5 mm. Biotite, with normal pleochroic colors, rims the scarce olivine crystals which are partially serpentinized. Abundant apatite predominantly occurs within sanidine grains, as do rounded grains of pseudoleucite. Abundant magnetite occurs as crystals less than 0.1 mm across, disseminated throughout the rock. Natrolite occurs interstitially with acicular feldspar crystals. Immediately adjacent to the chill zone (sample 19) augite textures indicate resorption.

As mentioned above, the mafic portion of the feeder dike contains pseudoleucite with distinct graphic textures and only minimal amounts of magnetite. Crystals of augite up to 3 mm form the bulk of the sample along with a small amount of olivine. Sanidine exhibits blocky and acicular textures with only a minimal amount of associated apatite and natrolite.

Petrographic Discussion and Summary

Overall, the petrographic work corroborates and extends interpretations based on field and geochemical evidence. The observed mineralogy correlates with the geochemical trends, and provides the basis for interpretation of the trends. Figure 29 depicts an interpretative sequence of crystallization, based on composite information from many thin sections.

Figure 29

Composite Crystallization Sequence

	Pre-Intrusion	.	Post-Intrusion
Olivine	?------------	.	
Augite	?----------------------		Aeg ----------
Leucite	?---------------	.	
Magnetite		.	-----------
Apatite		.	-----------------------
Biotite		.	---------------------
Sanidine		.	------------
Natrolite		.	-----------------

The distinct contrast in chill zones and variation across the feeder dike supports the hypothesis that much of the differentiation at Snake Butte took place prior to intrusion. However, though crystal fractionation of the mafic minerals forsteritic olivine and augite dominated pre-intrusion trends, crystallization of apatite, sanidine, magnetite, and biotite dominated post-intrusive trends.

Calcite and natrolite apparently crystallized as primary minerals. Numerous samples reveal that natrolite occurs as a late magmatic mineral. The interstitial occurrence of these minerals between euhedral sanidine crystals and the overall lack of deuteric alteration within the laccolith strongly supports this conclusion. Though less evidence supports the conclusion that the carbonate formed as a primary mineral, the evidence seems definitive. Some of the carbonate and probably some of the natrolite represent secondary phases, as evidenced by local veinlets and replacement textures.

Aegirine, magnetite, and natrolite coincide with the geochemical trends of sodium and ferric iron enrichment during late stages of differentiation. The lack of magnetite and aegirine rims within the main shonkinite also furnishes evidence concerning the oxidation state of iron.

Throughout the laccolith, biotite provides clues to the partitioning of titanium. The sharp transition to distinctly red rims evidences the abrupt late buildup of titanium in the syenite and syenite pegmatite. The battlement structures, with distinctly lighter color than the red rims, presumably indicate increased nucleation rate, possibly due to sudden expulsion of fluids from the system.

Magnetite probably also controlled the distribution of titanium. Three analyses of magnetite from Shonkin Sag laccolith reveal from three to six percent titanium in the magnetite (Nash and Wilkinson, 1970). Magnetite from a syenite contained the highest amount of titanium. This coincides with the observed enrichment of titanium in the syenites at Snake Butte.

Bowen (1928) suggested a simple petrographic test for immiscibility based on thermodynamic theory. In the words of Bowen,

> "As a matter of fact there is a very simple test, arising from theoretical considerations, that can be applied to any pair of liquids for which an immiscible relation may be proposed. It is to be remembered that unmixing is a manifestation of phase equilibrium with each other. Not only are they in equilibrium with each other but both must be in equilibrium with any additional phase that may be formed. Thus in the asociation, gabbro-granophyre, if it is assumed that their liquids constitute an immiscible pair and if we imagine that they are cooled until crystallization begins in one of them, then the crystals formed in it should be in equilibrium with plagioclase of composition Ab31 An69 (and there is such a stage), the associated granophyre liquid should also be in equilibrium, not merely with some plagioclase, but with the precise plagioclase Ab31 An69 and any crystals that might migrate across the border into the granophyre liquid would be entirely at home there."

Applying this test to Snake Butte, the striking contrast between fresh olivine and augite in the main shonkinite with serpentinized olivine and resorbed augite crystals in the syenite suggests they did not separate immiscibly. Though these disequilibrium textures only prove the crystals were out of equilibrium with the final liquid, the extent of resorption indicates a longer period of disequilibrium. Similarly, Edmond (1980) stated the following about the petrographic relationships at Shonkin Sag:

> "The augite crystals in the syenite differ from those in the shonkinite. They are embayed and corroded and lack the oscillatory zoning characteristic of the augite in the chilled zone and shonkinite layers. Many more show rims of brown biotite, and several of the smaller grains are almost completely replaced."

Microprobe analyses on individual minerals presented by Nash and Wilkinson (1970) confirm and extend the petrographic observations.

X-RAY DIFFRACTION

X-ray diffraction (Appendix III) served mainly to supplement petrographic observations, confirming: the presence of natrolite, the Mg:Fe ratio of olivine, and the presence of sanidine.

PETROGENESIS

Together, the field, density, geochemical, petrographic, and x-ray evidence support a model of crystal fractionation dominated by settling of augite and olivine crystals in the feeder dike prior to intrusion. Flotation of leucite possibly contributed to the pre-intrusion differentiation. A series of increasingly mafic magmas injected into the laccolith accounts for the major characteristics of the intrusion. Post-intrusion differentiation yielded volumetrically minor felsic differentiates and eventually led to formation of the syenite pegmatite. Violent expulsion of fluids during the lastest stages of crystallization probably terminated the magmatic history of Snake Butte.

The evidence supports an interpretation of the petrogenetic history of Snake Butte as outlined below. Though the relative time of formation for the syenite and syenite globules remains problematical, the best available data suggests the interpretation given.

1. Differentiation of the parent magma by crystal settling and flotation in the wide feeder dike prior to intrusion. Crystal/liquid processes due to differences in the degree of partial melting at the source possibly contributed to an unknown extent (Fig. 30A).
2. Intrusion of the uppermost portion of the dike formed the chill zone on the edges of the feeder dike and the lower chill zone in the laccolith. Earlier folding and/or faulting possibly contributed to the location of the laccolith, with the precise level of emplacement

controlled by the presence of a relatively competent siltstone bed (Fig. 30B).

3. Intrusion of the felsic shonkinite coincided with or immediately followed intrusion of the lower chill zone (Fig. 30C).
4. Intrusion of the remaining mafic portion of the butte to form the main shonkinite. Intrusion probably occurred in several discrete pulses after partial solidification of the felsic shonkinite, creating a gravitational instability within the laccolith (Fig. 30D)
5. Crystal settling of olivine and augite within the main shonkinite to form cumulate layers, coinciding with migration of residual liquids from the felsic shonkinite upward along marginal dikes to form the syenite cap. The central portion of the shonkinite remained relatively fluid as the outer portions solidified. Residual liquids from the upper portion of the main shonkinite probably contributed to formation of the syenite and syenite pegmatite. Alternatively, the syenite cap possibly formed as a discrete injection of syenitic magma from the feeder dike into the upper portion of the laccolith, or from intrusion of the main shonkinite into the central portion of the earlier, felsic intrusive phase (Fig. 30E). The available geochemical evidence supports the first hypothesis, as does the presence of marginal syenite dikes.

6. Continued cooling. Initial jointing and formation of the master joint set creates low pressure zones. Volatile pressure drives residual fluids into the master joint set forming pegmatitic dikes with mafic selvages.
7. Cooling in the upper portion of the syenite layer inhibits crystal settling adjacent to the upper chill zone; migration of residual fluids into the lower, largely molten, base of the syenite leads to volatile enrichment and eventual formation of the pegmatite. Volatiles also drive residual fluids upward from the upper portion of the main shonkinite into the pegmatite layer (Fig. 30F).
8. Syenite globules form prior to complete solidification of the main shonkinite. Fluids migrating through the crystalline mush coalesce along zones of low stress (Fig. 30G)
9. Further jointing of the laccolith into columns approximately coincides with formation of the pegmatite layer. Fluids migrate toward column edges but the felsic residual fluids largely remain within the columns.
10. At some point, fluid overpressures due to volatile buildup exceeded the fracture strength of the overlying rocks and the laccolith vented, with rapid crystallization of remaining fluids, including the formation of battlement structures on biotite and natrolite as a primary phase.

FIGURE 30

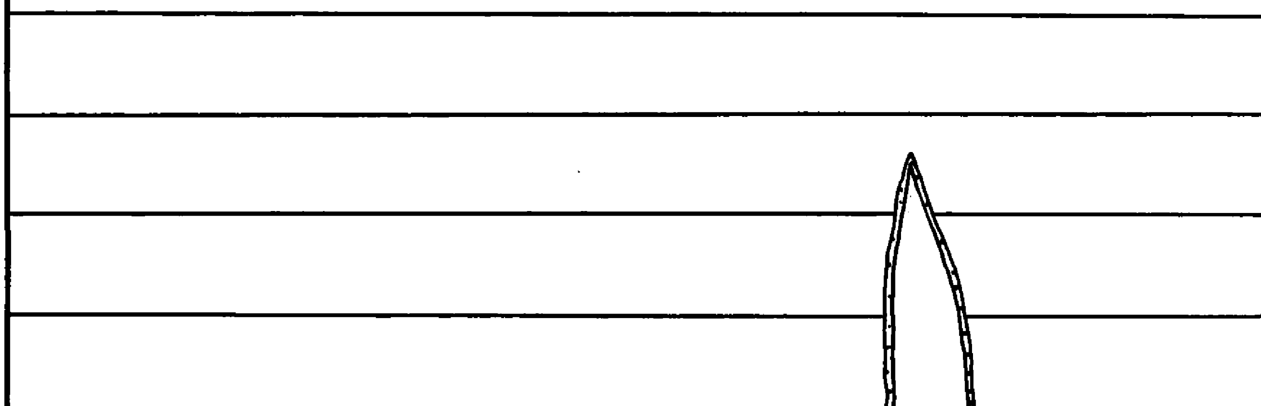
PETROGENETIC MODEL FOR SNAKE BUTTE

SCHEMATIC ONLY, NOT DRAWN TO SCALE

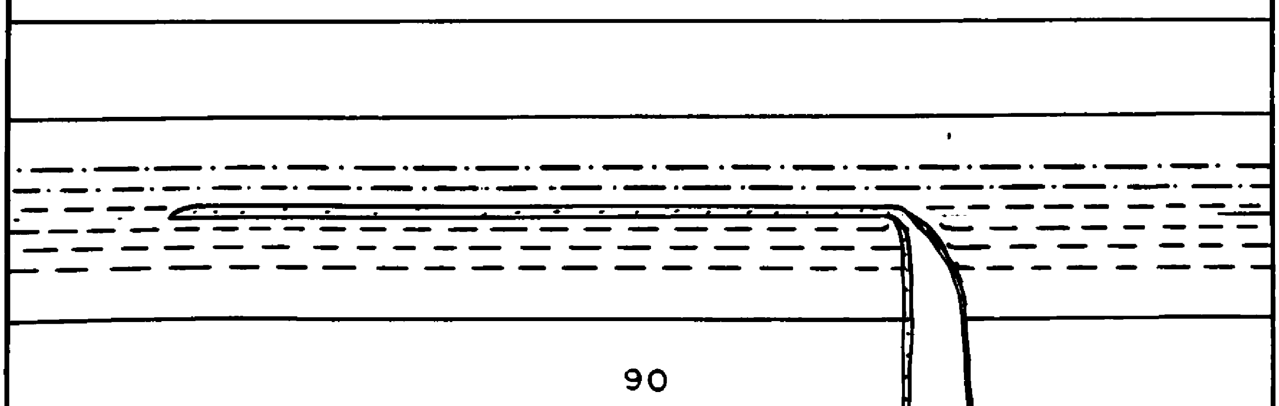
KEY

- Upper Chill Zone
- Syenite
- Syenite Pegmatite
- Syenite Globule
- Main Shonkinite
- Felsic Shonkinite
- Pegmatitic Dike
- Lower Chill Zone
- Bearpaw Shale

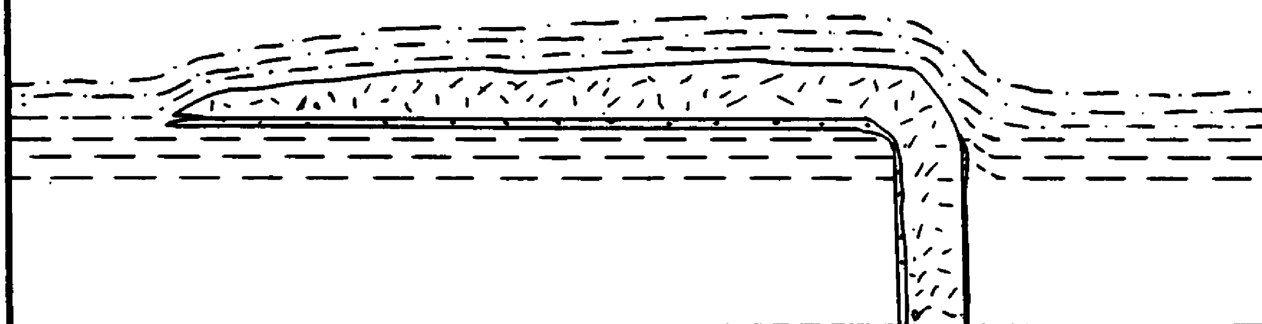
A. CRYSTAL SETTLING DURING RISE OF MAGMA IN THE DIKE.
POSSIBLE FLOTATION OF LOW DENSITY CRYSTALS.
FELSIC CHILL ZONE FORMS.



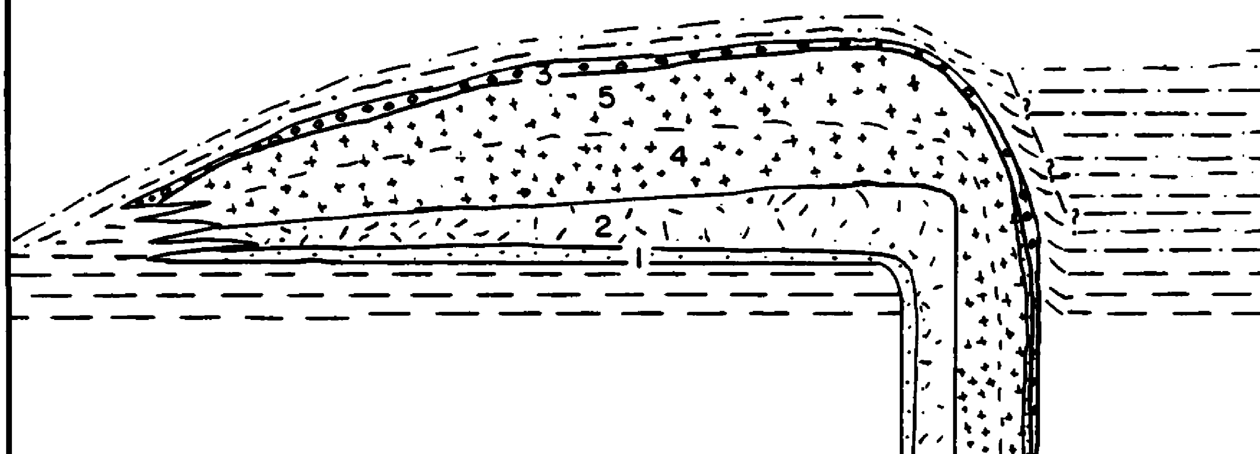
B. INTRUSION OF THE UPPER, MAFIC PHENOCRYST DEPLETED PORTION OF THE DIKE TO FORM THE LOWER CHILL ZONE.
MORE COMPETENT SILTY BEDS CONTROL EMPLACEMENT LEVEL.



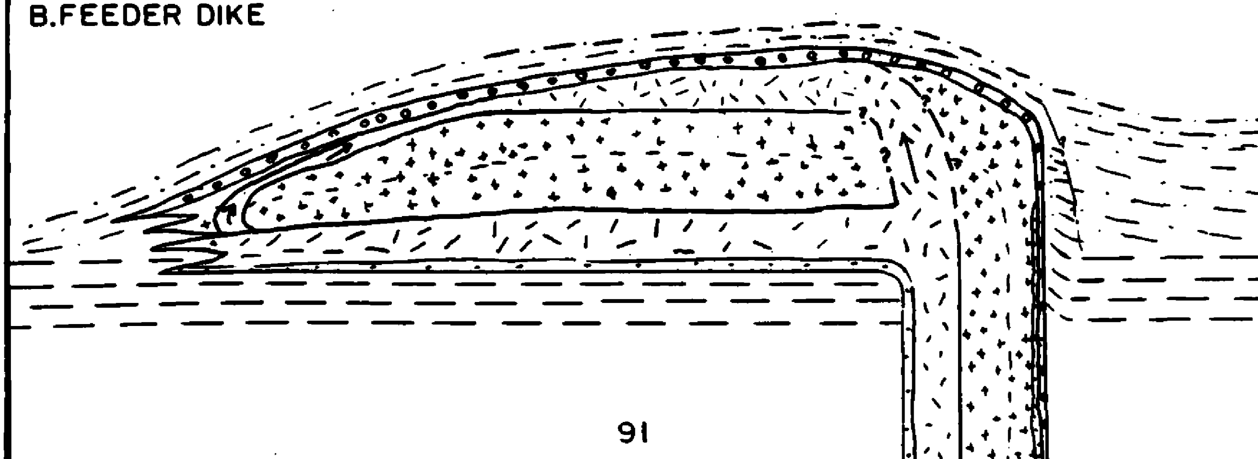
C. INJECTION OF THE FELSIC SHONKINITE, DEPLETED IN MAFIC PHENOCRYSTS PRIOR TO INTRUSION.



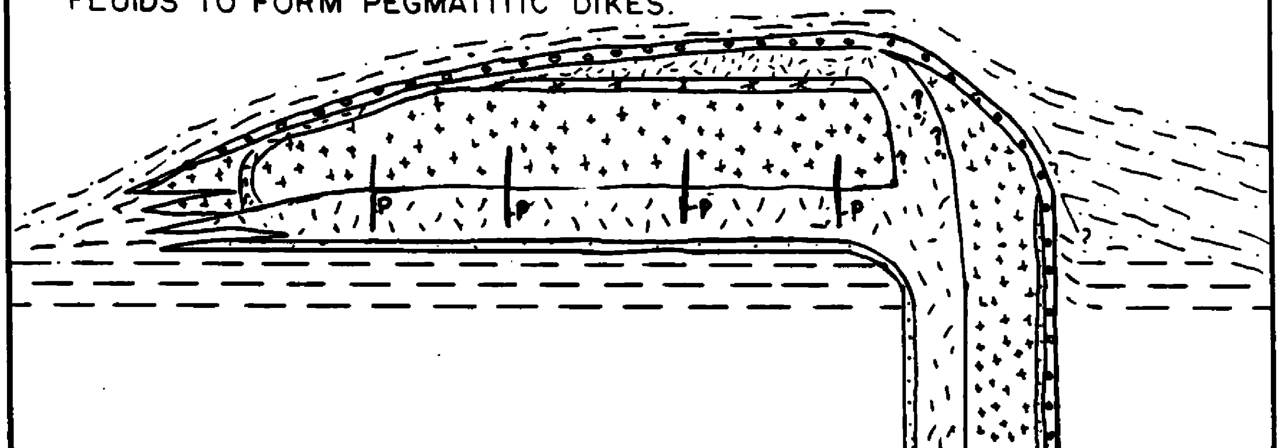
D. INJECTION OF THE MAIN SHONKINITE, PROBABLY IN AT LEAST 2 PULSES. CREATION OF GRAVITATIONAL INSTABILITY DUE TO INJECTION OF DENSE MAGMA OVER LIGHTER FELSIC SHONKINITE.



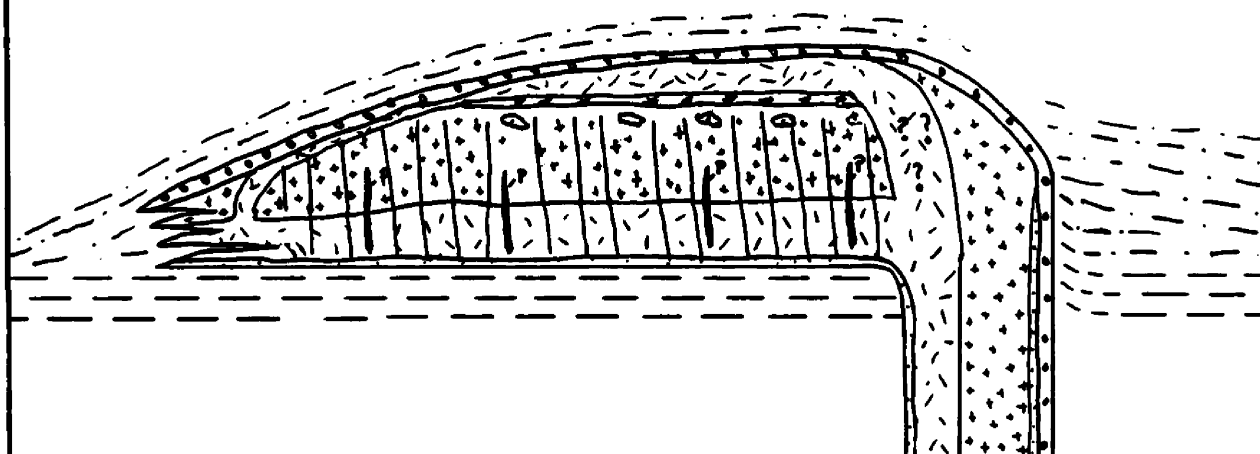
E. CRYSTAL SETTLING WITHIN THE MAIN SHONKINITE AND MIGRATION OF RESIDUAL FLUIDS UP TO FORM SYENITE FROM THE:
A. FELSIC SHONKINITE VIA MARGINAL DIKES AND/OR;
B. FEEDER DIKE



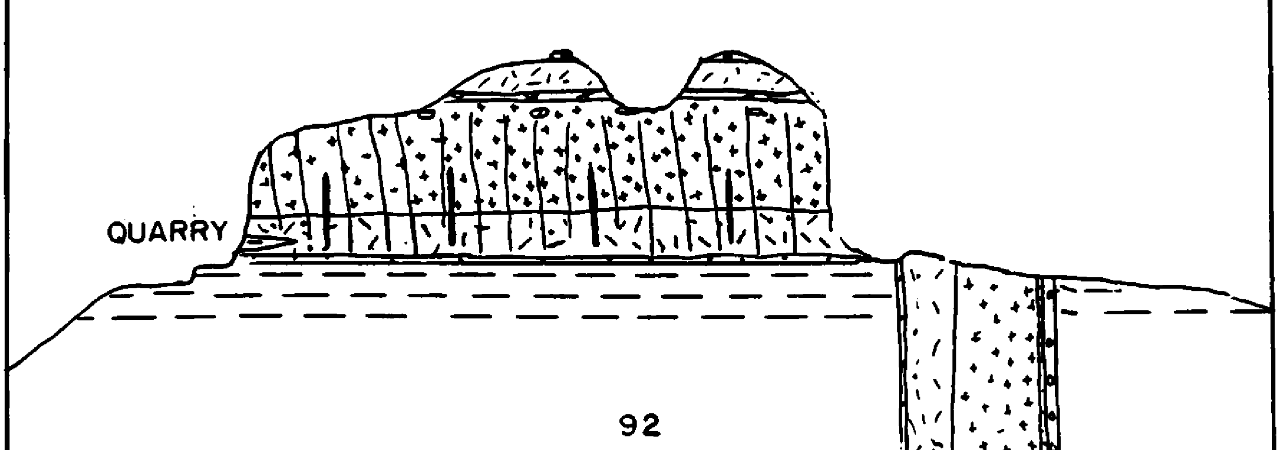
F. FORMATION OF THE SYENITE PEGMATITE FROM THE BUILDUP OF RESIDUAL FLUIDS, ESPECIALLY VOLATILES.
FORMATION OF MASTER JOINTS INITIATES MIGRATION OF RESIDUAL FLUIDS TO FORM PEGMATITIC DIKES.



G. FORMATION OF COLUMNS, MIGRATION OF FLUIDS TOWARD JOINTS, COALESCENCE OF GLOBULES, FINAL CRYSTALLIZATION



H. EXPOSURE THROUGH EROSION, GLACIATION AND QUARRYING



11. Erosional unroofing, including glaciation, exposes the laccolith (Fig. 30H)

Figure 31

Petrogenetic Sequence of Events

Ascent of Magma	----------------
Crystal settling/flot	-----------------
Lower Chill Zone Intr.	---
Felsic Shonk. Intr.	---
Upper Chill Zone	---
Main Shonk Intr.	------
Master Joints	-------
Pegmatite Dikes	-------
Columns	----
Globules	?---?---?---?---?
Syenite	--------------
Syenite Pegmatite	---------

The contrast between the chill zones and variation across the feeder dike offers conclusive evidence that some differentiation of Snake Butte took place prior to intrusion. The geochemical evidence, combined with petrographic observations, demonstrates that crystal settling of olivine combined with flotation of leucite can account for the bulk of the observed variation within the laccolith. Though obscured by later differentiation, some pre-intrusion chemical variation probably resulted from variations in source material and/or degree of partial melting at the source.

Comparison of density values for basaltic glass compared to molten and crystallized basalt gives a basis for estimating the density of shonkinite magma. Basalts decrease in density approximately 10 percent with melting and basaltic glass decrease about 5 percent with melting (Hyndman, 1985, p. 128). The chill zones at Snake Butte contain only a minimal amount of glass so the 10 percent change best approximates the density of the shonkinitic magma.

Assuming that the upper chill zone (D=2.80) represents the "average" shonkinitic magma at Snake Butte, a 10 percent decrease in density to obtain a density value for the "average" shonkinite magma yields a value of 2.52, at surface pressures. Since the AFM diagram and relatively high P content suggest the upper chill zone is more felsic than average, the magma density should be slightly lower. Therefore, leucite, with a density of 2.47-2.50 (Deer, Howie and Zussman, 1966) would have only a minimal tendency to float but olivine (Fo 85, D=3.4) and augite (D=3.2-3.3) would sink. At high pressures, the density of the magma would increase significantly, much more than the included crystalline phases, enhancing flotation of leucite at depth. Plagioclase displays similar behavior leading to flotation with increasing magma density (Kushiro, 1980).

Rough calculations show that crystal settling could account for the amount of pre-intrusion differentiation. The calculations utilized low end estimates to provide an order of magnitude estimate of the amount of felsic differentiate expected to form prior to intrusion. The calculations utilized the following assumptions:

1. 2 mm olivine or augite crystals sink at 0.5 m/hour during ascent of the magma. Kushiro (1980) provides this figure as an estimate for the settling rate of olivine in an olivine tholeiite magma at surface pressures. At depth, settling rates increase due to decreasing viscosity of the magma.
2. 2 months (1440 hours) for rise of the magma from the mantle. This is a low end estimate based on Hyndman's (1985, p. 133) estimate of a 5 month rise time.
3. Constant 20 m dike width. Actual measurement of the dike gives a width of 217 meters, but much of this width probably represents separate intrusions progressively increasing the width of the dike. 20 m provides a low end estimate.
4. 800 meters of dike feeding Snake Butte.

Using these figures, 2 mm mafic phenocrysts should sink 720 m during the ascent of the magma (1440 hr x 0.5 m/hr), assuming they formed at significant depth. Obviously, the closer they formed to the surface, the less time they would have to sink. This means that approximately the upper 700 m of the dike should be depleted in mafic phenocrysts, regardless of dike width.

A simple wedge shape 4000 m long by 2000 m wide and 100 meters at the eastern end tapering to 0 to the west approximates the volume of the laccolith. This calculation gives a volume of 0.4 cubic km for the entire volume of Snake Butte. The above figures allow calculation of the minimum volume of magma depleted in mafic phenocrysts. With 800 m of dike feeding the laccolith and a constant 20 m width at depth, 700 m vertically gives an estimate of 0.11 cubic km for the volume of depleted magma. This estimate is approximately three percent of the total volume of the laccolith. Given the limitations on the order of magnitude calculations, crystal settling prior to intrusion could easily account for the approximately twenty percent of the laccolith which is syenitic.

The distinctive layering within the laccolith, chemical and mineralogical contrast between chill zones, and variation across the feeder dike suggest that intrusion occurred in a number of pulses. One of the pulses ripped up the previously formed lower chill zone. The sharp boundary between the contrasting bases and caps of hoodoos may represent one of the boundaries between injections.

Following injection of the laccolith, differentiation in place followed trends contrasting the earlier period of pre-intrusion differentiation. Crystal fractionation of olivine and augite ceased to dominate the differentiation trends, though variations in density and cumulate textures in the main shonkinite suggest that minor crystal settling continued within the intrusion. Crystal settling within the laccolith would cease with increasing viscosity and formation of a crystal mush. However, residual fluids could continue to migrate through a crystal mush. Formation of the pegmatitic dikes and development of felsic rims on columns provide evidence that residual fluids could continue to migrate after a high degree of solidification. The syenite globules may represent a similar phenomenon with accumulation of fluids at regions of low stress (Spera, 1980). Crystallization of apatite and sanidine define post-intrusion differentiation trends. Titanium continued to partition into residual fluids, along with Na, ferric Fe, and volatiles. Precipitation of apatite caused retention of P in the felsic shonkinite.

Intrusion of the dense, mafic shonkinite over the lighter felsic shonkinite caused gravitational instability within the laccolith. The strong density contrast made migration of the partially molten felsic shonkinite inevitable. Syenite dikes low on the margin of the laccolith, just a few meters below the upper chill zone, provide evidence of this migration. The "split" in composition of the felsic shonkinite and syenites on the geochemical diagrams supports the hypothesis that they were cogenetic, derived from a magma similar in composition to the lower chill zone. Though no evidence exists, continued differentiation within the feeder dike possibly also provided residual magma to the syenite.

The presence of syenite "globules" within the main shonkinite requires more detailed analysis. Other studies of alkalic laccoliths in central Montana attribute similar globules to processes of silicate liquid immiscibility. The low phosphorus and titanium content of the analyzed syenite globule corresponds to immiscibility theory, but extreme crystal fractionation could also produce this effect.

The amount of Ti and P in the syenite globule compared to the Ti and P of the shonkinite makes it unlikely they formed from the shonkinite via immiscibility. The high density (D=2.96) of the shonkinite directly adjacent to the globule suggests an indistinct mafic selvage may separate the syenite globule from the main shonkinite.

However, the chemical composition and lack of other evidence casts doubt on an early hypothesis that residual fluids from the felsic shonkinite migrated via diapiric rise to form the globules. Hyndman (oral communication) argues against the hypothesis that the globules formed due to the migration of fluids into cooling fractures on the basis of their geometry. Though somewhat elongate, I agree that they do not look like any type of fracture filling.

Spera (1980) provides a possible mechanism for formation of the syenite globules. In a review of processes of magma transport by flow through a porous media such as a crystal mush, he states that "The basic idea is that melt will flow to regions of low stress at rates greater than the surrounding deformable crystal network." In other words, fluids flowing through a crystal mush may coalesce. Such a process would require that pressure differentials exist to initially cause movement. Obviously, pressure gradients caused migration of fluids elsewhere within the laccolith and presumably existed near the globules at some point in time. A discontinuity in the shonkinite at the base of the syenite globule, evident from differential weathering of the shonkinite (Fig. 17), possibly controlled the location of a low stress zone.

The complex fluid dynamics of a crystalline mush prevent further analysis of the syenite globules with respect to the segregation of melt phase from it. I suggest it as a plausible hypothesis which merits further investigation but lies beyond the scope of this project.

At some point, master joints began to form in the felsic shonkinite, creating zones of low pressure. Consequent expansion of volatile phases previously concentrated in the residual fluids of the felsic shonkinite forced the fluids to migrate into the fractures, leaving prominent mafic selvages adjacent to the dike. The extremely felsic composition of the pegmatitic dikes indicates they formed at a very late stage in the crystallization of the felsic shonkinite, but field relationships show they formed prior to final splitting of the laccolith into columns. The more extreme composition and lack of correlation with geochemical trends related to the syenites point to their genesis by an independent process.

As syenitic magma accumulated below the upper chill zone, its uppermost part began to cool and solidify. Inward progressing solidification of the syenite may account for the observed trend of upward increasing density within the syenite (Fig. 12). Residual fluids, including volatiles, would continue to migrate downward, out of the solidifying syenite. The upper chill zone above the syenite prevented them from migrating upward. Simultaneously, upward migration of residual fluids from the main shonkinite contribute to buildup of the syenitic cap. At some point, volatile concentration reached a level high enough to inhibit nucleation within the magma and extremely large crystals grew, forming the syenite pegmatite. Increasing volatiles, particularly water, inhibits nucleation by breaking Si-O-Si bonds as noted above (p. XOX geochem section, immiscibility). A mafic selvage at the base of the syenite demonstrates that at least part of the fluids for the pegmatite originated within the syenite. The exceptionally high density of the uppermost portion of the main shonkinite suggests that it yielded some felsic differentiates, which presumably migrated up.

Distinct red rims on biotite crystals in the pegmatite indicate the late enrichment of the magma in Ti (p. XOX). Prominent green aegirine-augite rims on augite and an abundance of magnetite crystals suggests a late enrichment of Na and Fe+3 in the melt.

"Battlement" structures (Fig. 28) on broken biotite grains provide a clue to the final crystallization of the pegmatite. The battlement structures indicate a sudden increase in nucleation rate. Shonkin Sag laccolith contains a syenite pegmatite which appears very similar to the pegmatite at Snake Butte. Edmond (1980) described similar "battlement" structures within the pegmatite at Shonkin Sag. An aplitic dike within the pegmatite layer at Shonkin Sag laccolith is not exposed at Snake Butte.

I suggest that during the final stages of pegmatite crystallization fluid overpressures exceeded the strength of the overlying rock and fluids escaped from the system. Violent expulsion of volatiles caused movement within the pegmatite which broke biotite grains. Loss of volatiles permitted nucleation at many points, especially on preexisting crystals, and subsequent formation of the battlement structures. A similar scenario for the formation of aplitic dikes associated with pegmatites.

Continued solidification of the main shonkinite and propagation of columnar joints into the upper portion of the main shonkinite probably coincided with formation of the syenite and syenite pegmatite. The extension of columnar joints up to but not into the syenite suggests the syenite (and syenite pegmatite) remained as the last portion of the laccolith to solidify (Jaeger, 1968; Spry, 1962) During columnar jointing, residual magma apparently retained enough volatiles to force migration of fluids from the center of columns toward the edges, but either insufficient of volatiles or residual fluids prevented the formation of pegmatitic dikes within the columnar joints of the main shonkinite. Spry (1962) noted the occurrence of columns with felsic rims elsewhere, though others display mafic rims. Minor amounts of natrolite did form in some of the columnar joints.

SUMMARY

Field and analytical work demonstrate that Snake Butte largely differentiated prior to intrusion, with crystal settling of olivine and augite and flotation of leucite as the dominant pre-intrusion process. The contrasting phenocryst content, major-element chemistry, strong trend on the AFM diagram consistent with differences in phenocryst content, and enrichment of the felsic fraction in Fe, P, and Ti support a model of crystal fractionation.

Immiscibility probably played an insignificant role in the differentiation at Snake Butte. Experimental and natural systems show that Fe, P, and Ti all strongly partition into the mafic phase with immiscibility, opposite to their behavior at Snake Butte. Immiscibility also tends to result in a Si-rich phase and Si-poor phase with a distinct gap in Si content. At Snake Butte, Si only shows slight enrichment in the felsic rocks with no distinct gap in silica content. Minor amounts of differentiation occurred within the laccolith after intrusion to produce the pegmatitic dikes, felsic rims on the columns, cumulate layers within the main shonkinite, the syenite pegmatite, and syenite globules. Origin of the syenite remains uncertain. It possibly formed as a separate injection from the feeder dike or as a differentiate from the felsic shonkinite. Alternatively, though not favored by the presence of marginal dikes, the syenite formed simultaneously with the felsic shonkinite and injection of the main shonkinite split it into two. Volatiles apparently played an increasingly important role in late stages of differentiation as their

concentrations increased and jointing occurred. In particular, they apparently provide the driving force for separation of residual fluids from the solidifying shonkinites.

Although other studies cite the presence of syenite globules as definitive evidence of silicate liquid immiscibility, at Snake Butte they apparently represent residual fluids which somehow coalesced into globules. The vague process of segregation within regions of low stress during flow through a porous media may provide an alternative explanation for their formation, but their origin remains enigmatic.

The general similarity of Snake Butte to some of the classic alkalic laccoliths in central Montana may provide important clues to their petrogenesis. The better preservation and exposure of Snake Butte, presence of the feeder dike, and emphasis on chill zone characteristics leads to the interpretations contained herein. Continued work on other differentiated alkalic laccoliths in central Montana may benefit from a similar approach, in addition to analysis of geochemical data by means other than the Grieg diagram.

In particular, studies of other alkalic laccoliths in central Montana must address the possibility that they were not intruded as a single "homogeneous" magma which differentiated in situ. Indeed, with the advantage of hindsight, it seems unlikely that a presumably low viscosity alkalic magma with abundant phenocrysts would not differentiate during ascent.

The distinctly felsic lower portions of other laccoliths suggests a similar petrogenesis. Earlier studies (Barksdale, 1937) recognized the less mafic portions at the base of the Shonkin Sag laccolith, but attributed it to incomplete crystal settling in the rapidly cooled lower portion of the laccolith. Later studies which favored silicate liquid immiscibility used the same argument, that is, rapid cooling inhibited complete separation of immiscible liquids. Re-examination may suggest that it formed as an early intrusive phase.

In conclusion, any study of igneous intrusions with phenocrysts present in their chill zones must consider the possibility of crystal settling prior to intrusion. This especially holds true for mafic intrusions with their high temperatures and low viscosities in comparison to granitic magmas (Hyndman, 1985, p. 126). Even a kimberlite, with its extremely rapid rate of ascent could display some differentiation prior to intrusion due to phenocryst settling.

Finally, I must re-emphasize that a variety of processes contribute to the differentiation of any igneous body. Many studies have emphasized a single process with insufficient consideration of others. Although at Snake Butte I recognize crystal fractionation as the dominant process, volatile transport probably contributed significantly. If immiscibility occurred, it apparently only contributed a minimal amount.

In future studies to further define the petrogenesis of Snake Butte, I suggest more detailed examination of the feeder dike and the layering within the main shonkinite. The contrast between calcite fracture filling and zeolitic fracture filling may provide significant information on the variation of volatile content of the magma or merely differences in groundwater conditions. Additional chemical analyses on the syenitic units may better define their origin. Additional field work should reveal more syenite globules and possibly provide a better explanation for their genesis.

REFERENCES CITED

Alverson, D.G., 1965, Geology and hydrology of the Fort Belknap Indian Reservation, Montana: U.S. Geological Survey Water Supply Paper 1576-F, 59 p.

Bowen, N.L., 1928, The Evolution of Igneous Rocks, Princeton University Press 332 p.

Bryant, B., Schmidt, R. G., and Pecora, W.T., 1960, Geology of the Maddux quadrangle, Bearpaw Mountains, Blaine County, Montana: U.S. Geological Survey Bulletin 1081-C, p. 91-116

Cathcart, S.H., 1922? U.S.G.S. unpublished manuscript.

Deer, W.A.; Howie, R.A. and Zussman, J.,1962, 1963, Rock Forming Minerals. John Wiley and Sons, Inc. New York, New York

Edmond, C.L., 1980 Magma immiscibility in the Shonkin Sag laccolith, Highwood Mountains, central-Montana: M.S. Thesis, University of Montana, Missoula, 97 p.

Fisher, B., 1946, Igneous rocks of the northeastern Bearpaw Mountains, Montana: Ph.D. Dissertation, Harvard University, 127 p.

Freestone, I.C., 1978, Liquid immiscibility in alkali-rich magmas: Chemical Geology (Amsterdam) 23:115-123

Hearn, B.C., 1976, Geologic and tectonic maps of the Bearpaw Mountains area, north-central Montana: U.S. Geological Survey Miscellaneous Investigations Series I-91a

_____ Pecora, W.T., and Swadley, W.C., 1964, Geology of the Rattlesnake quadrangle, Bearpaw Mountains, Blaine County, Montana: U.S. Geological Survey Bulletin 1181-B, p. 1-66

Hess, P. C., 1980, Polymerization Model for Silicate Melts. In: Physics of Magmatic Processes, Hargraves, R.B. (ed.) Princeton University Press. p. 3-48

Hurlbut, C.S., 1939, Igneous rocks of the Highwood Mountains, Montana, Part 1, The laccoliths: Geological Society of America Bulletin, 50:1032-1112

Hyndman, D.W., 1985, Petrology of Igneous and Metamorphic Rocks, Second Edition. McGraw-Hill, Inc. 786 pp.

_____ and Alt, D., 1983, "Emplacement of Alkalic Intrusive, Central Montana," Abstracts with programs, Geological Society of America, 36th Annual Meeting, Rocky Mountain Section, May 24, 1983, page 420

Jaeger, J.C., 1968, Cooling and Solidification of Igneous Rocks. In: Basalts: The Poldevaart Treatise on Rocks of Basaltic Composition. Hess, H., H. and Poldevart, A., (ed.) John, Wiley and Sons, New York, 2:503-536

Johnson, G.K.; Flotow, H.E.; O'Hare, P.A.G.; and Wise, W.S.; 1983, Thermodynamic studies of zeolites: natrolite, mesolite and scolecite. American Mineralogist 68:1134-1145.

Kerr, J.H., Pecora, W.T., Stewart, D.B., and Dixon, H.R., 1957, Preliminary geologic map of the Shambo quadrangle, Bearpaw Mountains, Montana: U.S. Geological Survey Miscellaneous Investigations Map I-236

Kendrick, G.D., 1980, Magma immiscibility in the Square Butte laccolith of central Montana: M.S. Thesis, University of Montana, Missoula, 90 p.

Knechtel, M.M., 1942, Snake Butte boulder train and related glacial phenomena, north-central Montana. Geological Society of America Bulletin 53:917-936

Kuhn, P.W., 1983, Magma immiscibility in the Box Elder laccolith of north-central Montana: M.S. Thesis, University of Montana, 86 p.

Kushiro, I, 1980 Viscosity, Density, And Structure of Silicate Melts at High Pressures, And their Petrological Applications: In Physics of Magmatic Processes, Hargraves, R.B. (ed.) Princeton University Press.

Lindgren W., w/Analyses by Melville, W.H., 1893, A sodalite-syenite and other Rocks from Montana. American Journal of Science 145:3:286-297

Liptak, A.R., 1984, Geology and differentiation of Round Butte laccolith, central Montana: M.S. Thesis, University of Montana, 49 p.

Lofgren, G., 1980, Experimental studies on the dynamic crystallization of silicate melts": In Physics of Magmatic Processes, Hargraves, R.B. (ed.) Princeton University Press.

Mysen, B.O., Virgo, D. and Kushiro, I. 1981 The Structural Role of Aluminum in Silicate Melts- a Raman spectroscopic study at 1 Atmosphere. American Mineralogist 66:678-701

Nash, W.P., and Wilkinson, J.F.G., 1970, Shonkin Sag laccolith, Montana- (Part 1), Mafic minerals and estimates of temperature, pressure, oxygen fugacity, and silica activity: Contributions to Mineralogy and Petrology, 25: 241-269

Pecora, W.T., Witkind, I.J., and Stewart, D.B., 1957, Preliminary geologic map of the Laredo quadrangle, Bearpaw Mountains, Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-234

_____Kerr, J.H., Brace, W.F., Stewart, D.B., Engstrom, D.B., and Dixon, H.R., 1957, Preliminary geologic map of the Warrick quadrangle, Bearpaw Mountains, Montana: U.S. Geological Survey Miscellaneous Geologic Investiagations Map I-237

Penn State University, (1981) Minitab Release 81.1, Computer program for statistical computing.

Philpotts, A.R. 1982 Compositions of Immiscible Liquids in Volcanic Rocks. Contributions to Mineralogy and Petrology 80:201-218

Reeves, F., 1924, Geology and possible oil and gas resources of the faulted area south of the Bearpaw Mountains, Montana. U.S. Geological Survey Bulletin 751-C

Roedder, E. 1979 Silicate Liquid Immiscibility in Magmas: In The Evolution of Igneous Rocks, Fiftieth Anniversary Perspectives, Yoder, H.S. (ed.) Princeton University Press

Ross, C.P., Andrews, D.A. and Witkind, I.J. 1955 Geologic Map of Montana Montana Bureau of Mines and Geology

Schmidt, R.G., Pecora, W.T., Bryant, B., and Ernst, W.G., 1961, Geology of the Lloyd quadrangle, Bearpaw Mountains, Blaine County, Montana: U.S. Geological Survey Bulletin 1081-E, p. 159-188

-----Pecora, W.T., and Hearn, B.C., Jr., 1964, Geology of the Cleveland quadrangle, Bearpaw Mountains, Blaine county, Montana: U.S. Geological Survey Bulletin 1141-P, p. 1-26

Spera, F.J., 1980, Aspects of Magma Transport: In Physics of Magmatic Processes. Hargraves, R.B. (ed.) Princeton University Press p.

Spry, A., 1962, The origin of columnar jointing, particularly in basalt flows. Journal Geological Society of Australia, 8:191-216.

Stewart, D.B., Pecora, W.T., Engstrom, D.B., and Dixon, H.R., 1957, Preliminary geologic map of the Centennial Mountain quadrangle, Bearpaw Mountains, Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-235

Walker, G.P.L., 1951, The amygdale minerals in the Tertiary lavas of Ireland. I. The distribution of chabazite habits and zeolites in the Garron plateau area, County Antrim. Mineralogical Magazine 29: 773

Watson, E.B., 1976, "Two-liquid Partition Coefficients: Experimental Data and Geochemical Implications": Contributions to Mineralogy and Petrology 56: 119-134

Weed, W.H., and Pirsson, L.V., 1896b, The Bearpaw Mountains, Montana: American Journal of Science, 1:283-301;2:136-148

Wise, W.S., and Tschernich, R.W., 1978, Habits, Crystal Forms and Composition of Thomsonite. Canadian Mineralogist 16: 487-493

Wood, M. and Hess, P.C., 1980, The Structural Role of Al2O3 and TiO2 in Immiscible Silicate Liquids in the System SiO_2-MgO-CaO-FeO-TiO_2-Al_2O_3. Contributions to Mineralogy and Petrology 72:319-328.

Yoder, H.S. and Sahama, Th.G., 1957, Olivine X-ray determinative curve. American Mineralogist, 42:475

Appendix I

Table 1

Snake Butte Laccolith Whole-Rock Densities and Rock Types.

Sample	Density	Rock Type	Comments	
1	2.89	M Sh, column rim,at benchmark		
1A	2.95	M Sh, column center		
2	2.98	M Sh		
3	2.93	M Sh		
4	2.55	Sy Peg		
5	2.65	Sy		
6A	2.80	UCZ	Top of remaining chill zone	
6B	2.82	UCZ	2 Meters below 6A	
6C	2.59	Sy	4 Meters below 6A	
7	2.57	Sy		
8	2.59	Sy		
9A	2.47	UCZ	At contact	
9D	2.70	UCZ	1.5 Meters below 9A	
10	2.89	M Sh		
12	2.20	PD		
14	2.66	M Sh	Poor density, inhomogeneous	
15A	2.60	LCZ	0.5 Meters above contact	
16	2.58	LCZ		
17	2.73	LCZ?	Near margin of laccolith	
18B	2.57	F Sh		
20	2.91	M Sh		
21	2.58	F Sh		
22	2.81	M Sh		
22A	2.24	PD		
24	2.82	M Sh		
25	2.79	M Sh		
26	2.91	M Sh		
28A	2.87	M Sh		
29D	2.56	LCZ	at contact	
29E	2.53	LCZ	1 Meter above contact	
30D	2.24	PD	Distance above Contact	
			Feet	Meters
32A	2.86	M Sh	77	23.5
32B	2.83	M Sh	59	18
32D	2.65	F Sh	35	10.7
32E	2.62	F Sh	29	8.8
32F	2.58	F Sh	23	7
32H	2.59	F Sh	14	4.3
32I	2.57	F Sh	9	2.7
32J	2.69	F Sh	2.5	0.8

32K	2.63	F Sh	1	0.3
32L	2.70	LCZ	0	0
36	2.93	M Sh		
38	2.57	F Sh	Meters Below Upper Contact	
39C	2.76	UCZ		0
39D	N/A	Up Sh,Friable		1
39G	2.68	Up Sh		4
39H	2.57	Marginal Sy Dike		5.6
40B	2.80	M Sh, light patch		
42	2.63	Sy/Sy Peg		
43	2.67	Sy		
44	2.75	Sy		
45	2.88	UCZ		
46	2.74	Sy		
47	2.78	UCZ		
48	2.66	Sy		
49	2.77	Sy		
50	2.69	Sy		
51	2.82	M Sh		
52	2.93	M Sh		
53	2.79	Sy		
54	2.89	M Sh		
55A	2.62	Sy Globule		
55B	2.96	M Sh adjacent to Sy Globule		
56	2.63	Sy Peg		
57	2.54	Sy Peg		
58	2.97	M Sh	Measured Section	
59	3.00	M Sh	Elevations, Feet	
60	2.64	Sy	3100	
61	2.91	M Sh	2940	
62	2.93	M Sh	2930	
63	3.04	M Sh	2960	
64	2.92	M Sh	2975	
65	2.89	M Sh	2995	
66	3.05	M Sh	3020	
67	2.95	M Sh	3045	
68	2.95	M Sh	3065	
69	2.99	M Sh	3080	
70	2.97	M Sh, Top of Hoodoo		
71	2.92	M Sh, Base of Hoodoo		
72	2.65	CZ, extreme western		
72A	2.67	CZ, extreme western		
73	2.65	LCZ		
74	2.67	LCZ		
75	2.91	UCZ		
76	2.85	UCZ		
77	2.62	Sy		
78	2.75	Sy		

79	2.64	Sy
80A	2.91	M Sh, column rim
80B	3.09	M Sh, column interior
	2.67	Quartz Crystal, Reference

Rock Type Abbreviations

LCZ	Lower Chill Zone
F Sh	Felsic Shonkinite
M Sh	Main Shonkinite
PD	Pegmatitic Dike
Sy Peg	Syenite Pegmatite
Sy	Syenite
Up Sh	Upper Shonkinite
UCZ	Upper Chill Zone

Table 2

Feeder Dike Whole-Rock Densities

Sample	Density	Meters from Western Chill Zone
19	2.58	1
19A	2.68	10
81	2.59	1
82	2.56	2.5
83	2.56	4
84	2.58	6
85	2.66	9
86	2.61	12
86A	2.67	15
87	2.70	16
88	2.85	27
89	2.82	38
90	2.92	49
91	2.90	58
92	2.86	69
93	2.92	78
94	2.66	214
95	2.81	217

Appendix II

Table 3

Snake Butte Chemical Analyses as Weight Per Cent Oxides

SPL	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	CaO	Na_2O	K_2O	P_2O_5	MnO	Den
6B	49.69	12.20	0.72	8.16	9.29	7.03	2.62	6.38	0.82	0.14	2.82
39C	49.60	11.90	0.73	8.23	8.25	7.28	1.94	6.39	0.81	0.13	2.76
39D	48.90	12.00	0.73	7.93	8.60	7.07	1.94	6.52	0.82	0.13	2.78
43	50.70	14.70	0.89	8.40	3.76	6.06	3.04	7.49	1.01	0.12	2.67
39H	50.40	15.00	1.02	8.36	3.94	5.02	3.48	7.31	0.84	0.12	2.57
4	50.20	14.80	1.25	9.70	3.03	5.23	3.89	6.80	0.75	0.15	2.55
69	48.90	8.47	0.61	9.44	13.10	9.81	1.37	4.74	0.66	0.15	2.99
55A	51.80	16.50	0.69	5.76	4.08	4.59	3.59	8.36	0.64	0.07	2.62
40B	49.00	10.00	0.52	8.49	11.70	8.59	2.54	5.25	0.59	0.13	2.80
32A	47.80	7.94	0.53	9.15	15.50	9.25	1.87	3.75	0.54	0.14	2.86
32B	49.10	8.67	0.58	9.25	14.30	9.93	1.39	4.53	0.60	0.14	2.83
14	47.60	7.91	0.52	9.23	15.60	9.07	1.89	3.78	0.53	0.14	2.66
32E	49.90	13.50	0.72	7.62	6.02	6.56	3.20	7.12	1.09	0.13	2.64
32I	50.70	14.60	0.82	7.88	4.58	6.05	3.77	6.90	0.91	0.13	2.57
32L	51.60	14.60	0.87	8.51	4.54	5.33	2.79	7.83	0.99	0.11	2.63
15A	49.30	14.20	0.83	7.71	4.14	6.97	2.29	8.07	0.94	0.12	2.60
30D	50.00	18.70	0.91	6.03	2.61	3.16	7.01	5.66	0.41	0.19	2.24
19	50.70	14.20	0.87	8.08	4.27	6.05	3.06	7.80	0.96	0.13	2.58
82	50.20	14.20	0.86	8.21	5.09	6.65	2.90	6.83	0.99	0.12	2.56
84	51.20	14.20	0.97	8.75	4.04	6.13	2.39	7.75	0.94	0.12	2.58
88	50.00	10.80	0.63	8.33	10.00	8.63	2.03	5.65	0.72	0.13	2.85
90	49.10	9.22	0.66	9.37	11.50	9.93	1.79	4.55	0.81	0.15	2.92
92	49.60	10.30	0.65	8.68	10.20	9.09	1.79	5.40	0.80	0.13	2.86
94	51.10	14.70	0.84	7.89	3.98	6.37	2.56	7.82	0.98	0.11	2.66

Table 4

Geochemistry: Atomic Proportions

SPL	Si	Al	Ti	Fe	Mg	Ca	Na	K	P	Mn
6B	0.826	0.239	0.0090	0.102	0.230	0.1253	0.0845	0.1354	0.0149	.00197
39C	0.825	0.233	0.0091	0.103	0.204	0.1298	0.0626	0.1356	0.0147	.00183
39D	0.813	0.235	0.0091	0.099	0.213	0.1260	0.0626	0.1384	0.0149	.00183
43	0.843	0.288	0.0111	0.105	0.093	0.1080	0.0980	0.1590	0.0183	.00169
39H	0.838	0.294	0.0127	0.104	0.097	0.0895	0.1122	0.1552	0.0152	.00169
4	0.835	0.290	0.0156	0.121	0.075	0.0932	0.1255	0.1443	0.0136	.00211
69	0.813	0.166	0.0076	0.118	0.324	0.1749	0.0442	0.1006	0.0120	.00211
55A	0.862	0.323	0.0086	0.072	0.101	0.0818	0.1158	0.1775	0.0116	.00098
40B	0.815	0.196	0.0065	0.106	0.290	0.1531	0.0819	0.1114	0.0107	.00183
32A	0.795	0.155	0.0066	0.114	0.384	0.1649	0.0603	0.0796	0.0098	.00197
32B	0.817	0.170	0.0072	0.115	0.354	0.1770	0.0448	0.0961	0.0109	.00197
14	0.792	0.155	0.0065	0.115	0.386	0.1617	0.0609	0.0802	0.0096	.00197
32E	0.830	0.264	0.0090	0.095	0.149	0.1169	0.1032	0.1511	0.0198	.00183
32I	0.843	0.286	0.0102	0.098	0.113	0.1078	0.1216	0.1465	0.0165	.00183
32L	0.858	0.286	0.0108	0.106	0.112	0.0950	0.0900	0.1662	0.0180	.00155
15A	0.820	0.278	0.0103	0.096	0.102	0.1242	0.0738	0.1713	0.0170	.00169
30D	0.832	0.366	0.0113	0.075	0.064	0.0563	0.2262	0.1201	0.0074	.00267
19	0.843	0.278	0.0108	0.101	0.105	0.1078	0.0987	0.1656	0.0174	.00183
82	0.835	0.278	0.0107	0.102	0.126	0.1185	0.0942	0.1451	0.0180	.00169
84	0.852	0.278	0.0121	0.109	0.100	0.1093	0.0771	0.1645	0.0170	.00169
88	0.832	0.211	0.0078	0.104	0.248	0.1538	0.0655	0.1199	0.0130	.00183
90	0.817	0.180	0.0082	0.117	0.285	0.1770	0.0577	0.0966	0.0147	.00211
92	0.825	0.202	0.0081	0.108	0.253	0.1620	0.0577	0.1146	0.0145	.00183
94	0.850	0.288	0.0105	0.098	0.098	0.1135	0.0826	0.1660	0.0178	.00155

Samples 6B through 15A approximate a vertical section through the represents a pegmatitic dike. Samples 19, 82-94 represent a section dike from west to east. For more information, see Appendix I.

Correlation Coefficients

Calculations for this table used the Minitab (1981) program to calculate correlation coefficients for all geochemical analyses.

	Si	Al	Ti	Fe	Mg	Ca	Na
Al	0.785						
Ti	0.606	0.755					
Fe	-0.470	-0.708	-0.100				
Mg	-0.824	-0.960	-0.840	0.548			
Ca	-0.715	-0.966	-0.751	0.670	0.900		
Na	0.427	0.808	0.550	-0.645	-0.666	-0.834	
K	0.842	0.810	0.656	-0.508	-0.891	-0.748	0.337
P	0.524	0.342	0.428	0.009	-0.540	-0.242	-0.124
Mn	-0.529	-0.206	-0.007	0.266	0.272	0.174	0.261
Den	-0.480	-0.847	-0.664	0.576	0.762	0.869	-0.860
Mg+Fe	-0.823	-0.975	-0.799	0.619	0.996	0.915	-0.693
Fe/Mg	0.653	0.826	0.952	-0.224	-0.881	-0.809	0.655
Na+K	0.743	0.986	0.727	-0.713	-0.932	-0.970	0.864
K/Na	-0.012	-0.338	-0.207	0.281	0.184	0.437	-0.766

	K	P	Mn	Den	Mg+Fe	Fe/Mg	Na+K
P	0.698						
Mn	-0.606	-0.448					
Den	-0.519	-0.094	-0.056				
Mg+Fe	-0.889	-0.506	0.283	0.776			
Fe/Mg	0.682	0.363	-0.044	-0.766	-0.851		
Na+K	0.765	0.289	-0.146	-0.866	-0.950	0.812	
K/Na	0.145	0.369	-0.372	0.559	0.202	-0.301	-0.446

Table 6

Correlation Coefficients: Pre-Intrusive

Calculation of correlation coefficients utilized the data from the following geochemical analyses: 6B, 39C, 39D, 69, 40B, 32A, 32B, 14, 32L, 15A, 19, 82, 84, 88, 90, 92, 94. The included syenitic rocks presumably underwent minimal differentiation after emplacement.

	Si	Al	Ti	Fe	Mg	Ca	Na
Al	0.838						
Ti	0.835	0.935					
Fe	-0.474	-0.798	-0.583				
Mg	-0.849	-0.986	-0.949	0.756			
Ca	-0.753	-0.941	-0.870	0.753	0.894		
Na	0.633	0.790	0.651	-0.653	-0.736	-0.827	
K	0.825	0.982	0.922	-0.796	-0.981	-0.918	0.718
P	0.833	0.934	0.946	-0.655	-0.956	-0.821	0.666
Mn	-0.730	-0.840	-0.706	0.705	0.807	0.814	-0.658
Den	-0.518	-0.767	-0.725	0.564	0.726	0.800	-0.742
Fe+Mg	-0.838	-0.988	-0.939	0.783	0.999	0.898	-0.742
Na+K	0.812	0.981	0.888	-0.800	-0.960	-0.949	0.871
K/Na	0.303	0.293	0.386	-0.220	-0.359	-0.147	-0.323
Fe/Mg	0.819	0.918	0.938	-0.570	-0.934	-0.850	0.700

	K	P	Mn	Den	Fe+Mg	Na+K	K/Na
P	0.909						
Mn	-0.808	-0.699					
Den	-0.716	-0.624	0.754				
Fe+Mg	-0.983	-0.950	0.812	0.726			
Na+K	0.967	0.884	-0.810	-0.776	-0.964		
K/Na	0.413	0.358	-0.194	0.036	-0.355	0.173	
Fe/Mg	0.914	0.873	-0.799	-0.808	-0.925	0.900	0.294

Table 7

Correlation Coefficients: Post-Intrusive

Calculations for correlation coefficients in this table used the following samples: 43, 39H, 4, 55A, 32E, 32I, 32L, 15A, 19, 30D, 82, 84, and 94.

	Si	Al	Ti	Fe	Mg	Ca	Na
Al	0.092						
Ti	-0.184	0.013					
Fe	-0.093	-0.678	0.688				
Mg	-0.016	-0.692	-0.580	0.062			
Ca	-0.211	-0.910	-0.204	0.474	0.658		
Na	-0.193	0.868	0.140	-0.505	-0.549	-0.848	
K	0.472	-0.468	-0.339	0.066	0.291	0.460	-0.796
P	0.007	-0.939	-0.198	0.562	0.741	0.897	-0.845
Mn	-0.593	0.379	0.453	0.067	-0.431	-0.372	0.704
Den	0.323	-0.787	-0.226	0.404	0.566	0.722	-0.899
Na+K	-0.013	0.941	0.011	-0.657	-0.597	-0.917	0.946
Fe+Mg	-0.061	-0.920	-0.128	0.564	0.859	0.788	-0.713
K/Na	0.177	-0.657	-0.221	0.300	0.356	0.729	-0.905
Fe/Mg	-0.148	0.214	0.930	0.522	-0.784	-0.324	0.274

	P	Mn	Den	Na+K	Fe+Mg	K/Na
K	0.462					
Mn	-0.871	-0.399				
DEN	0.787	0.803	-0.786			
Na+K	-0.558	-0.913	0.500	-0.812		
Fe+Mg	0.275	0.901	-0.322	0.675	-0.831	
K/Na	0.837	0.669	-0.630	0.719	-0.795	0.448
Fe/Mg	-0.343	-0.347	0.517	-0.312	0.192	-0.381	-0.259

Appendix III

X-ray Diffraction

X-ray diffraction supplemented details of mineralogical information available through petrographic work. The pegmatitic dikes provided pure crystals of natrolite, but x-ray identification of other minerals required the use of mineral concentrates. Diffraction studies concentrated on the identification of zeolites present within the groundmass of the rocks, determination of the Mg:Fe ratio of olivine, and confirmation of the type of feldspar present.

Sample preparation consisted of crushing and wet sieving whole-rock specimens to obtain the -80 +115 size fraction. Repeated passes through a Frantz magnetic separator utilizing various current strengths separated the mafic minerals from the felsic minerals. Portions of the felsic fraction were treated with hydrochloric acid to remove zeolite and feldspathoid minerals, facilitating evaluation of the felsic portion of the rock.

Numerous attempts to identify zeolites other than natrolite proved fruitless. If other species exist within these rocks their relative concentration was below detectable levels with the methods used. Other studies of similar laccoliths have revealed the presence of stilbite, chabazite, and analcime in minor quantities (Edmond, 1980). Some analcime probably exists within Snake Butte, especially within the lower chill zone. With the strong sodium enrichment trends, I doubt that a Ca-rich zeolite such as chabazite exists at Snake Butte, except possibly as a minor alteration product. It would not form as a primary mineral as natrolite apparently did.

Diffraction studies on olivine confirmed the petrographic estimate of a Mg:Fe ratio of 85:15 based on 2V measurements. The method of Yoder and Sahama (1957) given by Deer, Howie and Zussman (1962, p. 4) based on the position of the d130 peak provided this estimate on two samples.

Studies of the non-magnetic fraction consisted largely of confirming the presence of sanidine and attempting to identify albite, zeolites, analcime, nepheline, leucite and other minerals likely to crystallize in these rocks. Fine-grained acicular feldspars crystallized relatively late, after Na enrichment of the residual fluids, could concievably be albite. The lack of albite in feldspar concentrates coincides with experimental data that suggests albite and natrolite cannot coexist together in equilibrium (Johnson, et. al., 1983). This investigation provided inconclusive evidence for the presence of nepheline. Acid treatment caused the disappearance of peaks coinciding with some major nepheline d spacings (sample 32I). Interference from sanidine remaining in the specimen and natrolite in the original specimen inhibited a definitive determination of the presence of nepheline. Possibly another method of concentration, particularly one utilizing heavy liquids could overcome the difficulties encountered. However, the intimate association of minerals on a microscopic scale within pseudoleucite grains makes separation difficult. The presence of distinct pseudoleucite in the feeder dike supports the contention that nepheline occurs in the felsic shonkinite as part of the rounded grunge, and that it originally crystallized at depth as leucite.

Similar acid treatment of felsic concentrates from sample 84 revealed the presence of natrolite, high sanidine, and a peak at 3.43 angstroms which could correspond to the presence of either leucite or analcime. Again, an intimate mixture of minerals prevented definitive identification.