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MAGMA IMMISCIBILITY IN THE SQUARE BUTTE LACCOLITH
OF CENTRAL MONTANA

By

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Approved by

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ABSTRACT

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Magma Immiscibility in the Square Butte Laccolith of central Montana (90 pp)

Director: Dr. Donald W. Hyndman

Square Butte, an alkalic laccolith in the Highwood Mountains of Central Montana, has long been considered a classic example of differentiation in place through fractional crystallization. My recent field work, chemical analyses, and petrographic studies provide evidence for a differentiation mechanism involving magma immiscibility. Rock textures and field relationships inconsistent with a fractional crystallization model are found at Square Butte, including a zone of isolated felsic globules up to 10 meters in diameter suspended in a mafic-rich matrix rock. This globule zone has a horizontal base, suggestive of a gravitationally-controlled separation process. Globules contain the same minerals as their host, in different proportions. Fe/Mg ratios are nearly identical for globules and their matrix rocks, indicating equilibrium. Major-element partitioning is consistent with liquid immiscibility theory. Although no phase diagrams exist for an orthoclase-augite system such as that at Square Butte, the Square Butte magma probably had the most favorable characteristics for immiscible separation: high K_2O/total alkalis; moderate Ti and P; moderate oxygen fugacity; low pressure environment. Minor crystal settling may have occurred during differentiation but the primary mechanism of differentiation appears to have been a gravitational separation of immiscible felsic globules from a mafic-rich shonkinite host, resulting in an upper felsic unit and a lower mafic unit. An increase in host viscosity due to cooling trapped felsic globules rising from lower levels and produced isolated patches of light-colored rock surrounded by shonkinite. Partial re-equilibration between the smaller trapped globules and their matrix produced a mottled rock of intermediate composition.

ACKNOWLEDGMENTS

I would like to thank Don Hyndman and Dave Alt for their cautious insights and inspired arm-waving. A tip of the hat to Tom Margrave for his critical reading, and to Steve Balogh for his critical polishing. Lorraine Edmond provided hours of illuminating discussions and mutual despair. Special thanks go to my wife Cay, whose support and rock-carrying abilities carried me through. This study was partially funded by a grant from Sigma Xi, the Scientific Research Society.

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LOCATION

Originality was not one of the strengths of the early Montana explorers, since no less than three "Square" Buttes lie within 160 kilometers of Great Falls. The Square Butte of this study rises from the high plains about 16 kilometers east of the Highwood Mountains in central Montana. Figure 1 shows the location of the ranges which make up the central Montana Alkalic Province as described by Larsen (1940), and Figure 2 provides a more detailed map of the location of Square Butte.

Visible from over fifty miles away, the imposing figure of Square Butte rises 520 meters above the surrounding flatlands to an elevation of 1740 meters. It towers over the nearby towns of Geraldine and Square Butte, and dominates the skyline as viewed from highway 80. The summit of Square Butte is nearly two kilometers across and almost as flat as the surrounding plains. This flat top and the encircling vertical cliffs inspired the name "Square" Butte. Round Butte, originally named Palisade Butte, lies six kilometers to the west.

Although the main body of Square Butte falls under the jurisdiction of the Bureau of Land Management, all of the surrounding lands are privately owned. This situation prompted the B.L.M. to drop Square Butte from a wilderness classification. Anyone wishing to visit the Butte should first contact the local landowners.

FIGURE 1. Location map of the central Montana alkalic province.

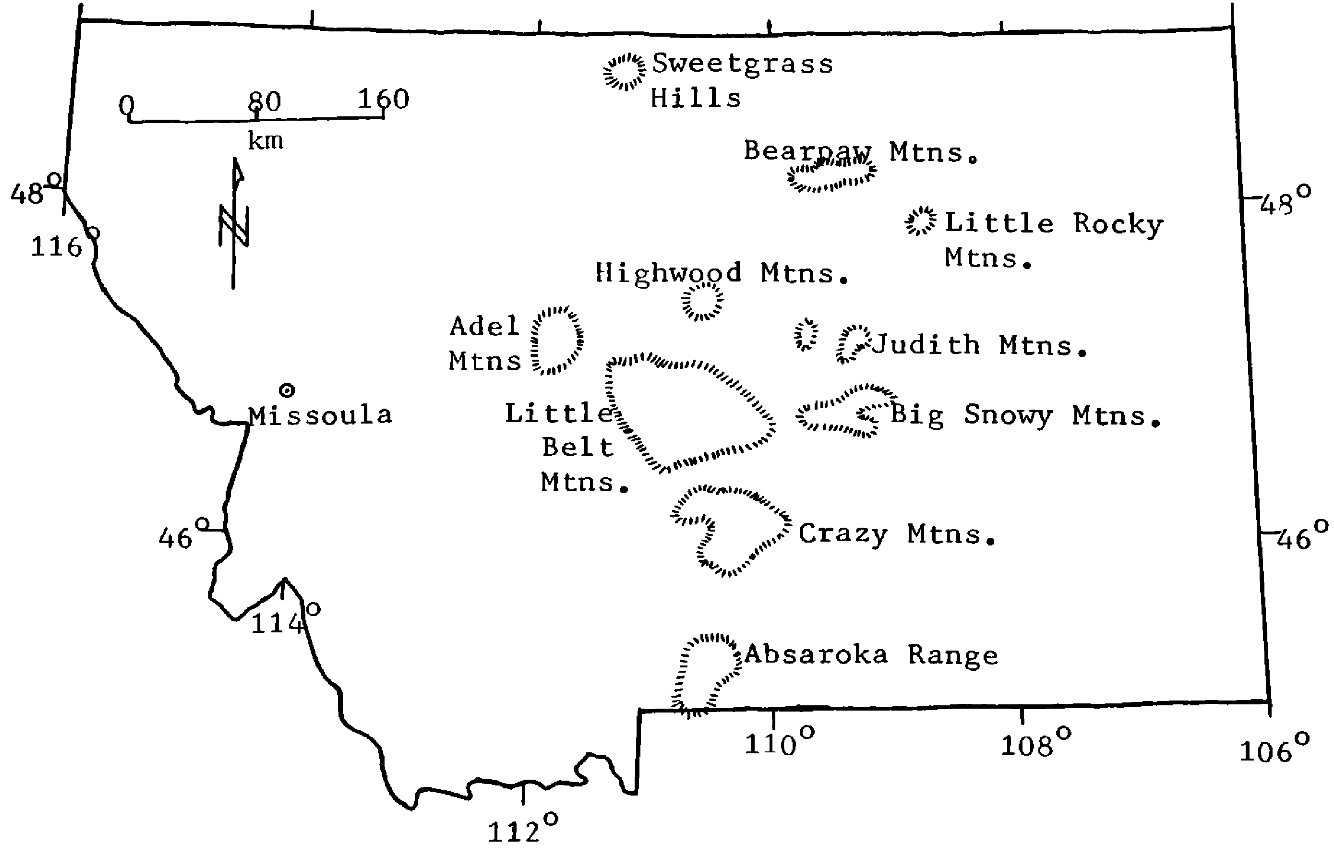
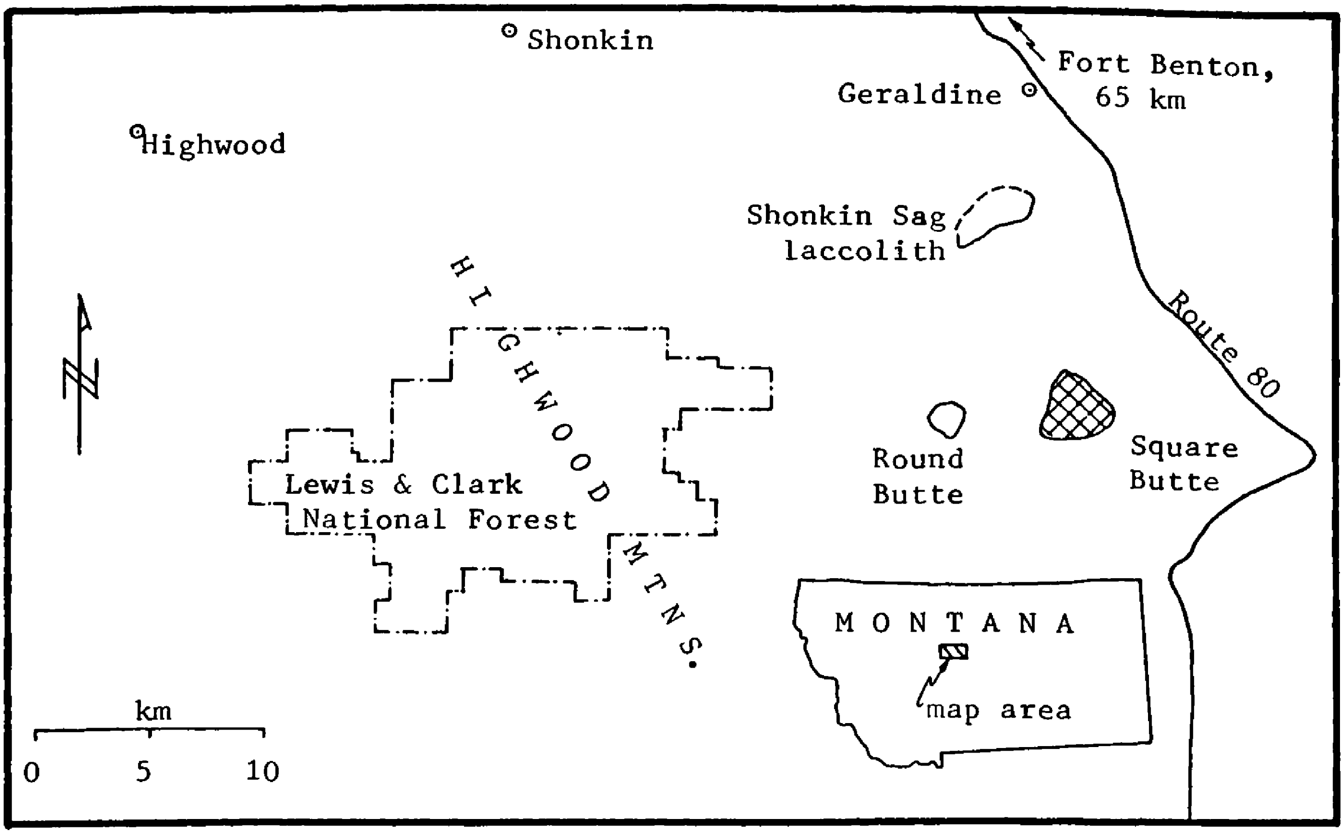


FIGURE 2. Location map of the Highwood Mountains.



REGIONAL GEOLOGY

The Highwood Mountains are part of the Petrographic Province of central Montana described by Pirsson (1905) and Larsen (1940). Consisting of a widely distributed group of early Tertiary igneous centers (Hearn and others, 1977), this province encompasses twelve mountain ranges or subprovinces (see Figure 1), including the Sweetgrass Hills, Bearpaw Mountains, Little Rocky Mountains, Highwood Mountains, Adel Mountains, Moccasin Mountains, Judith Mountains, Little Belt Mountains, Big Snowy Mountains, Castle Mountains, Crazy Mountains, and the Absaroka Range.

Igneous rocks in the central Montana Petrographic Province range from mafic syenite and phonolite to granite and rhyolite, with both silica-undersaturated and -oversaturated rocks of the same age commonly exposed within the same mountain range. The Judith and Highwood ranges have perhaps the widest range of coeval rock types. Granite, quartz monzonite, and rhyolite stocks in the Judith Mountains coexist with syenite plugs, alkali syenite stocks, and tinguaite (augite syenite) dikes and sills. The Highwood Mountains consist of quartz latite flows and tuffs overlain and cut by mafic phonolite and syenite flows, tuffs, dikes, plugs, and laccoliths (Larsen and others, 1941; Woods, 1974). This bimodal relationship is also found in most of the other subprovinces, as described below. Syenite is the most common alkaline rock in the province, ranging in composition from mafic syenite to nepheline syenite.

Shonkinite is also found in most of the ranges, and thus is a fairly common rock type within the province. It is also found in several outlying areas, such as the Franklin mining district of southeastern British Columbia, where it occurs as dikes, sills, and as globules in syenite dikes (Drysdale, 1915).

Another unusual feature of the central Montana Alkalic Province is the presence of identical clinopyroxenes over the entire province. Augite is ubiquitous and constant in composition from one range to the next. Some aegirine is found in several areas, such as the "transition" rock in the Shonkin Sag laccolith (Hurlbut and Griggs, 1939), but diopsidic augite is by far the most abundant pyroxene (c.f.: Nash and Wilkinson, 1970).

Most of the rocks in the subprovinces show a high K_2O/Na_2O ratio, but the Crazy Mountains have a low ratio. There is a general increase eastward in this ratio. All of the subprovinces contain both silica-oversaturated and -undersaturated rocks, as mentioned above. This results in a wide range in SiO_2 values within each subprovince. Any theory on the origin of these rocks must be able to explain this wide range of silica.

Accompanying its location in a stable, nonorogenic region, the central Montana province has a structure dominated by broad arching typical of the high plains. Reeves (1929) noted that the Cretaceous section seemed stacked northeast of the Highwood Mountains and ascribed this to thrust faulting. A gravity-gliding mechanism may have produced this stacked Cretaceous section. Slabs of Cretaceous rocks could have slid off rising domes, triggered by intrusion of the Eocene alkaline magmas. Local doming or subsidence generated by the Tertiary igneous activity has been noted in several of the ranges (for example Reeves, 1929; Pecora, 1940; Wallace, 1953), but is absent in others (for example, the Highwood Range).

The tectonic setting of the province has been the subject of debate for decades, ranging from simple back-arc-basin models to South African-style rift-zone models. Woods (1974) and Whiting (1977) provide summaries of the various models which have been proposed. The subduction models all share a common problem in that the alkalic province is located more than 300 kilometers east of the Eocene subduction zone. This would seem to eliminate the possibility that the alkalic magmas rose from a descending oceanic slab. The rift zone models do not explain why the subprovinces are not in a straight line but rather are scattered over a fairly large area. Clearly, more work on the tectonics of the region needs to be done before meaningful conclusions can be made.

Differentiation of primary magmas probably produced the varied rock types of the province, but which process dominated is debatable. Larsen (1940) postulated that a mantle-derived primary magma differentiated at depth through fractional crystallization to form separate parent magmas for the subprovinces, and additional differentiation and/or crustal assimilation produced the range of rock types within each subprovince. The same clinopyroxene is present in all of the subprovinces, which would support a fractional crystallization model, but the theory does have several problems. The coeval nature of silica-undersaturated and -oversaturated magmas is difficult to rationalize via fractional crystallization, since this process does not enable a magma to cross the "thermal divide" (c.f. Hyndman, 1972, p. 67). Whichever differentiation process operated had to be one which could produce both nepheline-bearing rocks and quartz-bearing rocks. Work by Powell and Bell (1970) has also shown that strontium isotope ratios in the igneous rocks of the alkalic province are low, suggesting that no appreciable old radiogenic crustal material was assimilated by the magmas.

One differentiation mechanism which could produce both silica-oversaturated and -undersaturated rocks from the same magma is liquid immiscibility. This process is not yet fully understood and thus has not been applied to large-scale petrogenesis. Nevertheless, one must consider immiscibility when considering the origin of the alkalic rocks of Montana and the surrounding area.

HISTORICAL SKETCH

Prompted by tantalizing reports of strange rocks in central Montana, geologists of the United States Geological Survey visited the Highwood Mountains in the late 1890's. Square Butte was the subject of several reports describing its striking layered appearance and an unusual rock type subsequently named shonkinite after the nearby Shonkin Sag, an abandoned course of the Missouri River. After ruling out assimilation and multiple intrusion as methods of producing the layering, the Survey geologists proposed several different mechanisms including: liquation (Weed and Pirsson, 1895); diffusion with convective overturn (Weed and Pirsson, 1901); fractional crystallization (Pirsson, 1905).

Although fractional crystallization was not fully accepted until Bowen's treatise on the subject (Bowen, 1928), liquation or liquid immiscibility, as it is now known, was considered a viable process at the turn of the century. Daly (1912) described the Square Butte and Shonkin Sag laccoliths as examples of originally homogeneous magmas which split into immiscible shonkinite and syenite magmas, but this idea was never mentioned in any later work on either laccolith. Bowen managed to destroy the credibility of liquid immiscibility as a viable process in silicate magmas.

The Highwood Mountains again received a flood of attention in the 1930's, dominated by a group of Harvard professors and graduate students. Differentiation in the Shonkin Sag laccolith became the main topic of debate (Osborn and Roberts, 1931; Barksdale, 1937; Hurlbut and Griggs, 1939) but eventually fractional crystallization was proclaimed by the Harvard group as the cause of differentiation at Shonkin Sag and all the other laccoliths.

More recent analytical work on rocks from the Shonkin Sag laccolith (Nash and Wilkinson, 1970) produced estimates of the pressure-temperature conditions of intrusion and compositional varitions in olivine, pyroxene, and biotite. The results appeared to support fractional crystallization as the primary mechanism of differentiation within the Shonkin Sag laccolith.

The increasing popularity of liquid immiscibility as a viable process in alkaline magmas (Roedder, 1979; Philpotts, 1976) encouraged further examintion of the Highwood laccoliths. A short reconnaissance of Square Butte revealed distinctive rock textures inconsistent with the model of crystal settling. A subsequent thorough examination of Square Butte during the spring, summer, and fall of 1979 has provided a wealth of intriguing field relationships.

FIELD RELATIONSHIPS

Square Butte offers excellent exposure of its several rock types. At least ten prominent knife-edged ridges or "combs" radiate from the laccolith, providing large expanses of bare rock with near-vertical cliff faces from 30 to over 150 meters high. Several of these combs are large enough to expose a nearly complete 500-meter-high cross section of the laccolith, passing from the lower shonkinite through the "mottled" rock zone to the base of the upper sodalite-barkevikite syenite (see Figure 3). These exposures permitted examination of the contact or transition zones between the different rock types. This chapter describes the field relationships discovered during my field work in 1979. Figure 4 shows the general surface geology of Square Butte and sample locations.

The laccolith shows a general layered aspect, with rock units grading from one to the next over several meters. The transitions between units are horizontal and thus appear to be gravitationally controlled. This horizontal nature can be seen from many kilometers away.

The field relationships also seem to suggest the coexistence of two magmas which did not mix. Large swirled streaks of light syenite and dark shonkinite reminiscent of marble cake cover broad areas on the cliff faces (Plates 1 and 2). The intertwined nature of these light and dark rocks suggests the presence of two magmas, rather than late injection of syenite magma into a partially solidified shonkinite, as Hurlbut suggested (Hurlbut and Griggs, 1939). Already solid shonkinite

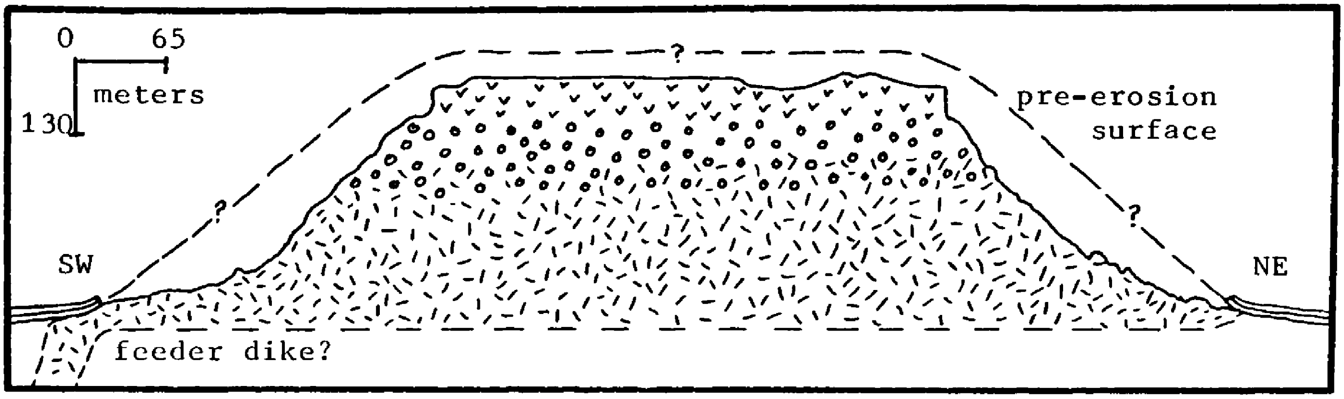


FIGURE 3. Geologic cross-section. Shonkininite = lower hachured pattern; mottled rock = circle pattern; sodalite-syenite = upper check pattern. Eagle sandstone upturned at margins of laccolith. Summit approximately 520 meters above surrounding high plains.

FIGURE 4. Geologic map of Square Butte

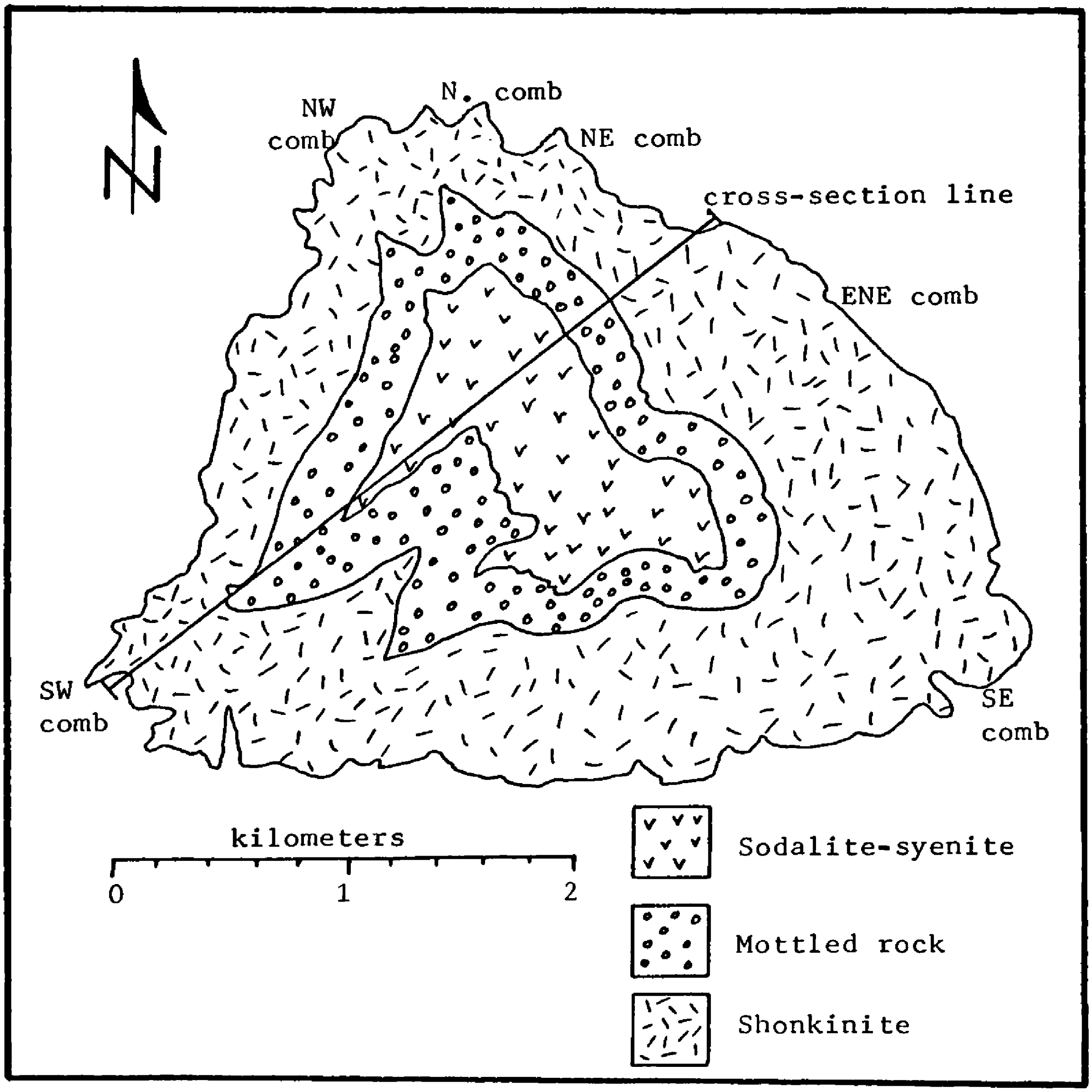


PLATE 1. Swirled streaks of shonkinite and mottled rock, southwest comb. Trees at lower left are 10 meters high.

PLATE 2. Swirled light and dark rock, southeast comb. Hammer handle is 40 cm long.

would not be sufficiently plastic so near the surface to give this form. These swirled areas are visible on most of the combs and are characteristically located between the 1480- and 1500-meter elevations.

The top of the butte is tilted to the southwest 3-4 degrees, resulting in a lower elevation at the southwest corner and a 3-4 degree tilt to the "layers" as well. All correlations between rock units and sample locations in this study area were made on a tilt-corrected basis. Although post-intrusion tectonics could be responsible for the tilting, I believe that it occurred immediately after intrusion and at least after partial solidification of the laccolith, since no major offsets are visible in the rock units.

The feeder dike for Square Butte could have been located at the southwest corner, in line with the main Highwood Mountains volcanic center. As magma from this feeder dike emptied into the laccolith, the pressure on the surrounding country rock could have decreased enough to allow subsidence on the southwest side. Detailed mapping and sampling in the area southwest of the main butte could reveal the location of this hypothesized feeder dike.

Chilled Margin

The contact of shonkinite with country rock crops out at the base of the eastern side of the butte and consists of Eagle sandstone which abruptly curves upward from a flat dip to a steep dip in contact with a fine-grained chilled-margin rock (Weed and Pirsson, 1895; Hurlbut and Griggs, 1939). This chilled rock contains augite laths up to 1 cm long in a fine-grained groundmass, with rare pseudoleucite crystals after leucite. The presence of euhedral augite crystals in this chilled rock indicates that crystallization of the magma had already begun when the magma intruded and puts a rough upper limit on the temperature of intrusion. According to Hurlbut and Griggs (1939), the mineral composition, chemical composition, and texture of the chilled-margin rock from Square Butte closely resembles that of the other alkalic laccoliths in the Highwood Mountains, as well as the chilled-margins of the hundreds of shonkinite dikes which cut across the countryside (Buie, 1941). This resemblance between the chilled rocks of so many separate igneous bodies strongly indicates that all of the magmas derived from the same source.

Lower Shonkinite

A 215-meter section of shonkinite extends from the bottom of Square Butte to the base of the "mottled" rock. Consisting of subequal amounts of augite and orthoclase, with olivine, biotite, magnetite, and apatite, this shonkinite shows a uniform mode and density over its entire thickness (Hurlbut and Griggs, 1939). Irregular patches of orthoclase 1 to 5 mm across surround clusters of mafic minerals. This gives the shonkinite a splotchy appearance, with no definite layering or other evidence of crystal accumulation (see Plate 10).

The shonkinite weathers to a somber gray-green color and forms the strange erosional monoliths or "hoodoos" described by Weed and Pirsson (1895). The rock is generally quite crumbly and provides a real challenge for the collection for fresh samples.

The shonkinite is slightly mottled at the base of the butte and this mottling increases upward to the zone of "mottled" rock. The elevation of this transformation depends on one's definition of "mottled". I chose the 1500-meter elevation as the changeover point primarily because above this elevation the volume percentage of augite is characteristically less than 40%. The mode of the shonkinite is quite constant below this elevation.

The shonkinite may actually have a greater thickness than is exposed at Square Butte. Several sills of shonkinite crop out in gullies east of the butte, at elevations 100 meters lower than the topographical base of the butte. This suggests that the shonkinite layer within Square Butte may actually be over 300 meters thick.

"Mottled" Rock Zone

Between the 1490- and 1500-meter elevations the lower shonkinite grades into a "mottled" rock. Interstitial patches of feldspar become larger upward from the lower shonkinite, to where they are subround patches 1 to 2 cm in diameter separated by clumps of mafic minerals, giving the rock a mottled texture. These small patches do not have sharp boundaries with their matrix but rather grade from one into the other over 5 to 10 mm. Plate 12 shows the texture of this mottled rock.

White-Patch Zone

Perhaps the most impressive features visible on the broad cliff faces are the large, white globular patches totally surrounded by darker shonkinite (Plates 3, 4, and 5). These patches range from 10 cm to over 10 meters in diameter and have elliptical or subround shapes. They contain orthoclase, augite, magnetite, apatite, barkevikite, sodalite, and some nepheline. The surrounding rock is composed of the same minerals in different proportions, a situation similar to but on a larger scale than the mottled rock described above.

The large white patches are found on all sides of the laccolith but only above the 1460-meter elevation with an apparently horizontal base to the zone (see Plate 6). They become more concentrated toward the top of the laccolith and may pass into the upper sodalite syenite, though the contact is not exposed. Several white patches in this zone have the same mineral composition and texture as the sodalite syenite, yet are at least 150 meters below the base of the syenite. These patches could not have broken off from the syenite and sunk through the mottled rock since they have a much lower density. It seems more likely that they were caught in the act of rising toward the sodalite syenite. Viewed from several meters away, these patches resemble bubbles frozen in ice, trapped by solidification of the host liquid. The white patches could be immiscible felsic globules which were trapped by increasing viscosity of the mafic liquid during cooling.

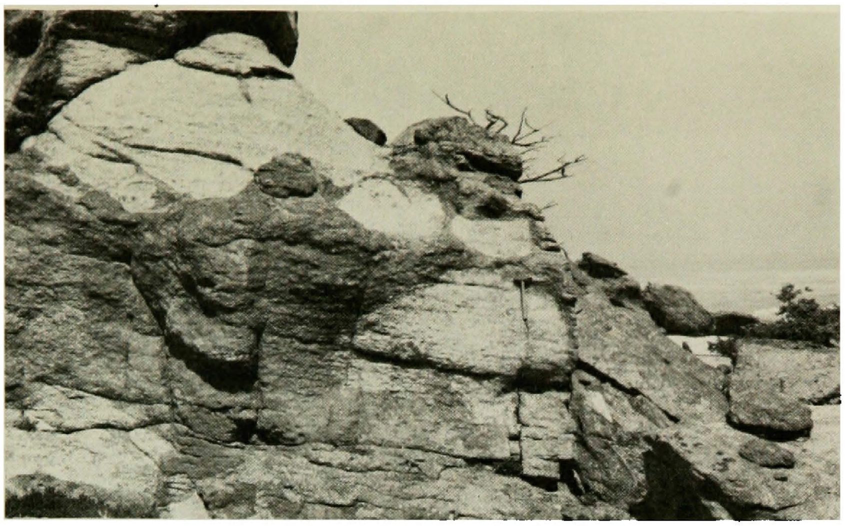
Sodalite Syenite

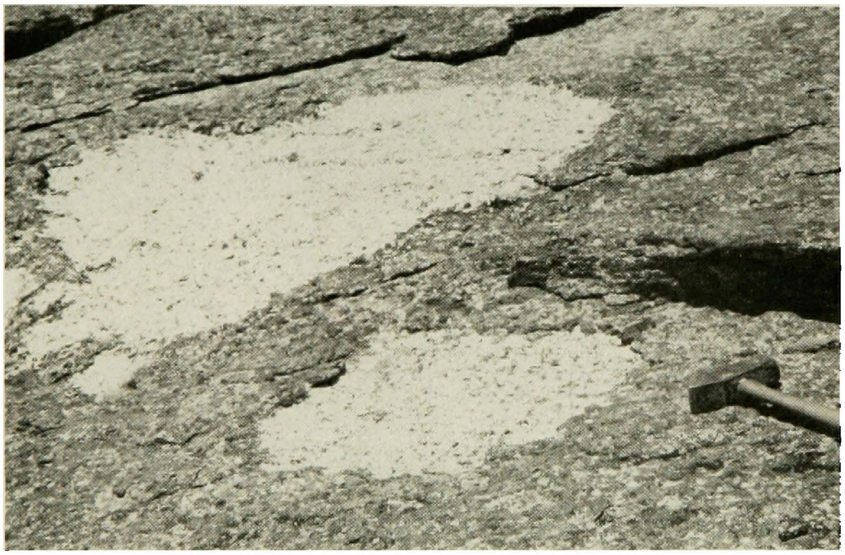
A horizontal joint set in the sodalite syenite is responsible for the butte's remarkably flat top and the 70-meter vertical cliffs

PLATE 3. White patch rocks suspended in shonkinite. Hammer handle is 40 cm long. 1490-meter elevation, northeast comb.

PLATE 4. White patch rocks surrounded by shonkinite. Hammer head is 12 cm long. 1460-meter elevation, southwest comb.

PLATE 5. White patch in shonkinite, showing surface-tension feature (?). Hammer handle is 40 cm long. 1495-meter elevation, east comb.





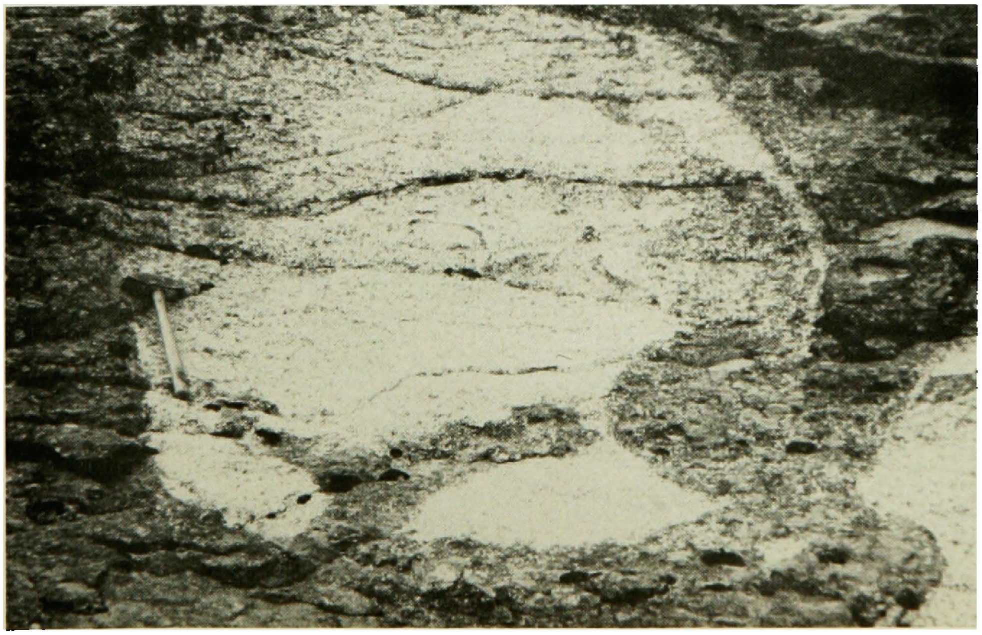
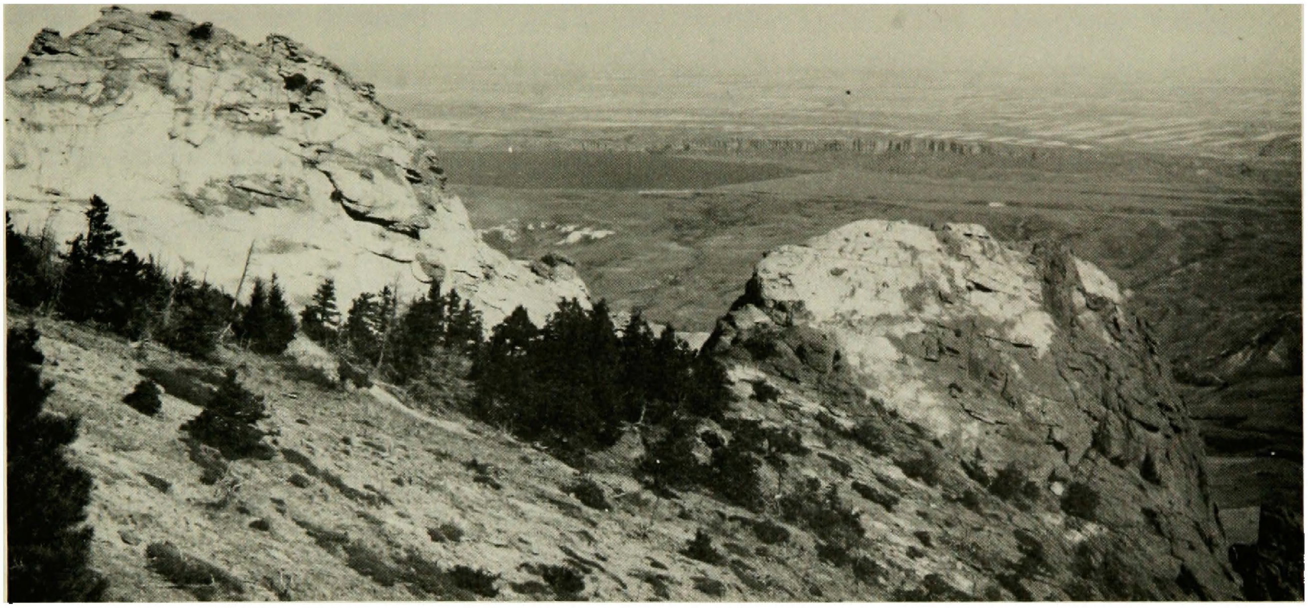
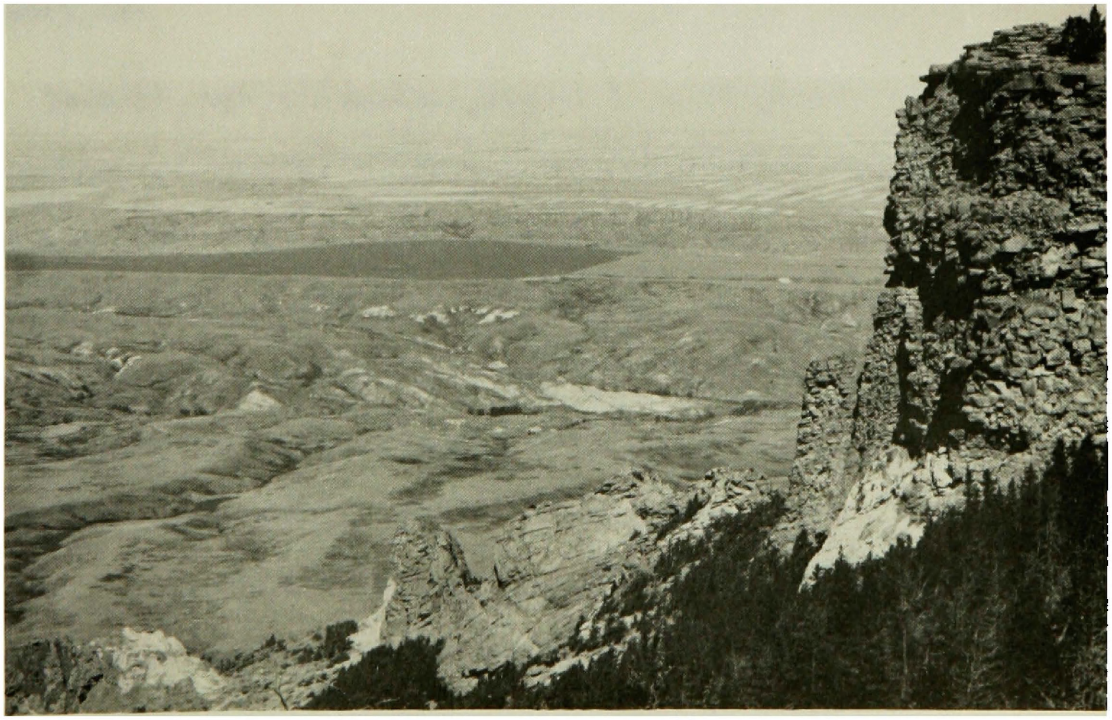


PLATE 6. Horizontal base to white-patch zone, northeast comb. Base is at 1490-meter elevation.

PLATE 7. Sodalite syenite cliffs at top of Square Butte. White-patch zone visible at lower left.





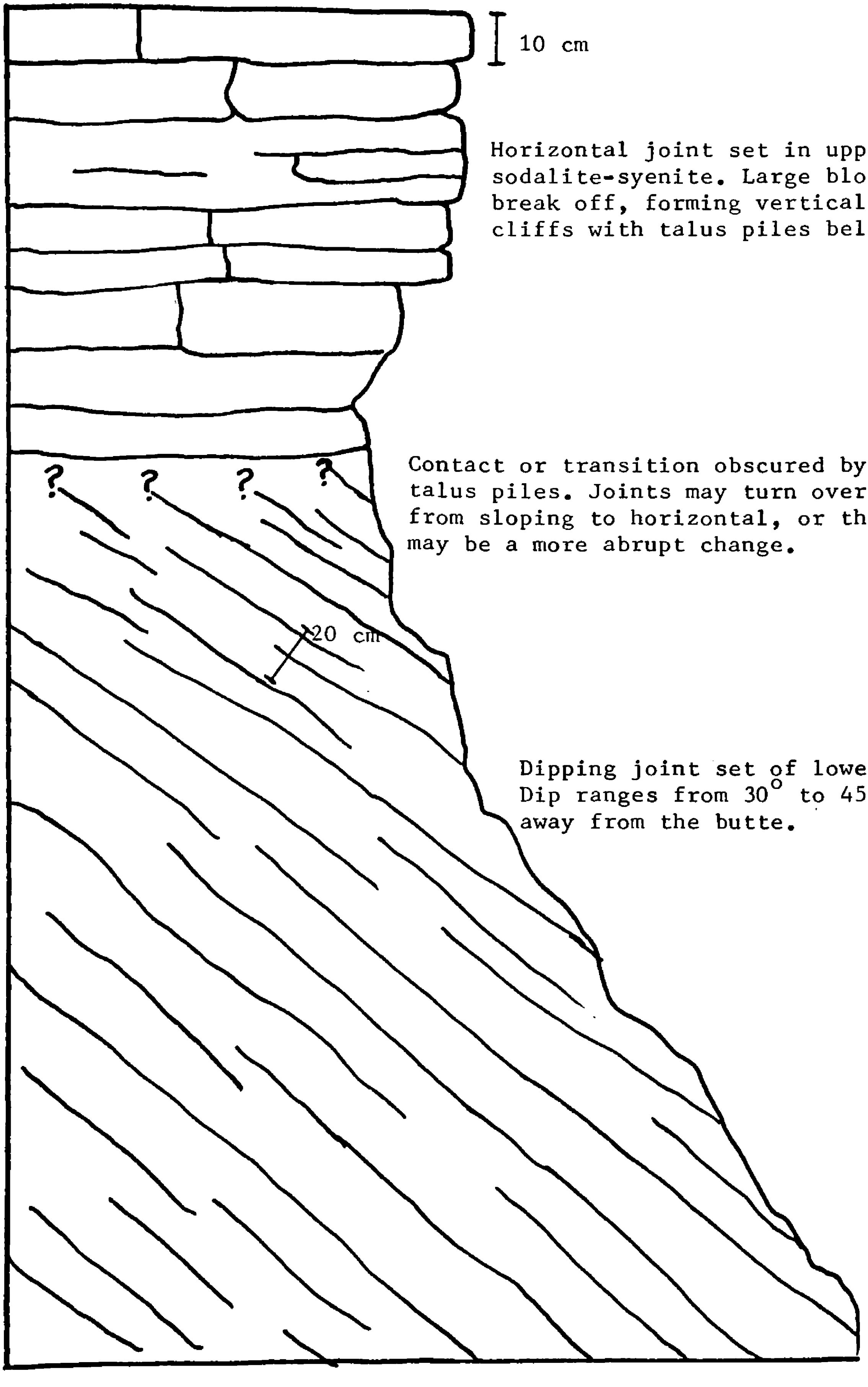
which encircle the summit. This joint set, visible in Plate 7, allows large rectangular blocks to detach from the main body and form talus piles at the base of the cliffs. These talus piles obscure the nature of the mottled rock-syenite contact or transition. Figure 5 compares this horizontal joint set with the sloping joint set of the lower units. The origin of the horizontal joint set, so different from the sloping joint set of the lower rock units, has not yet been adequately explained, nor have I found any reasonable explanations.

Since most of the upper syenite is either covered by talus or otherwise not exposed, I was able to see no farther into this unit than the previous authors. The reader is referred to Lindgren and Melville (1892) and Weed and Pirsson (1895) for more detailed descriptions of this unit.

Roof Xenoliths

Several dark elliptical masses 5 to 20 meters long and 3 meters thick surrounded by mottled rock are visible in the white-patch zone between the 1490- and 1525-meter elevations (Plates 8 and 9). Consisting of augite, olivine, orthoclase, magnetite, and apatite, these dark masses also have the same textures and chemical composition as the upper shonkinite of the Shonkin Sag laccolith. I believe these dark blobs are roof xenoliths, pieces of the dense shonkinite section of an upper chill zone, which broke off and sank through the differentiating magma. These roof xenoliths may have been trapped by solidification of the magma, the same process which may have trapped rising globules of

FIGURE 5. Sketch of joint patterns at Square Butte.



Horizontal joint set in upper sodalite-syenite. Large blocks break off, forming vertical cliffs with talus piles below.

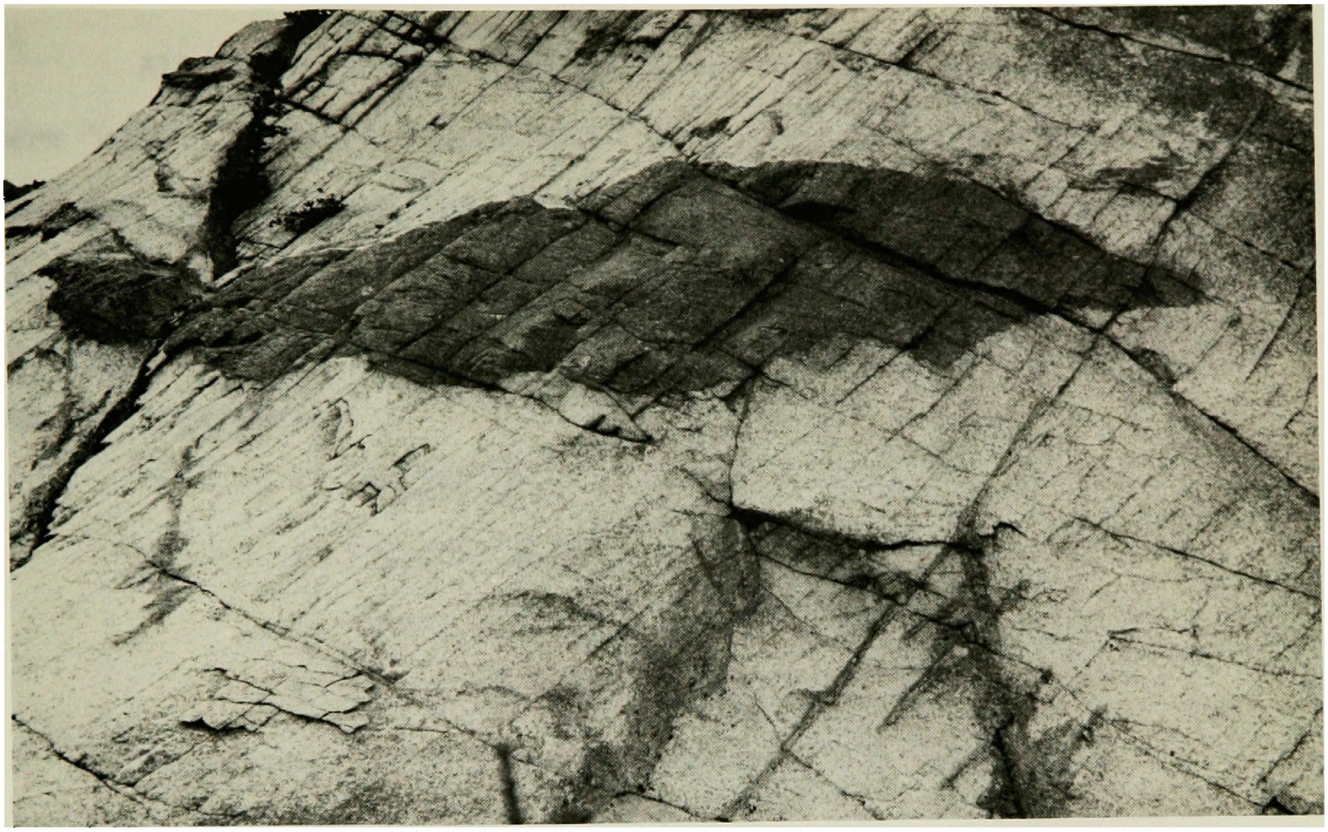
Contact or transition obscured by talus piles. Joints may turn over from sloping to horizontal, or there may be a more abrupt change.

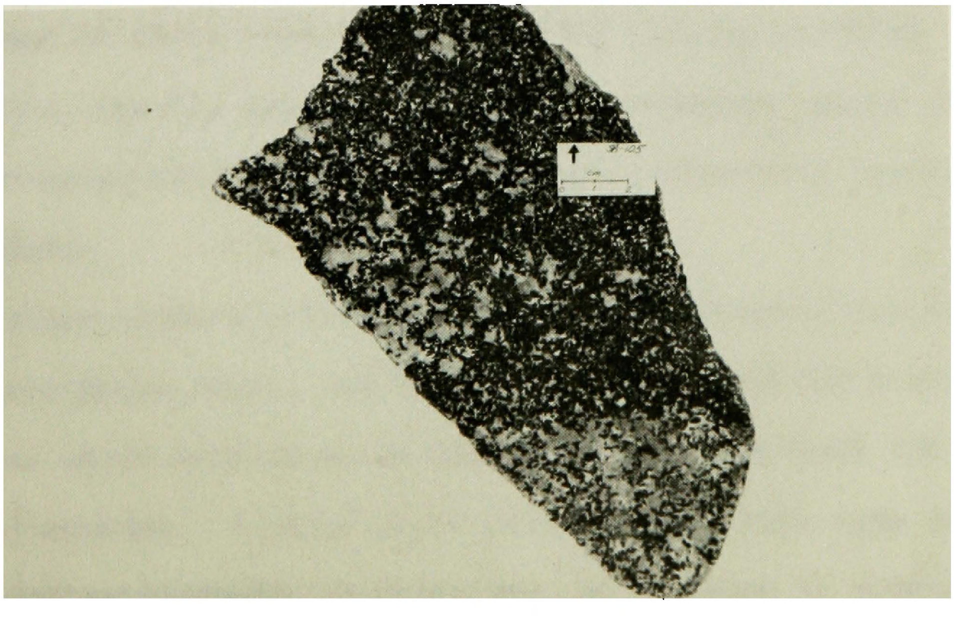
Dipping joint set of lower slopes. Dip ranges from 30° to 45° away from the butte.

syenite. If the xenoliths are remnants of an upper shonkinite, then Hurlbut's theory that erosion has removed all evidence of an upper shonkinite is correct (Hurlbut and Griggs, 1939).

PLATE 8. Shonkinite roof xenolith in mottled rock. North comb, 1500-meter elevation. Dark mass is approximately 20 meters long.

PLATE 9. Closeup of bottom contact of xenolith shown in Plate 8. Arrow indicates field orientation.

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PETROGRAPHY

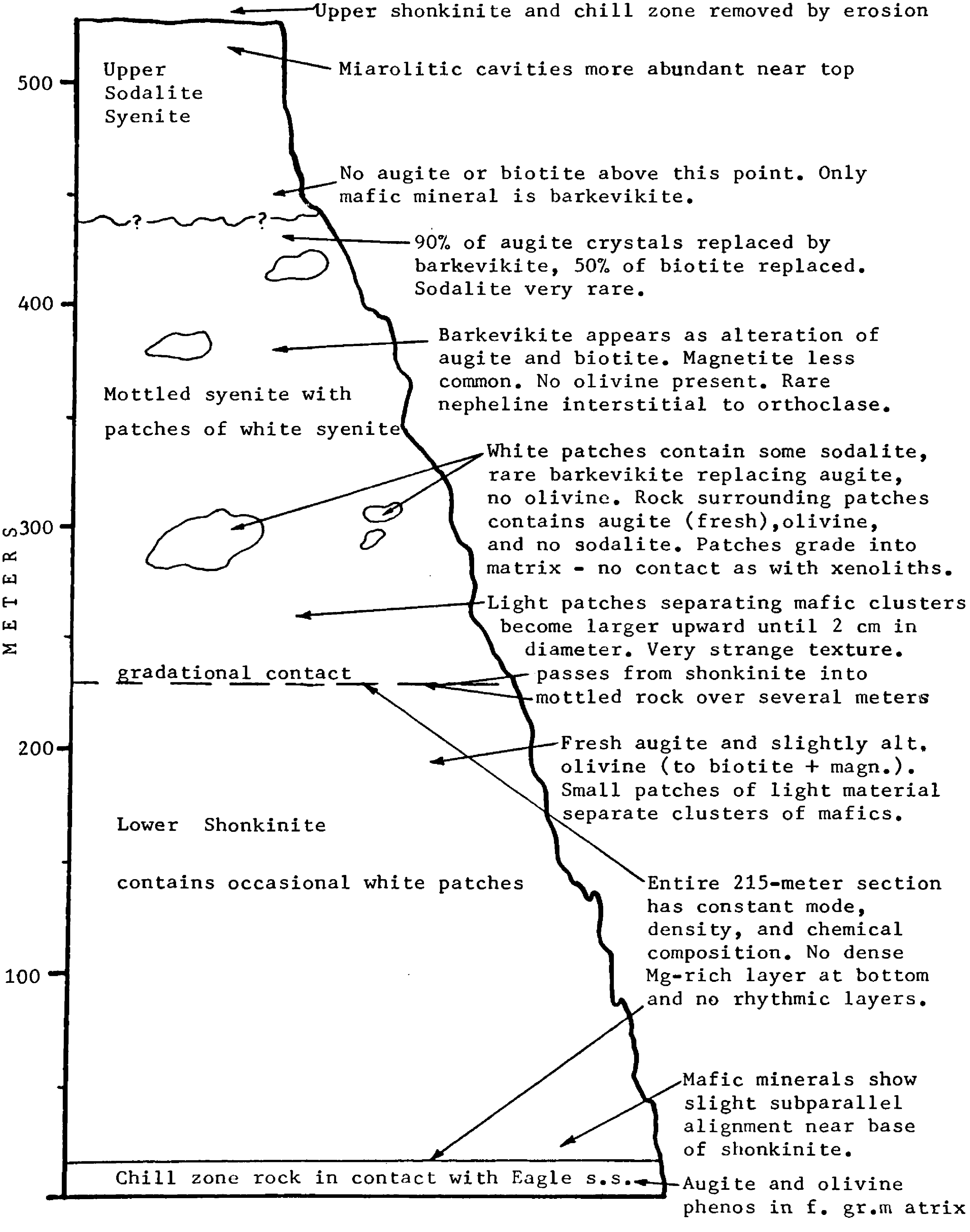
All of the rocks at Square Butte would fall under the general term "alkali syenite" if they were classified according to the I.U.G.S. system and would range from olivine-augite-rich-syenite to sodalite-barkevikite-syenite. This study has delineated four main rock types utilizing the names coined by previous authors to simplify comparisons between the studies:

1) Shonkinite
2) Mottled rock
3) White-patch rock
4) Sodalite-barkevikite-syenite

Shonkinite (an olivine-augite-rich-syenite) comprises the lower 200 meters of the laccolith and grades into the slightly less mafic "mottled" rock (augite-syenite) (see Figure 6). This mottled rock makes up the central 250 meters of Square Butte and encloses the large patches of white rock (augite-bearing syenite patches). The augite-bearing syenite patches increase in abundance upward and pass into the 80-meter-thick section of sodalite-barkevikite-syenite which caps the butte.

Earlier authors provided excellent petrographic descriptions of the Square Butte rocks, and to them I am indebted for providing the careful work which enabled me to more thoroughly evaluate the complex field relationships. A brief description of each rock type follows. More detailed petrographic descriptions can be found in Appendix 1.

FIGURE 6. Lithologic section from Square Butte laccolith.



Shonkinite

This unusual mafic syenite covers a 215-meter section extending from the bottom of Square Butte to the base of the "mottled" rock. Easily weathered, the shonkinite is a gray, coarse-grained rock composed of clusters of euhedral greenish-black augite laths up to 1 cm long, small greenish olivine crystals, and bronze biotite flakes 1-2 cm across poikilitically enclosing olivine and augite, with irregular 0.5-1 cm patches of pale yellow feldspar separating the clusters of mafic minerals (Plates 10 and 11). The average shonkinite mode is as follows:

Augite	50 %
Olivine	5 %
Biotite	5 %
Magnetite	4 %
Apatite	4 %
Orthoclase	30 %
Nepheline	tr
Sodalite	tr
Zeolites	tr-1 %

Crystallization sequence has been determined through study of thin-section mineral interrelationships and is as follows:

1. apatite and magnetite
2. olivine
3. augite and brown biotite
4. orthoclase and nepheline
5. sodalite, zeolites, and green biotite.

Olivine crystals are commonly cracked, with serpentine and iddingsite contained in the cracks, or are altered to green biotite where the olivine comes into contact with orthoclase. The augite laths display weak, normal zoning and rarely show oscillatory zoning. Both brown and green biotite are present as alteration products of augite, though the brown biotite also occurs as primary, euhedral crystals enclosing augite and olivine crystals. In general, the shonkinite is quite fresh, with little or no zeolitization evident. Surface exposures are quite crumbly, partially due to weathering but also due to the high percentage of smooth-sided, euhedral augite crystals. These allow the rock to crumble much the way concrete which contains too many smooth pebbles will disintegrate.

The juxtaposition of white patches of feldspar separating dark clusters of mafic minerals gives the shonkinite a slightly "mottled" appearance, though not as pronounced as that of the "mottled" rock described below. Weed and Pirsson (1895) also noted that the shonkinite appeared mottled, even in the lowest outcrops. The augite and olivine crystals within the mafic clusters locally have a subparallel orientation, but not as a rule. They appear to have clumped together in a more random fashion, perhaps through the "synneusis" process where early-formed minerals grow together in a magma, as described by Vance (1969).

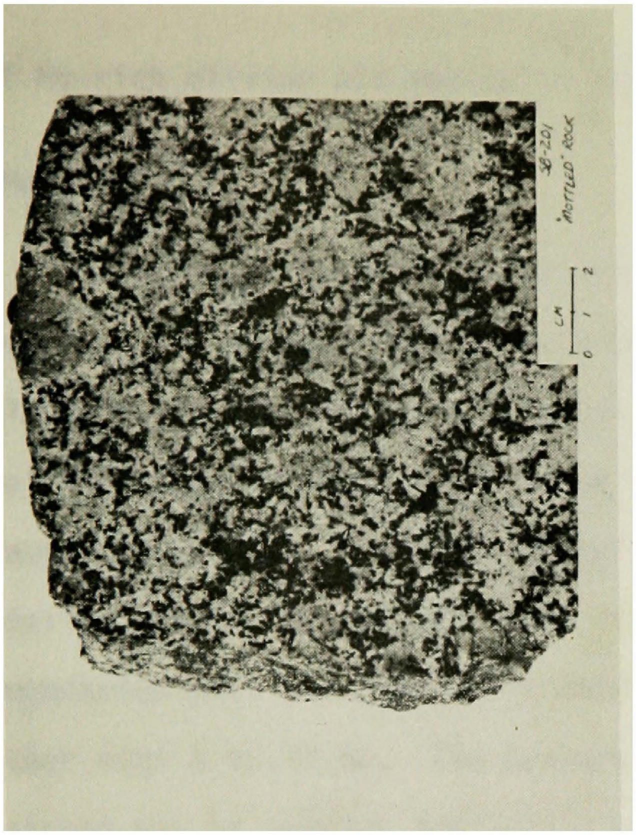
There does not appear to be any layering or concentration of mafic minerals in the lower section of the shonkinite. In fact, it has a totally uniform mode and density (3.05 gm/cc) over the entire 215-meter section (Hurlbut and Griggs, 1939). This uniformity seems inconsistent with a model of differentiation involving early-formed crystals settling out of a magma, which should produce a concentration

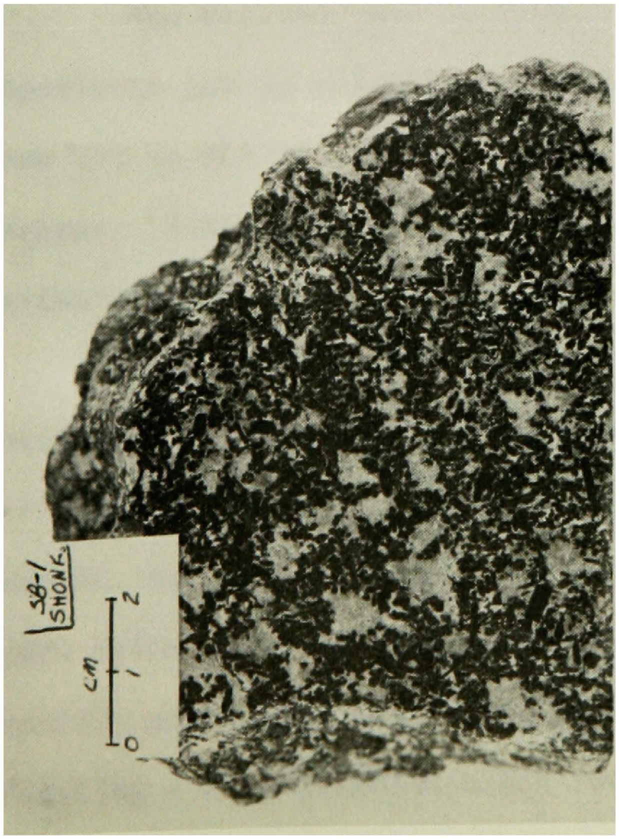
PLATE 10. Shonkinite slab, showing irregular felsic patches separating mafic clusters.

PLATE 11. Photomicrograph of shonkinite showing clustered mafic minerals. Augite crystals are dark, apatite crystals are small, transparent prisms. Interstitial material is orthoclase.Opaque crystals are titanomagnetite. Magnification 10 X, normal light.

PLATE 12. Mottled rock slab, showing subround felsic patches.

PLATE 13. Photomicrograph of mottled rock, showing mafic cluster touching felsic patch. Dark grey crystals are augite, opaque are titanomagnetite, white material is orthoclase and nepheline. Magnification 10 X, normal light.


SB-201
'MOTTLED' ROCK
CM
0 1 2


SB-1
SHONK.
CM
0 1 2

of Mg-rich olivine and augite in the lower rock units.

"Mottled" Rock

Although the shonkinite has also been described as slightly mottled, the mottled rock shows a more distinct contrast between clusters of light and dark minerals. Interstitial patches of feldspathic material become larger upward from the shonkinite, until they are subround patches 1 to 2 cm in diameter separated by a matrix of augite and biotite (Plates 12 and 13). The felsic patches do not have sharp boundaries with the more mafic matrix, but rather grade from one into the other over 5 to 10 mm. The texture of this rock suggests that the felsic patches may be remnant immiscible globules which partially re-equilibrated with their matrix.

The mottled rock contains the same overall minerals as the lower shonkinite but in slightly different proportions. Orthoclase ranges from 25% to 60% of the rock, with augite decreasing as orthoclase increases. Other minerals are biotite, magnetite, apatite, and rare barkevikite.

Thin-section study has shown that the small patches in the mottled rock contain the same minerals as their matrix, again in different proportions. Augite and biotite occur in the small felsic patches, but in such small crystals that they do not detract from the light color of the patches. The matrix contains augite and biotite crystals comparable in size to those in the shonkinite described above, producing a dark greenish-black rock enclosing evenly-spaced, pale yellow, globular patches.

Subround "fingerprint" intergrowths of alkali feldspar and augite are randomly scattered throughout the mottled augite syenite. Ranging in size from 0.5 to 2 cm in diameter, these intergrowths may represent a eutectic composition liquid which crystallized after the other minerals within the mottled rock.

The mineral composition of the mottled rock changes with increasing elevation, as shown in Figure 7. Olivine, common in the shonkinite and lower sections of the mottled rock, decreases upward due to replacement biotite and is totally absent from the mottled rock 190 meters below the top. Augite also decreases upward as it is replaced by biotite. Barkevikite appears as an alteration of augite and biotite 130 meters below the top of the butte, and 45 meters from the summit both augite and biotite are totally resorbed. Albite, nepheline, and sodalite increase in abundance toward the top of Square Butte, filling spaces between the alkali feldspar laths. This increase in feldspathic components and the decrease in mafic minerals toward the top of the laccolith is gradual, and so the mottled rock gradually passes into the sodalite-barkevikite-syenite.

White-Patch Rock

The white-patch rock is an augite-bearing syenite and contains the same minerals as the surrounding rock but in different proportions. Most of the patches contain orthoclase, augite, magnetite, apatite, rare barkevikite, rare sodalite, and some nepheline. Augite is partially

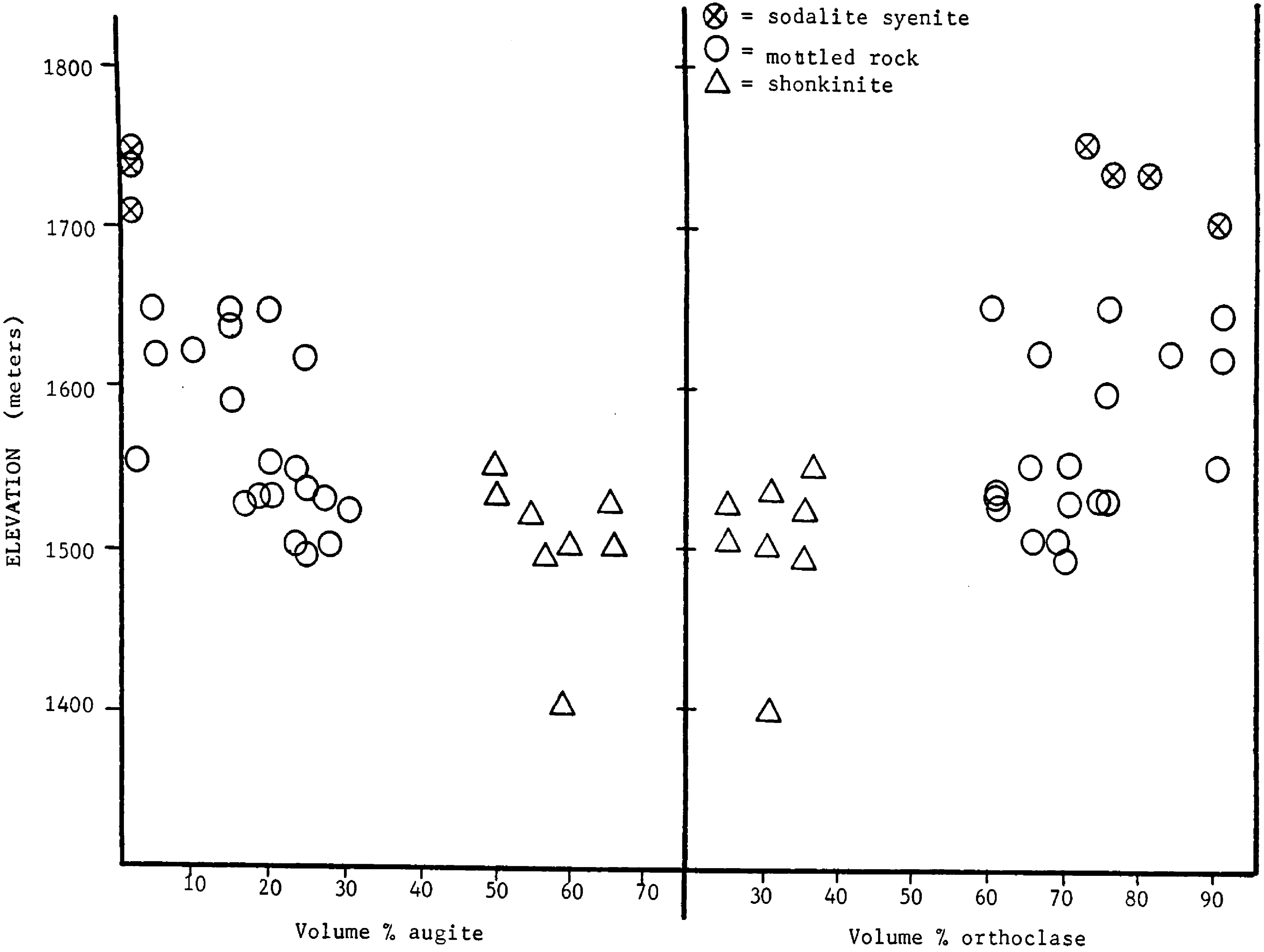


FIGURE 7. Mode versus elevation.

replaced by barkevikite in the white patches but is relatively fresh in the mottled rock, indicating that the augite may have been out of equilibrium in the patches but not in the mottled rock. Several patches contain only orthoclase, barkevikite, albite, and sodalite, a mineralogy identical to the upper syenite. Plates 14 and 15 show the macroscopic and microscopic textures of the white-patch rock.

Sodalite-Barkevikite-Syenite

First described by Lindgren and Melville (1892) as a sodalite-syenite, this rock comprises the top 70 meters of Square Butte. Several of the large white patches already described have the same mineral composition and chemical composition as the upper sodalite-barkevikite-syenite but are located more than 150 meters below its base. This relationship suggests that the upper syenite unit may have formed by the accumulation of syenite globules rising from lower levels in the laccolith.

In hand specimen (Plate 16) the rock is coarse-grained, white in color with a slight pinkish tinge, slightly miarolitic, and consists mainly of feldspar laths up to 1 cm long. Scattered throughout are slender laths of dark brown amphibole up to 2 cm long. These mafic crystals do not diminish the syenite's whiteness since they make up less than 25% of the rock.

In thin section the syenite appears very fresh, with unaltered orthoclase as the dominant mineral. Albite usually is interstitial to the orthoclase but is rarely found as tiny square crystals. Sodalite

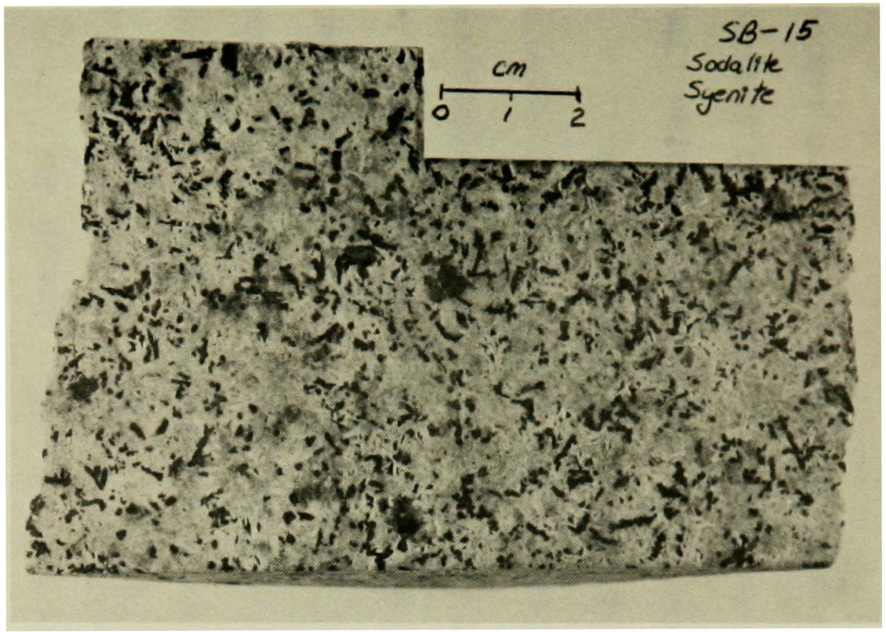
PLATE 14. White-patch rock slab. Large dark crystals are augite and biotite.

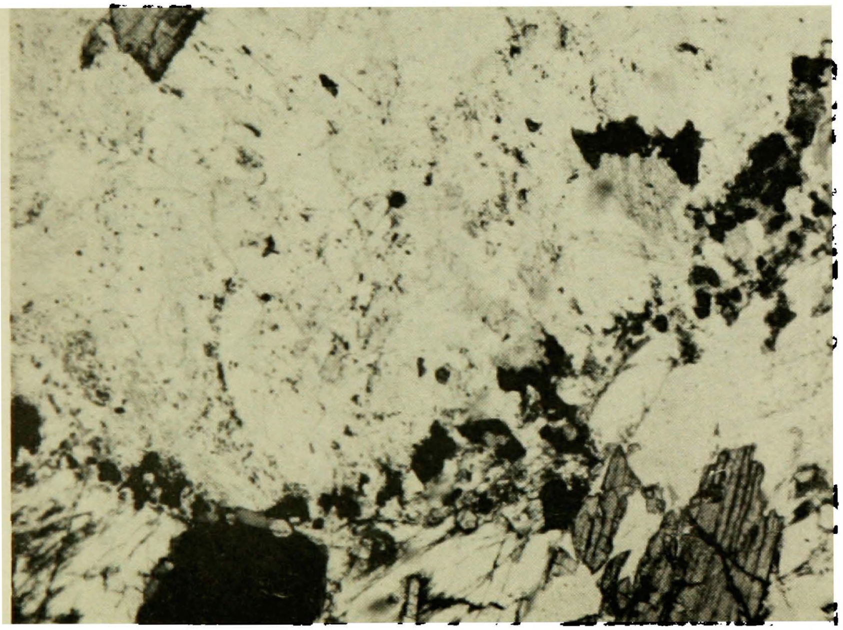
PLATE 15. Photomicrograph of white-patch rock. Subround white patch has opaque iron oxide at interface with more mafic material. Magnification 10 X, normal light.

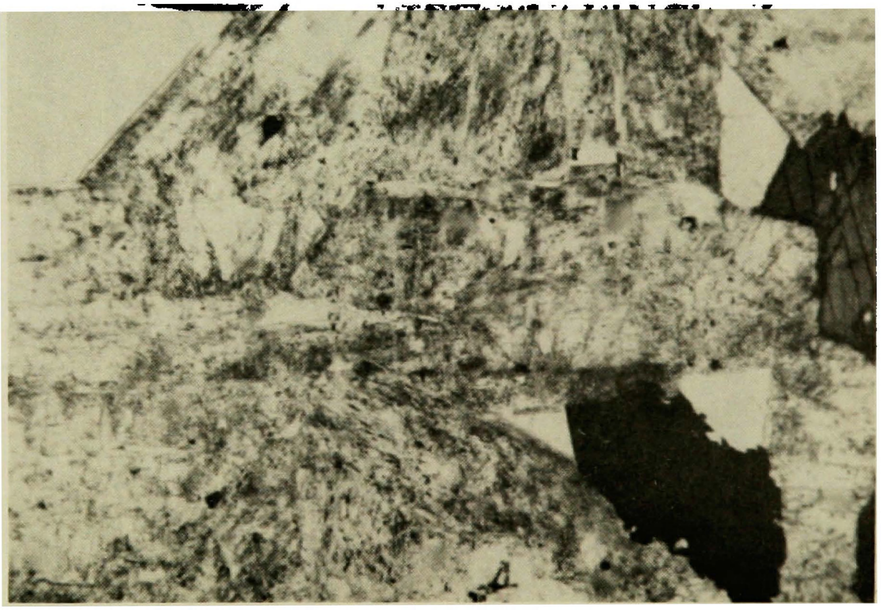
PLATE 16. Sodalite-syenite slab. Long, dark crystals are barkevikite, the only mafic mineral in this rock. Light-colored material is orthoclase with sodalite, albite, and rare analcite.

PLATE 17. Photomicrograph of sodalite-syenite. Sodalite is interstitial to orthoclase (grey crystals) and may be secondary after nepheline. Barkevikite crystal at right edge. Sodalite in upper left corner. Magnification 10 X, polars crossed.


cm
0
1
2
SB-102
White-Patch


SB-15
Sodalite
Syenite
cm
0
1
2





occurs only as isotropic interstitial material, and presumably is a product of pre-existing nepheline reacting with volatiles containing NaCl which concentrated in the upper regions of the laccolith.

Barkevikite forms long, thin crystals with a deep brown color, usually intergrown with the orthoclase laths. Narrow rims of a green amphibole (arvedsonite?) are rarely found on the barkevikite crystals. Pirsson (1905) reported some iron oxide inclusions in the amphibolte crystals, but I found none in my thin sections. No other mafic minerals occur in the sodalite-barkevikite-syenite. An obvious question at this point is, why did barkevikite form in this upper unit rather than biotite? There are several possible explanations.

The growth of biotite is facilitated by a relatively high ferric iron/ferrous iron ratio and a moderate amount of potassium (Deer and others, 1977). Formation of barkevikite, on the other hand, is enhanced by a low ferric iron/ferrous iron ratio and a moderate amount of calcium. If the magma at the top of the laccolith had a low ferric/ferrous ratio, then barkevikite might have formed rather than biotite. In order to achieve this low ratio, the water content of the syenite magma must also have been low. This premise is supported by the lack of zeolitization in the syenite, which is described below.

If most of the potassium in the syenite was tied up in orthoclase formation, then perhaps there was not enough to have formed biotite as well. A high concentration of sodium and calcium in the magma could also have inhibited the formation of biotite. Since there was probably not enough silica available to form plagioclase from the

Na and Ca, these components may have combined with available Al-Si structures to form an amphibole.

Minor amounts of natrolite replacing sodalite as well as some analcite after albite occur in the sodalite-barkevikite-syenite but generally less than 1%. Hurlbut (1939) noted that the sodalite syenite at Square Butte appears remarkably fresh, with considerably less zeolitization than the rocks of the Shonkin Sag laccolith. Recent work by Edmond (personal communication, 1980) confirms this observation. This lack of zeolitization would seem to indicate that the Square Butte magma, at least at the time of zeolite growth, contained a lower percentage of water than the Shonkin Sag magma.

Both magmas were probably mantle-derived and therefore relatively dry, but meteoric water from the Eagle sandstone or Madison limestone aquifers would have entered the magmas after intrusion. If the same volume of water were added to each magma, the huge volume of the Square Butte magma would have contained a much lower percentage of water than the smaller Shonkin Sag magma, producing a much higher percentage of zeolites in the Shonkin Sag rocks than those at Square Butte. Any excess water at Square Butte would presumably have concentrated in the upper section of the laccolith. The relative absence of zeolites in the upper syenite indicates that there was not a significant amount of water in the Square Butte laccolith.

The relatively high percentage of magnetite in the Square Butte rocks poses a problem for this hypothesis, however. The presence of iron-oxide minerals indicates that a moderate oxygen fugacity was present in significant amounts. Calc-alkaline magmas characteristically contain 2 to 4 weight percent water, and tholeiitic basalts range from 1 to 3 weight percent (Hyndman, 1972, pp. 74-75. The Square Butte magma may therefore have contained 1 or 2 percent water at the time of intrusion, enough to allow the formation of iron-oxide minerals. Formation of zeolites, however, would require a much higher percentage of water in the magma. This additional water would have had to be derived from the surrounding country rocks.

CHEMISTRY

The three previous studies of Square Butte (Lindgren and Melville, 1892; Weed and Pirsson, 1895; Hurlbut and Griggs, 1939) reported only four whole-rock chemical analyses, one from each of the main rock types. My work includes an additional twenty whole-rock analyses. The twenty rocks chosen for analysis included six white patch-matrix pairs, three each of syenite and shokinite, and two mottled rock samples. This chapter summarizes and evaluates the analyses.

The twenty rocks were crushed and ground to a fine powder and fused in carbon crucibles at 1000° C. The buttons were then polished and cleaned and analyzed by x-ray fluorescence methods. The data are presented in Table 1, with the calculated C.I.P.W. norms. Iron was reported as 44% Fe_2O_3 and 56% FeO.

I consider these rocks to be alkaline because of their silica depletion rather than an alkali enrichment. The agpaitic index (Na_2O+K_2O/Al_2O_3) of the Square Butte rocks ranges from 0.53 to 0.63, placing the rocks in the "miaskitic" category. The presence of the alkaline amphibole barkevikite and the absence of free quartz also suggest that these rocks fall under the general category of alkali syenites.

Evaluation of the whole-rock analyses indicates that the rocks at Square Butte are derived from a single injection of magma. The sum of the chemical compositions of the shonkinite, mottled rock, white

Table 1. Whole-rock chemical analyses.

	F	M	F	I	M	P	M	F	M	P	M			
	100P	101M	102	118F										
SAMPLE:	100P	101M	102	118P	119M	125P	125M	132P	132M	133P	133M	136P	137M	140P
SITE #:	1			10		19		23		24		29		
ELEV:	1536	1536	1536	1505	1505	1524	1524	1438	1438	1463	1463	1475	1475	1475
SiO_2	50.12	45.63	50.13	65.45	46.74	61.06	46.63	48.60	45.24	48.72	45.23	61.30	45.63	61.40
TiO_2	0.99	1.44	1.17	1.22	1.24	0.94	1.36	1.20	1.52	1.32	1.76	1.07	1.86	1.09
Al_2O_3	15.01	10.51	16.13	19.03	10.63	18.62	11.37	13.64	11.55	16.02	11.81	17.11	12.12	16.66
Fe_2O_3	4.38	6.63	4.64	3.22	6.07	4.18	4.20	6.31	6.78	8.07	7.13	4.17	6.79	4.18
FeO	5.02	7.59	5.37	1.69	6.96	4.78	7.10	6.08	7.77	6.81	8.16	4.77	7.77	4.83
MnO	0.14	0.19	0.11	0.11	0.19	0.10	0.19	0.14	0.17	0.14	0.17	0.12	0.18	0.12
MgO	4.91	7.54	3.60	1.72	7.47	3.57	8.75	9.73	8.37	4.45	8.45	3.30	8.62	3.28
CaO	8.76	11.98	7.43	4.11	11.84	7.21	11.38	9.22	11.30	8.48	10.88	6.38	11.14	6.59
Na_2O	2.33	2.04	2.93	4.28	2.38	2.68	1.65	2.54	2.10	2.90	1.55	3.04	2.07	3.09
K_2O	7.06	4.16	7.25	6.78	4.72	7.62	6.52	6.37	6.33	6.76	5.48	7.76	6.08	7.67
P_2O_5	1.35	1.86	1.10	0.41	1.78	1.00	1.76	1.49	1.92	1.33	1.81	0.85	1.86	0.83
TOTAL	99.99	100.00	99.99	99.99	100.00	99.97	100.01	100.02	100.00	99.99	100.00	100.00	100.01	100.00
							C.I.P.W. NORMS							
OR	41.72	25.76	42.84	39.69	27.89	46.21	32.63	37.64	31.50	39.89	33.96	45.80	29.96	45.32
AB	4.06	5.55	8.51	37.75	3.90	4.39	1.43	4.56	0.46	3.31	0.40	7.28	4.88	7.78
AN	9.65	6.64	9.39	12.78	4.47	10.22	6.28	7.56	6.35	8.03	6.70	10.16	8.81	9.48
NE	8.43	6.35	10.45	4.86	8.70	9.40	7.70	9.17	9.37	11.50	8.72	9.99	6.48	10.24
OL	14.31	24.20	11.37	2.67	25.90	10.66	22.88	16.51	21.28	14.51	19.54	8.46	19.39	9.50
HD	4.47	7.23	4.41	1.21	7.42	4.15	7.15	6.59	7.63	6.20	8.16	3.40	7.28	3.85
FO	3.74	6.30	2.94	2.17	4.54	2.77	4.35	3.76	4.12	3.05	3.16	3.01	3.33	2.60
FA	1.42	2.00	1.44	1.24	1.64	1.36	1.72	1.61	1.87	1.38	1.87	1.52	1.60	1.33
MT	6.35	9.61	6.73	4.67	8.80	6.06	8.99	7.70	9.83	7.38	10.31	6.05	9.35	6.08
IL	1.88	2.73	2.22	2.32	2.36	1.79	2.58	2.28	2.89	2.51	3.34	2.03	3.63	2.07
AP	3.20	4.48	2.61	0.97	4.24	2.37	4.17	3.53	4.65	3.16	4.20	2.28	6.41	2.70
	99.83	99.85	99.93	99.94	99.86	99.89	99.87	99.90	99.85	99.88	99.85	99.82	99.84	99.93
DIFF INDEX:	54.26	37.66	58.80	71.99	40.60	60.61	41.76	61.37	41.34	64.73	42.48	63.07	38.04	62.61

			103 RP	122 SS	123 SS	120 SD	
SAMPLE:	10SH	121SH	103RP	122SS	123SS	120SD	
SITE #:	30	22	2	16	17	72	
ELEV:	1402	1371	1561	1706	1731	1372	
SiO_2	49.50	48.90	49.01	58.92	55.49	58.14	SiO_2
TiO_2	0.97	0.87	1.12	0.37	1.23	0.47	TiO_2
Al_2O_3	9.65	9.47	12.10	20.30	19.30	19.28	Al_2O_3
Fe_2O_3	4.87	4.99	8.23	2.08	3.13	2.42	Fe_2O_3
FeO	5.58	5.71	5.99	2.39	3.58	2.78	FeO
MnO	0.17	0.19	0.17	0.13	0.12	0.08	MnO
MgO	8.79	8.78	6.34	0.56	1.55	1.15	MgO
CaO	12.99	13.54	10.70	2.03	3.66	2.83	CaO
Na_2O	2.28	2.48	2.20	5.56	4.65	4.33	Na_2O
K_2O	3.74	3.77	6.72	7.56	6.79	8.86	K_2O
P_2O_5	1.45	1.36	1.41	0.11	0.40	0.25	P_2O_5
TOTAL	99.99	99.99	99.99	100.01	100.00	99.99	
			C.I.P.W. NORMS				
OR	22.10	18.32	33.40	44.67	40.12	52.35	OR
AB	11.02	8.54	5.18	31.40	27.16	23.27	AB
AN	5.05	4.42	6.25	8.11	13.18	7.00	AN
NE	4.48	6.83	7.28	8.48	6.16	7.24	NE
OL	32.53	35.11	22.89	0.40	2.22	1.08	OL
HD	6.40	3.01	6.50	0.58	1.10	0.80	HD
FO	4.77	4.27	3.63	0.85	1.98	1.66	FO
FA	1.19	1.06	1.10	1.54	1.23	1.59	FA
MT	7.06	7.22	7.58	3.02	4.64	3.51	MT
IL	1.84	1.84	2.13	0.70	2.34	0.89	IL
AP	3.43	3.22	3.36	0.26	0.95	0.59	AP
TOTAL	99.87	99.88	99.88	100.00	99.97	99.97	
DIFF INDEX:	37.60	35.71	46.26	84.66	73.43	82.86	

Note: Abbreviations after sample numbers: SH = shonkinite; P = patch; M = matrix; SS = sodalite syenite; SD = syenite dike; RP = roof pendant. DIFF INDEX = Thornton & Tuttle differentiation index.

patches, and sodalite syenite equals the composition of the Square Butte chill zone rock. The varied rock types at Square Butte are presumed to have derived from differentiation of a single homogeneous magma, since a chill zone's composition is considered to be the same as the composition of its parent magma.

Mg, Ca, and Fe generally decrease and Na, K, and Al increase upward from the lower shonkinite through to the upper sodalite syenite, as shown in Figure 8. This trend would most easily be explained by the removal of the mafic constituents from the upper syenite via settling out of mafic minerals, i.e., through crystal settling. However, the same chemical trend could be achieved through the accumulation of immiscible felsic globules at the top of the laccolith.

Recent experimental work has determined that certain elements will partition into specific fractions depending onthe differentiation process. Watson (1976) found that phosphorous and the rare-earth elements tend to partition into the felsic fraction in crystal settling but into mafic fractions in immiscible systems. Ryerson and Hess (1978) confirmed Watson's work and also found that Ti, Fe, Mn, Zr, Cr, and U concentrate in the mafic melt in liquid immiscibility. Other workers have shown that the Fe/Mg ratios of immiscible liquids are generally the same. Figure 9 shows a plot of the Fe/Mg ratios of the Square Butte rocks. My recent analyses of Square Butte rocks do not include trace-element and rare-earth analyses, and thus, on this basis, cannot prove or disprove the crystal settling model.

Evaluation of trace-element data from similar rocks from the

FIGURE 8. Oxides vs, elevation. Data from 1980 analyses.

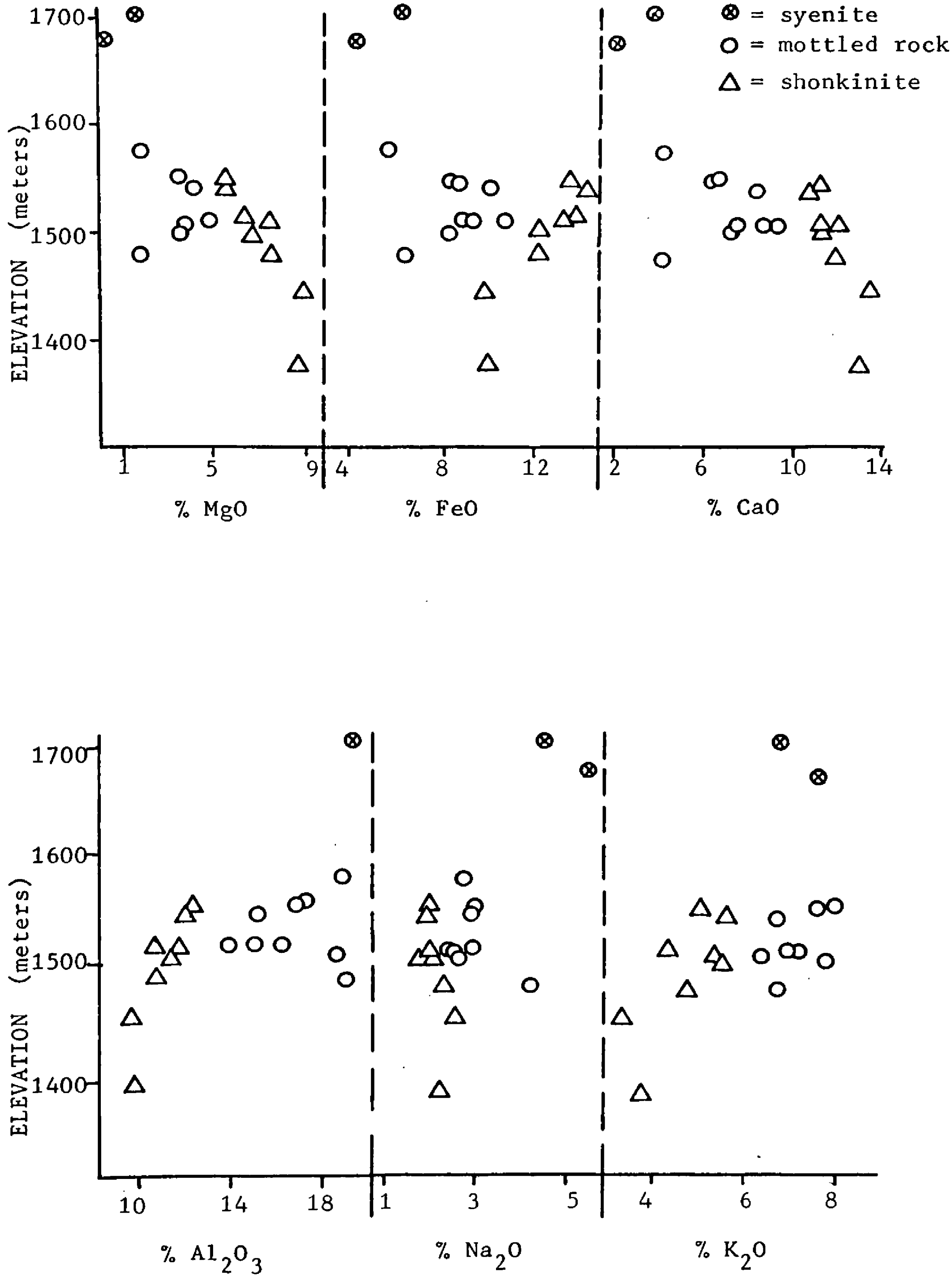
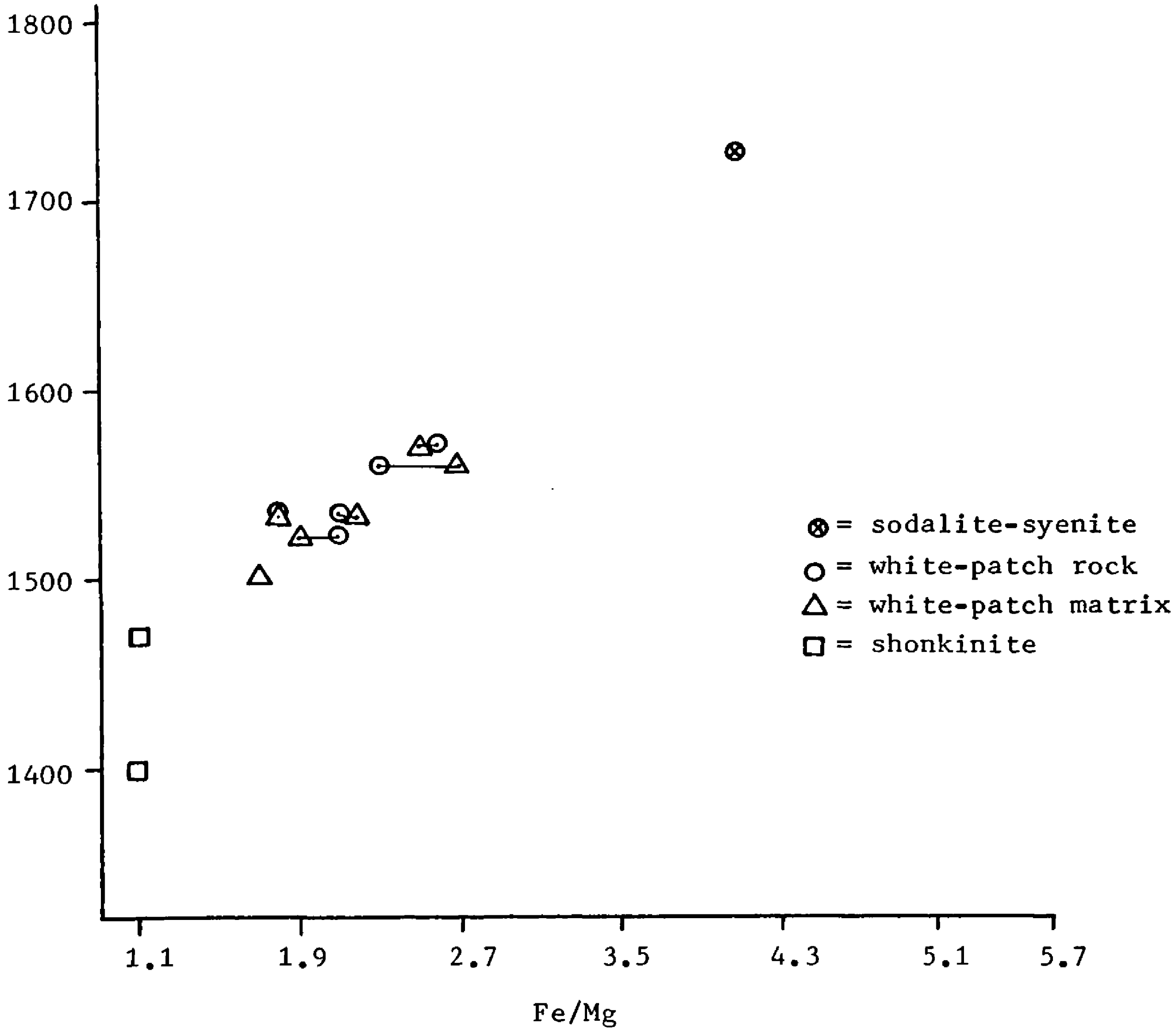


FIGURE 9. Fe/Mg ratio plotted against elevation for patch-matrix pairs.



Shonkin Sag laccolith does, however, indicate a partitioning of elements incompatible with crystal settling but in close agreement with immiscibilith theory (C. L. Edmond, personal communication). Trace-element and rare-earth element analyses of Square Butte rocks could positively determine which differentiation mechanism dominated at Square Butte.

Figure 10 presents my analyses on the ternary diagram SiO_2-mafics-alkalis. The shonkinites all plot within a relatively small area, indicating a constant composition, but the white-patch rocks fall on a line trending away from the mafic corner. This trend may result from immiscible felsic globules separating from a parent magma at different times, producing a range of compositions. This range in compositions could also result from varying degrees of re-equilibration between the globules and their host. The Fe/Mg ratios of patches and their matrix rocks are nearly identical, suggesting that the patches were in equilibrium with their host and could have gradually changed composition by re-equilibration with falling temperature. As noted above, however, additional analytical work must be done before liquid immiscibility can be absolutely confirmed as the primary mechanism of differentiation at Square Butte.

Although sampling errors may have slightly skewed the results, the internal precision appears to be quite good. For example, samples 131 and 10 are shonkinites taken from about the same elevation, but on opposite sides of the laccolith. These analyses are nearly identical, suggesting that the data are accurate for internal comparison. These shonkinite analyses differ slightly from those reported by Hurlbut and

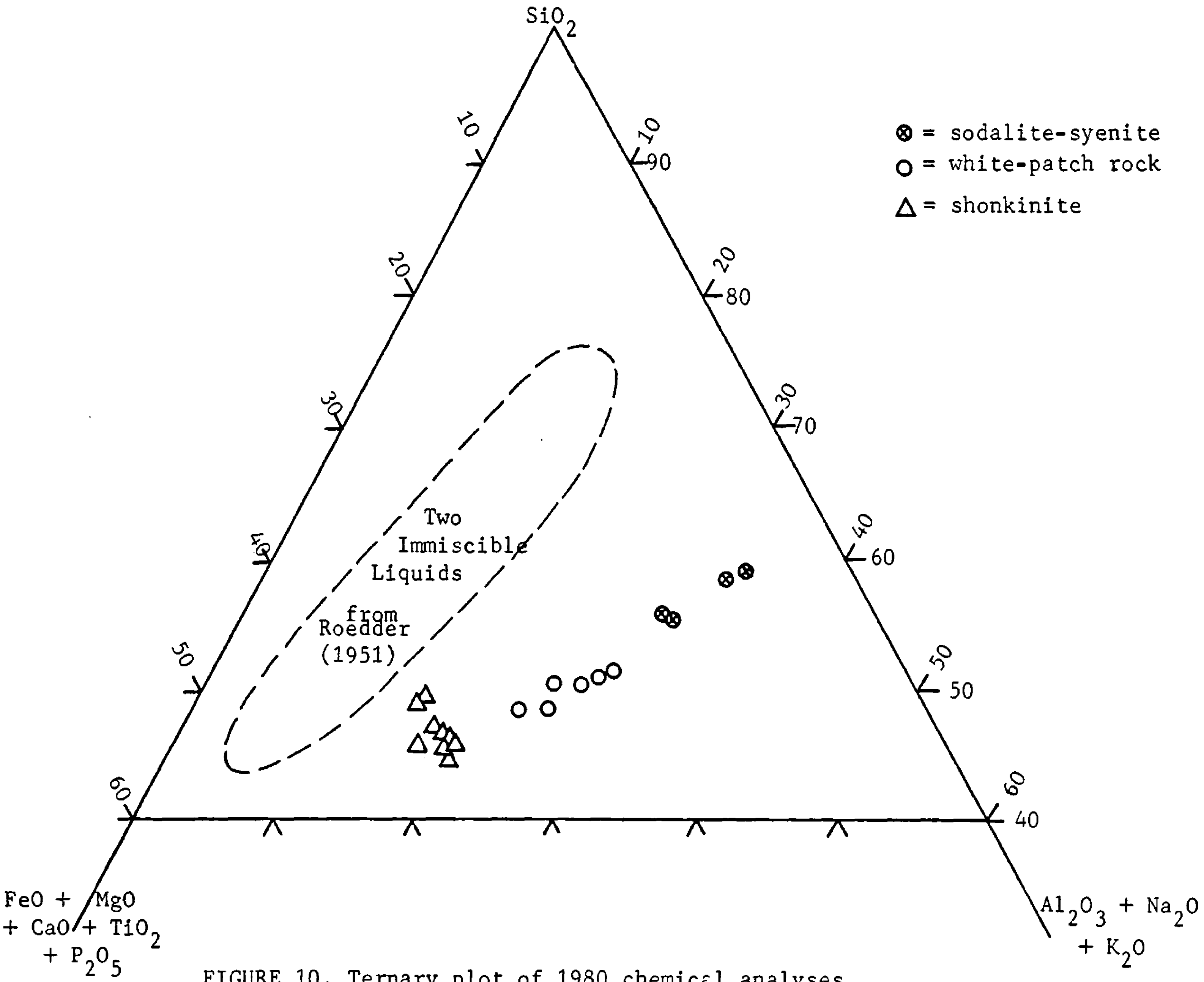


FIGURE 10. Ternary plot of 1980 chemical analyses.

Griggs (1939) listed in Table 2. This difference may result from different analytical methods, or Hurlbut's sample may have come from a lower or higher elevation. Because of this difference, I chose not to combine the older analyses with the new and have only considered the new analyses in evaluating differentiation at Square Butte.

TABLE 2. Previous whole-rock chemical analyses.

	A	B	C	D	
SiO_2	48.74	46.73	52.30	56.45	SiO_2
TiO_2	0.82	0.78	1.18	0.29	TiO_2
Al_2O_3	14.32	10.05	18.92	20.08	Al_2O_3
Fe_2O_3	4.30	3.53	2.51	1.31	Fe_2O_3
FeO	4.51	8.20	3.52	4.39	FeO
MnO	0.11	0.28	-	0.09	MnO
MgO	6.24	9.27	1.81	0.63	MgO
CaO	8.68	13.22	4.12	2.14	CaO
Na_2O	1.89	1.81	2.57	5.61	Na_2O
K_2O	5.80	3.76	10.33	7.13	K_2O
P_2O_5	0.81	1.51	0.09	0.13	P_2O_5

A) chill zone rock (Hurlbut and Griggs, 1939)

B) shonkinite (Pirsson, 1905)

C) white patch rock (Larsen and others, 1941)

D) sodalite-syenite (Lindgren and Melville, 1892)

DIFFERENTIATION AT SQUARE BUTTE

Evaluation of chemical analyses suggests that all of the rocks at Square Butte derived from a single magma, as explained in the chapter on chemistry. This magma must, therefore, have differentiated in place following intrusion. Mechanisms of differentiation could include assimilation, volatile movement, flow differentiation, filter pressing, thermogravitational diffusion, crystal settling, and liquid immiscibility. These differentiation mechanisms are discussed below as they apply to differentiation in the Square Butte laccolith.

Bowen (1928) enshrined fractional crystallization as the answer to almost all problems in petrology, and as a result most of the workers in the 1930's only considered fractional crystallization when evaluating bodies which seemed to have differentiated in place. This was certainly true of most studies of the Highwood Range. Granted, there is ample evidence for a model of differentiation involving crystal settling, especially in the lower sections of the many laccoliths in the area, but there are also many field relationships which are not compatible with such a model. These relationships were fit into the model if possible, and otherwise apparently ignored. Several rather awkward explanations resulted, such as the idea of "auto-injection" (Hurlbut and Griggs, 1939). Perhaps the most significant omission on Hurlbut's part involved ignoring the huge white patches of Square Butte. Since they did not readily fit into any rational model of crystal settling, they were barely mentioned. I have attempted to include all field relationships in my discussion, whether they fit my "model" or not, in order to provide a fair assessment of the various differentiation mechanisms.

Assimilation

The assimilation of country rocks into a body of magma has often been proposed to explain the existence of bimodal rock assemblages. The rocks at Square Butte are incompatible with this process.

If the original magma at Square Butte was syenitic, then assimilation of mafic rock would be required to produce the shonkinite. Aside from the difficulty of assimilating a large amount of refractory material with a felsic magma, there is no mafic country rock near Square Butte. Producing the syenite from a shonkinitic magma via assimilation of a silica-deficient country rock such as limestone may be plausible, but the only nearby country rock at Square Butte is the Cretaceous Eagle sandstone, a feldspathic quartzite. Assimilation of Eagle sandstone would result in a silica-rich rock, not a syenite.

If the parent magma assimilated deeper crustal rocks, or even units from a lower part of the section, then strontium-isotope values would reflect this. Recent work by Powell and Bell (1970) on rocks from the Highwood Mountains shows that strontium 87/86 values are low, suggesting that no old radiogenic crustal material was assimilated by the magmas.

Field evidence also disproves assimilation as a viable mechanism for producing the varied rock types at Square Butte. The chill zones at both Square Butte and the nearby Shonkin Sag laccolith consist of Eagle sandstone in contact with a mafic phonolite. Any "baking" effect on the sandstone diminishes within one foot of the contact, and there is no evidence that any of the sandstone was assimilated at the contact. In fact, several sandstone xenoliths are exposed in both laccoliths, well within the main bodies of the intrusions. They show only a minor amount of reaction with the magma. The original bedding of the xenoliths is well preserved. One of these xenoliths is well exposed high on a cliff face on the northeast comb at Square Butte.

The above-mentioned field evidence combined with strontium isotope determinations suggest that the Square Butte magma can be considered a primary, mantle-derived magma, which did not assimilate appreciable crustal material before, during, or after intrusion.

Volatile Movement

The movement of volatiles within a magma chamber may be a viable process of differentiation in large magma chambers, but it does not seem to be applicable in the Square Butte laccolith. According to the volatile-movement theory, elements such as potassium. sodium, and the rare-earth elements will be concentrated in a water-rich phase during differentiation. These elements will be moved within the system if the water phase separates, or rises, producing an elemental zonation within the magma chamber (c.f., Hyndman, 1972, pp. 78-79). The implementation of this mechanism of differentiation requires the presence of a significant amount of water which does not seem to have been the case at Square Butte.

The evidence cited in the above chapter on chemistry suggests that there was relatively little water in the Square Butte laccolith, and it would seem reasonable to expect to find an abundance of miarolitic cavities if another gas phase was present during solidification of the Square Butte magma. The upper sodalite-barkevikite syenite does contain some miarolitic cavities, but not so many as to suggest a vigorous degassing of the laccolith. The presence of sodalite and some fluid inclusions does indicate that volatiles, at least NaCl, were present in the upper parts of the laccolith, but I can make no quantitative estimates of volatile amounts.

Flow Differentiation

The process of flow differentiation may occur in dikes and sills, where a relatively high velocity flow of magma can move early-formed crystals, but in a more quiescent environment such as a large intrusion this process probably plays a very minor role, if any. The narrow confines of a dike allow the fast-moving magma to quickly move crystals about and can produce a zonation of crystals in the final rock. The larger volume of a laccolith, however, would probably not contain fast-moving magma. Thermal convection currents probably are present in larger bodies, but the absence of layering and flow features in the Square Butte rocks suggests that convection currents were nearly absent in the Square Butte laccolith.

Flow differentiation may have occurred in the shonkinite dikes which crop out to the west of Square Butte, as evidenced by the large leucite and pseudoleucite crystals concentrated toward the center of the dikes (Buie, 1941), but there does not seem to be any indication that this process operated within the Square Butte laccolith.

Filter Pressing

This process may be compared to squeezing the juice out of an orange: when you finish, all you have left is some pulp. In order to differentiate a magma through filter pressing, the entire magma body must be physically compressed, so that interstitial fluids are squeezed out from between the crystal mush. These fluids can subsequently separate from the main body of the magma, producing a differentiated rock. During the process, however, the pre-existing crystal mush has been compressed, and the crystals should be broken, cracked, or at least strained.

Rocks from Square Butte show no evidence of undergoing stress of any kind. It seems probable that in order to obtain a significant portion of felsic liquid from a shonkinite crystal mush, extensive compression would have had to occur. In addition to the fact that there is no textural evidence for this compression in the Square Butte rocks, the butte is located in a nonorogenic region. It seems likely, therefore, that filter press differentiation did not occur at Square Butte.

Thermogravitational Diffusion

Convection-driven thermogravitational diffusion (CDTD) which produces compositional zoning in a magma chamber independent of crystal-liquid equilibria and prior to any crystal settling, has recently received careful attention (Hildreth, 1979). This process cannot be ruled out as a process at Square Butte, but neither is there direct evidence to suggest it. Insufficient chemical data are available to evaluate the CDTD process in a system such as that at Square Butte. Hildreth has suggested that CDTD probably operates only in large magma chambers which contain greater than 74% SiO_2 in the upper levels. This would appear to eliminate CDTD from consideration in this study, but Hildreth was referring to calc-alkaline systems and did not consider alkaline magmas. Additional work is necessary before the process of diffusion can be ruled out at Square Butte.

Crystal Settling

Magmatic differentiation through crystal settling became a widely accepted process primarily because of Bowen's work (Bowen, 1928). This process explains the various textures found in large mafic layered intrusions (Wager and Brown, 1968; Sorenson, 1970), but one must use more caution when applying the crystal settling model to other examples of differentiation in place. Other methods of differentiation must be considered equally. Intellectual tunnel vision may have produced many erroneous interpretations of differentiated bodies.

Irvine (1979) has aptly summarized the most recent work on crystal settling and provides excellent descriptions of the process. Briefly, crystal settling operates as the name implies. Early-formed crystals such as olivine, pyroxene, and plagioclase will settle to the floor of a magma chamber if they have a density greater than the liquid enclosing them. This commonly results in mineralogical (rhythmic) or chemical (cryptic) layering within the intrusion. Likewise, lighter crystals such as leucite could rise to the ceiling to form additional layers if their density is less than the liquid. These separated, "cumulus" crystals are isolated from the remnant liquid system, which has a composition further along the liquidus surface than the original magma. Continued crystallization of the remnant liquid can produce additional differentiation through crystal settling, or crystallization of an "intercumulus" phase from residual liquid trapped between cumulus crystals. This intercumulus liquid can also produce "adcumulus" growth, where the existing cumulus crystals provide nucleation sites for further crystal growth, resulting in distinctive enlargement of the original, cumulus crystals.

The Square Butte laccolith has been described as an obvious example of differentiation in place through crystal settling (Hurlbut and Griggs, 1939), evidenced mainly by its proximity to the Shonkin Sag laccolith. The general lack of mafic minerals in the upper syenite at Square Butte and the more mafic character of the lower units suggested to Hurlbut that crystal settling had produced the broad "layering" of the laccolith.

The horizontal nature of the rock units does suggest a gravitational influence in differentiation, and the lower shonkinite locally displays a subparallel arrangement of pyroxene crystals, but I found no definite cumulate textures in any of the Square Butte rocks. Augite crystals appear to have adhered to one another in the shonkinite, but these pyroxene clusters do not form layers. Rather, they are separated by non-optically continuous patches of felsic material. While previous authors regarded this material as intercumulus, I consider it a matrix, that is, not bits of liquid trapped by falling crystals but rather a liquid medium enclosing the mafic clusters. The pyroxene crystals are weakly zoned, indicating that the magma composition changed slightly during crystal growth as would be expected, but typical adcumulus growth on pyroxenes is absent.

I found neither rhythmic layering nor cryptic layering in the laccolith. In fact, the entire 215-meter shonkinite section is of a totally uniform composition and mode. It is possible that the Square Butte laccolith was not large enough to generate the convection currents or density flows necessary for rhythmic layers, but extensive crystal settling should have produced a dense lowermost shonkinite with a gradual upward decrease in density. The uniform density (3.05 g/cc) of the 215-meter section of shonkinite (Hurlbut and Griggs, 1939) suggests that the early-formed augite and olivine crystals may have grouped together to form clusters but did not settle to form distinct mineralogical layers.

The chemical composition of the Square Butte rocks does not prove or disprove the crystal-settling model, as explained in the chemistry chapter. Additional detailed sampling and analytical work, especially for trace elements and rare-earth elements, may provide criteria for evaluating crystal-settling on a chemical basis.

The field evidence described above poses major problems for a crystal-settling model. The unusual large-scale texture of the mottled rock and the existence of the large syenite globules seem to outweigh in importance any microscopic textures favoring crystal-settling, and indicate that another process dominated at Square Butte. I will now turn to the preferred model of liquid immiscibility.

Liquid Immiscibility

The last decade has seen a revival of silicate liquid immiscibility as an accepted differentiation process, after many years of disrepute. The work of Roedder (1951) finally dusted off this theory which had been discarded in the last 1920's (Greig, 1927; Bowen, 1928) and thrust it once again into the company of other differentiation processes. Subsequently, differentiation through liquid immiscibility has been invoked for a wide variety of rock occurrences. The main aspects of liquid immiscibility are summarized in this section. The reader is referred to Roedder (1979) or Lelek (1979) for more detailed compilations of immiscibility theory and its petrogenetic applications.

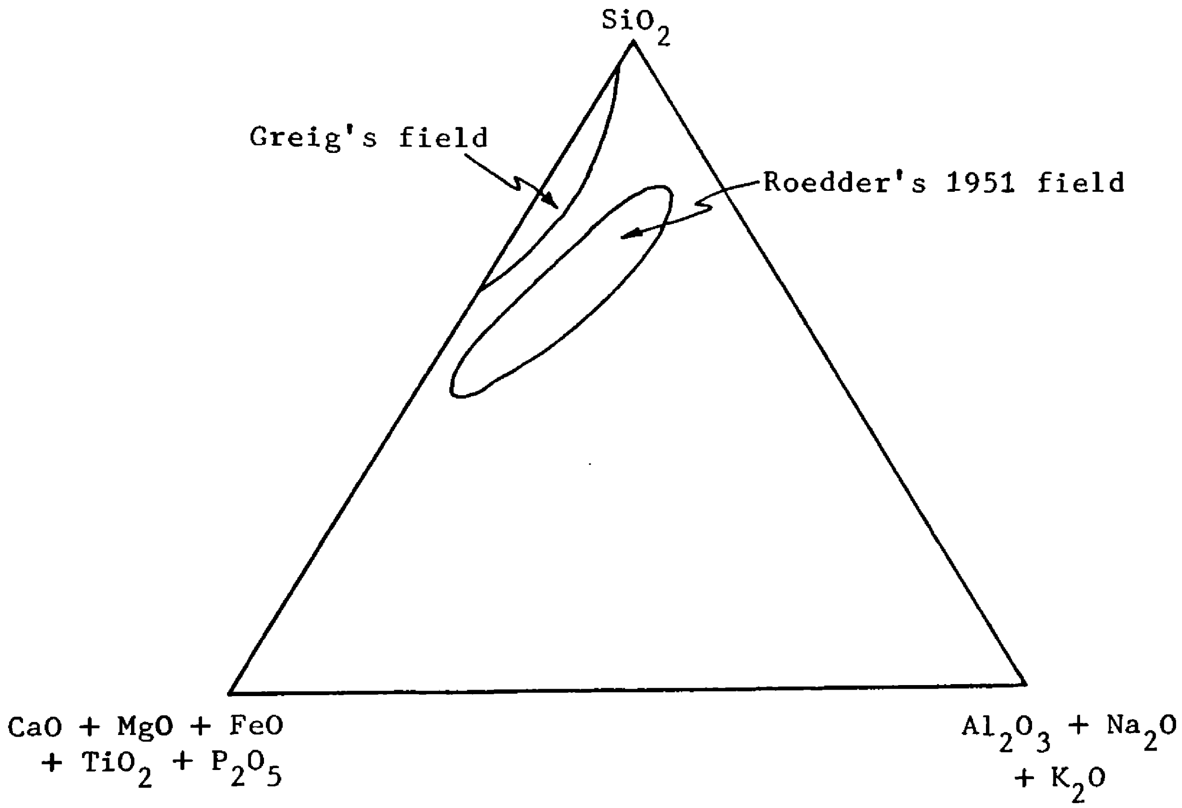
Nineteenth-century geologists accepted liquation, or liquid immiscibility, as a valid process which produced differentiated rock bodies. The familiar separation of oil and water seemed to them a rational mechanism for the separation of magmas as well. This open-mindedness enabled Weed and Pirsson (1895) and Daly (1912) to describe both the Square Butte and Shonkin Sag laccoliths as obvious examples of differentiation through liquation. This open-mindedness was short-lived however.

Greig (1927) showed through experimental work that immiscibility in several oxide-silica systems occurred only at extremely high temperatures (greater than 1700° C). If Greig had only worked with "real" rocks instead of his binary mixtures (which were themselves of "geologically unreasonable compositions"), he might have observed immiscibility at lower temperatures.

Roedder (1951) discovered an immiscibility field in the system leucite-fayalite-silica (shown in Figure 11) at temperatures below 1400° C., bringing liquid immiscibility back to the realm of geologically reasonable conditions (Holgate, 1954). The concept was not, however, fully accepted until studies on the lunar rocks provided conclusive evidence that silicate liquid immiscibility did indeed operate in real rocks (Weiblen and Roedder, 1973; Rutherford and others, 1974). Gradual acceptance of the process prompted numerous experimental investigations (for example: Currie, 1972; Yoder, 1973; Irvine, 1975; Naslund, 1976; Freestone, 1978; Visser and Koster van Groos, 1979a-c). This more-recent work showed that liquid immiscibility can occur over a wide range of temperatures and in many different compositions.

The size of the immiscible field was a critical factor in petrologic applications of the theory. Greig's field covered a very small region at high temperatures, and though Roedder's was slightly larger it still did not encompass many rock types. Several scientists

FIGURE 11. Experimentally-determined fields of immiscibility. Adapted from Roedder (1979) and Greig (1927).



studied expansion of the field of immiscibility in order to provide a more usable model in petrologic applications.

Kushiro (1975) felt that the addition of TiO_2 and P_2O_5 would expand the field significantly, and Freestone (1978) proved that the addition of 1% TiO_2 and 3% P_2O_5 caused marked expansion of Roedder's field toward K-rich compositions. Roedder's original experiments dealt with TiO_2- and P_2O_5-free mixtures, and thus delineated only a minimum immiscible field. Irvine (1975) and Naslund (1976) discovered that the immiscible field also expands with increasing volatiles and oxygen fugacities. Since Freestone (1978) worked with a dry system at low oxygen fugacities, then even his field must represent a minimum area. Although the immiscible field shrinks at pressures above 15 kb (Nakamura, 1974) it is possible that within lower pressure regimes (less than 5 kb?) the field can expand enough to encompass many common rock types. Thus, a large immiscible field could form in a system containing large amounts of TiO_2, P_2O_5, and K_2O, at pressures less than 5 kb, and moderate to large oxygen fugacities. It seems that the Square Butte system fits this description.

The encouraging experimental results spurred re-evaluations of many geologic bodies, and as a result, differentiation through liquid immiscibility has been invoked for a wide range of rock types including:

lunar basalts (Rutherford and others, 1974);

terrestrial plateau basalts (De, 1974);

Archean variolitic lavas (Ferguson and Currie, 1972; Gelinas, 1974; Gelinas and others, 1976);

high-Mg basalts (Cawthorn and others, 1979);

gabbroic layered intrusions (McBirney and Nakamura, 1974);

ultramafic intrusions (Ferguson and Currie, 1971; Carman and others, 1975; Lelek, 1979);

alkalic intrusions (Philpotts, 1976, 1974, 1972, 1971, 1970, 1968; Eby, 1979);

carbonatites (Rankin and LeBas, 1974; Woods, 1974);

ophiolite suites (Dixon and Rutherford, 1979).

The outcrop-scale textures at Square Butte as described above suggest that immiscible felsic globules formed in a shonkinitic magma, coalesced and rose to form an upper syenite. Re-equilibration of globules with their matrix during cooling may have reduced any compositional differences, although the original compositions could have been reasonably close at the time of initial immiscible separation (for example, see Reisman, 1970). The subsequent crystallization of the laccolith probably destroyed any classic ocelli textures (i.e., menisci) and masked the immiscible relationships. The similar Fe/Mg ratios of patches and their matrix rocks indicate that the patches were in equilibrium with the matrix, a situation necessary in liquid immiscibility. I feel that silicate liquid immiscibility provides the most straightforward explanation of the field relationships, chemistry, and textures of the Square Butte rocks.

DISCUSSION

Magma Immiscibility at Square Butte

Differentiation through liquid immiscibility seems to best explain the field relationships at Square Butte. The lack of rhythmic or cryptic layers and the constant mode and density of the shonkinite suggest that crystal settling did not operate on a large scale during differentiation. The isolated white patches strongly resemble large globules of felsic magma suspended in a mafic magma, and the mottled nature of the lower rock units suggests small felsic globules separated by mafic minerals. The horizontal boundaries of the shonkinite-mottled rock transition and the white-patch zone indicate a gravity-controlled differentiation process. The density difference between shonkinite and syenite is sufficient to have allowed the rise of syenite globules within the calculated cooling time. The presence of sodalite-syenite globules 150 meters below the base of the sodalite-syenite unit is explained easily by an immiscibility model, not so easily by crystal settling.

The major-element partitioning at Square Butte could be explained by either crystal settling or liquid immiscibility. But trace element and rare-earth element analyses could provide a method for determining which process dominated. The similar Fe/Mg ratios for patch and matrix rocks and the high percentage of phosphorous in the mafic rocks do suggest that liquid immiscibility may have operated at Square Butte.

Although no experimental work on immiscibility has dealt with orthoclase-augite systems such as that at Square Butte, I can place several constraints on probable phase diagrams based on field evidence. Since euhedral olivine and augite crystals are contained in the chill zone rocks, they were present at the time of intrusion. Thus, the magma was already on a liquidus surface before immiscible separation, and so the proposed immiscible field must intersect the liquidus as a dome rather than remain above the liquidus as a closed loop. This also suggests that immiscible separation occurred at temperatures less than 1200^{o} C., a region not yet fully investigated by experimental work.

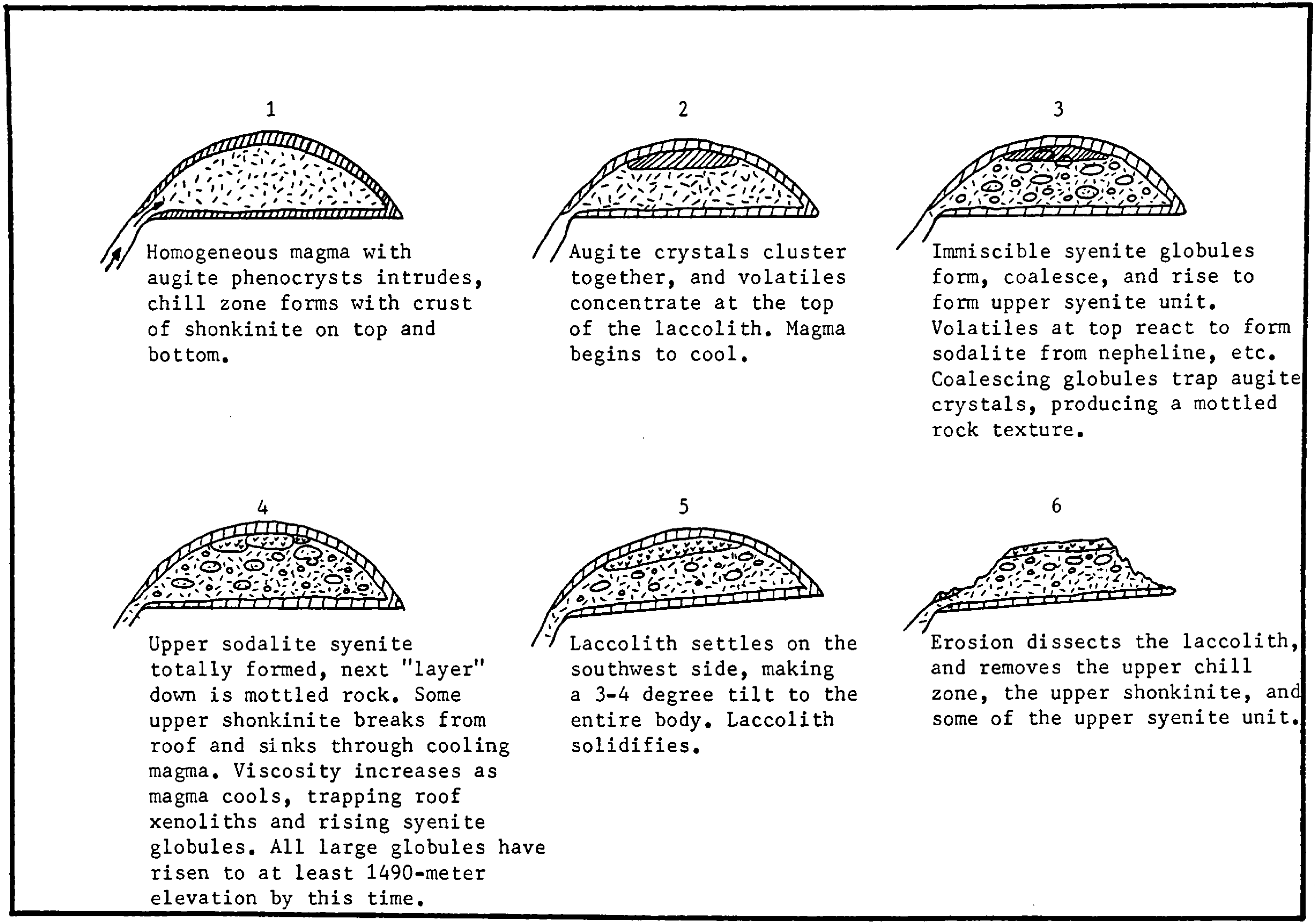
Expansion of the immiscible fields of known phase diagrams could encompass the rocks of Square Butte. As explained above, expansion can be achieved by addition of TiO_2, P_2O_5, K_2O, and volatiles, and by placing the system in a low pressure regime. All of these conditions were present in the Square Butte magma, which may have prompted immiscible separation. Clearly, more work needs to be done in the area of immiscibility in potassium-rich systems before we can fully understand this type of differentiation.

Hypothesized Origin of Square Butte

Figure 12 depicts my hypothesized origin of the Square Butte laccolith. During or after initial intrusion of a homogeneous magma containing olivine and augite phenocrysts, immiscible felsic droplets formed, coalesced, and began rising. These rising globules may have collected mafic phenocrysts on their surfaces, which may explain the presence of mafic minerals which seem to ring the lighter patches in the mottled rock. As the larger globules collected at the top of the laccolith, they formed a felsic unit rich in volatiles such as CO_2 and NaCl. Pre-existing augite and biotite altered to barkevikite, and nepheline reacted with Cl to form sodalite.

Globules which were trapped in lower levels by increased host viscosity partially re-equilibrated with the host. The degree of re-equilibration was probably proportional to the size of the original globule. Thus, small globules were almost totally assimilated but persisted as small patches in the mottled rock, and the larger globules were preserved as white patches.

Evacuation of magma from a feeder dike to the southwest could have prompted subsidence of the laccolith at that corner, resulting in a 3-4 degree tilt to the body. This tilt could also have been generated by post-intrusion tectonic activity in the area. Later erosion has produced the Square Butte that we see today.



1

Homogeneous magma with augite phenocrysts intrudes, chill zone forms with crust of shonkinite on top and bottom.

2

Augite crystals cluster together, and volatiles concentrate at the top of the laccolith. Magma begins to cool.

3

Immiscible syenite globules form, coalesce, and rise to form upper syenite unit. Volatiles at top react to form sodalite from nepheline, etc. Coalescing globules trap augite crystals, producing a mottled rock texture.

4

Upper sodalite syenite totally formed, next "layer" down is mottled rock. Some upper shonkinite breaks from roof and sinks through cooling magma. Viscosity increases as magma cools, trapping roof xenoliths and rising syenite globules. All large globules have risen to at least 1490-meter elevation by this time.

5

Laccolith settles on the southwest side, making a 3-4 degree tilt to the entire body. Laccolith solidifies.

6

Erosion dissects the laccolith, and removes the upper chill zone, the upper shonkinite, and some of the upper syenite unit.

FIGURE 12. Hypothesized origin of the Square Butte laccolith. Not drawn to scale.

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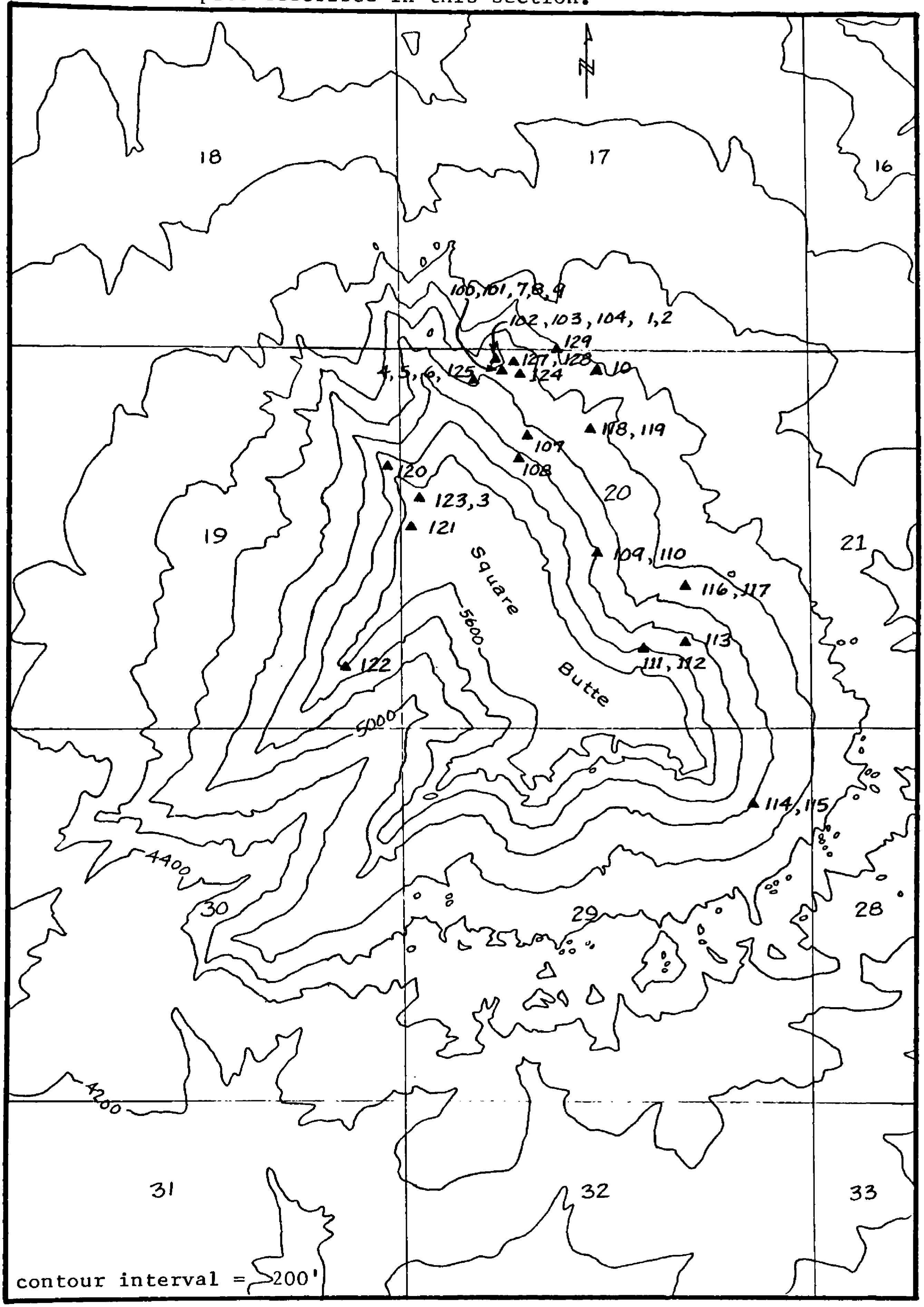
APPENDIX 1

DETAILED PETROGRAPHIC DESCRIPTIONS

Location of samples described in this section.



Sample: SB-100
Location: northeast comb
Elevation: 1536 meters
General Description: white patch, 1 meter in diameter.

Mode

25%	augite
1%	olivine
5%	brown biotite
1%	green biotite
3%	titanomagnetite
3%	apatite
tr	sphene
60%	orthoclase + anorth.
tr	zeolites

Notes

All phenocrysts contain apatite. Olivine corroded, contains iddingsite, rimmed by green biot. where in contact with feldspar. Augite corroded, rimmed by both green and brown biotite, shows some zoning and larger crystals contain zoned inclusions of ap. and sphene. Magnetite commonly rimmed by brown biotite. Oliv. appears out of equil., augite only slightly out of equil.

Sample: SB-101
Location: northeast comb
Elevation: 1536 meters
General Description: dark matrix surrounding SB-100, shonk.

Mode

50%	augite
3%	olivine
10%	biotite
4%	titanomagnetite
2%	apatite
tr	sphene
30%	orthoclase + nepheline
tr	zeolites

Notes

Augite is zoned, some reverse and some oscillatory, and is commonly rimmed by green biotite. Pieces of corroded olivine crystals enclosed by brown biotite laths. Apatite laths enclosed by all euhedral crystals. Magnetite rarely rimmed by brown biotite. Olivine much fresher than in SB-100.

Sample: SB-102
Location: northeast comb
Elevation: 1552 meters
General Description: light rock surrounding roof pendant

Mode

19%	augite
1%	olivine
5%	biotite
2%	titanomagnetite
2%	apatite
tr	sphene
70%	orthoclase
tr	zeolites

Notes

Corroded remnants of olivine scattered throughout felsic material, olivine resorbed and out of equil.? Augite is rimmed by green biotite locally, and shows some weak oscillatory zoning. Apatite and sphene enclosed by all crystals. Magnetite only in augite and oliv.

Sample: SB-103
Location: northeast comb
Elevation: 1552 meters
General Description: roof pendant of upper shonkinite ?

Mode

25% augite
10% olivine
2% titanomagnetite
1% apatite
4% biotite
57% orthoclase + kaolinite
tr zeolites
tr microcline
tr albite

Notes

Olivine crystals corroded, rimmed by light green biotite, contain some iddingsite and serpentine, and inclusions of apatite and magnetite. Olivines appear fresher than in SB-102. Augite crystals very fresh, rarely rimmed by green biotite. Mafic crystals seem more in equil. here than in SB-102.

Sample: SB-104
Location: northeast comb
Elevation: 1554 meters
General Description: white selvedge on top of roof pendant

Mode

5% augite
2% olivine
1% titanomagnetite
1% biotite
1% apatite

90% orthoclase + anorth.

Notes

Olivine extremely corroded, rimmed by green biotite, with extensive replacement by serp. and iddingsite. Augite crystals commonly rimmed by green biotite, appear moderately resorbed. Mod. alteration of feldspars to kaolinite (?). Complex intergrowths of orthoclase and anorthoclase, appears as a graphic texture locally - may be an exsolution texture ? In general, this rock seems to have formed from residual liquids which may have concentrated at the upper (low pressure) side of a descending roof pendant.

Sample: SB-107
Location: above east-northeast comb
Elevation: 1549 meters
General Description: mottled transition rock

Mode	Notes
23% augite 3% biotite 6% titanomagnetite 1% barkevikite 2% apatite 65% orthoclase	Orthoclase shows oscillatory zoning, normal zoning in some augite crystals. Augite being replaced by barkevikite - 10% of augites show some replacement. No olivine crystals present, may have been totally replaced by biotite, since up to 1% euhedral green biotite. Orthoclase present primarily as interstitial material, but some laths present also.

Sample: SB-108
Location: above east-northeast comb
Elevation: 1591 meters
General Description: mottled transition rock

Mode	Notes
15% augite 5% biotite 3% titanomagnetite 1% barkevikite 1% apatite 75% orthoclase tr nepheline	Augite partially replaced by brown biotite, with Fe oxides concentrated at interface. Less than 2% of the augites partially replaced by amphib. Apatite enclosed by all augite and biotite phenocrysts. 40% of feldspar is interstitial, and appears to be a complexly intergrown orth.+anorth+neph. group (exsolution ?). 60% of the feldspar occurs as laths.

Sample: SB-109

Location: east comb #1
Elevation: 1616 meters
General Description: pegmatitic white globule 30cm X 20cm.

Mode	Notes
5% augite 2% biotite 2% titanomagnetite tr apatite 90% orthoclase tr zeolites (?)	No intact augite crystals, all corroded or replaced by green biotite. All magnetite crystals rimmed by brown biot. All mafics appear out of equil. Orth. laths are zoned, some oscillatory. Interstitial feldspar not optically continuous. Again, complex intergrowth of orth.+ anorth.

Sample: SB-110
Location:east comb #1
Elevation: 1616 meters
General Description: dark rock surrounding SB-109 rock

Mode	Notes
25% augite 5% biotite 2% titanomagnetite tr barkevikite 1% apatite 66% orthoclase + glass(?) or fluid inclusions(?)	Augites are unzoned, and only partly altered to green biotite. Only one crystal found with barkevikite after augite. Apatite occurs both as inclusions in augite and as laths interstitially. Orthoclase appears extremely altered at first, but actually contains high % of microlites and glass fragments (or fluid inclusions - too small to tell).

Sample: SB-111
Location: east comb #2
Elevation: 1646 meters
General Description: white globule

Mode	Notes
4% augite 1% biotite 2% titanomagnetite 3% barkevikite tr apatite tr hematite tr natrolite 90% orthoclase + neph (?) + zeolites + albite	Feldspar appears to be perthitic, with a complex intergrowth of orth + albite(?) + neph. One mass of radiating (fan-shaped) natrolite was found, interstitial to the feldspar laths. Augite is replaced by green biotite and/or barkevikite. Much amphib. pseudomorphic after augite. Most augites are corroded, but those rimmed by biotite are fresher. Fresh augites are unzoned.

Sample: SB-112
Location: east comb #2
Elevation: 1646 meters
General Description: dark rock surrounding SB-111

Mode

20% augite
10% biotite
1% titanomagnetite
1% barkevikite
3% apatite
4% albite
60% orthoclase

Notes

Albite occurs as 1-2 mm square crystals w/good albite twins. Feldspar is perthitic, w/small beads of Na feldspar. Biotite is poikilitic w/augite, magnetite, apatite, and fspar inclusions. Pyroxenes unzoned and quite fresh.

Sample: SB-113
Location: east comb #3
Elevation: 1622 meters
General Description: mottled transition rock

Mode

10% augite
2% biotite
3% titanomagnetite
1% barkevikite
1% apatite
5% orthoclase laths
78% perthite

Notes

Pyroxene unzoned where fresh, altering to green biotite or barkevikite in 50% of crystals. Appears to be globs of Cpx and magnetite crystals floating in feldspar matrix. No zeolites or other alteration products visible in the feldspars.

Sample: SB-114
Location: southeast comb
Elevation: 1506 meters
General Description: white rock surrounding SB-115

Mode

23% augite
4% biotite
3% titanomagnetite
2% apatite
68% perthite + glass (?)

Notes

Biotite is poikilitic and contains apatite, magnetite, and augite inclusions. Green biotite replacing 25% of augite crystals. Corroded cpx fragments floating in perthite matrix.Augites out of equilibrium ?

Sample: SB-115
Location: southeast comb
Elevation: 1506 meters
General Description: shonkinite blob

Mode	Notes
60% augite 2% olivine 3% biotite 2% titanomagnetite 3% apatite tr pseudoleucite 30% perthite	Augites weakly zoned, fairly fresh compared with other rocks of the laccolith. Olivines partially resorbed, cracked, w/iddings. and serp. on cracks. Apatite inclusions in all phenocrysts. 25% of feldspar laths contain glass (fluid?) inclusions.

Sample: SB-116
Location: east side hoodoos
Elevation: 1494 meters
General Description: white globule in shonkinite

Mode	Notes
25% augite 1% biotite 2% titanomagnetite tr apatite 1% albite 70% perthitic orthoclase	Augites slightly zoned, most are rimmed by brown biotite. Orthoclase is slightly kaolinized, and contains exsolved blebs of Na feldspar. Magnetite crystals also rimmed by brown biotite.

Sample: SB-117
Location: east side hoodoos
Elevation: 1494 meters
General Description: dark rock surrounding SB-116

Mode	Notes
56% augite 1% olivine 5% biotite 1% titanomagnetite 2% apatite 35% perthitic orthoclase	Biotite is poikilitic, contains inclusions of augite, olivine, and apatite. Mafic minerals much fresher than those in SB-116.

Sample: SB-118
Location: east-northeast comb
Elevation: 1506 meters
General Description: white globule

Mode	Notes
28% augite 2% biotite 3% titanomagnetite 2% apatite 65% perthitic (?) orth.	Very weak zoning in augites, most are mod. fresh. Biotite replacing some augite crystals. No kspar laths - all feldspar appears to be interstitial, w/ complex intergrowth or exsolution texture. Most magnetite crystals totally rimmed by biot.

Sample: SB-119
Location: east-northeast comb
Elevation: 1506 meters
General Description: dark rock surrounding SB-118

Mode	Notes
66% augite 4% biotite 2% titanomagnetite 3% apatite 25% orthoclase (50% perthitic)	No zoning in augites, which may be cumulus - many are in grain to grain contact. Orthoclase appears interstitial.Poikilitic biotite contains augite, apatite, and magnetite crystals.

Sample: SB-120
Location: northwest comb
Elevation: 1646 meters
General Description: mottled transition rock

Mode	Notes
14% augite 5% biotite 2% titanomagnetite 2% barkevikite 1% apatite tr sphene tr natrolite 75% orthoclase (20% laths, 55% interstitial)	Most augite crystals replaced partially by barkevikite, some by green biotite - all seem out of equilibrium. Some augites are normally zoned, others oscillatory. Apatite inclusions in augite and biotite, but not in barkevikite. Complex intergrowths in interstitial feldspar. May be unusual perthite.

Sample: SB-121
Location: summit, west side
Elevation: 1732 meters
General Description: sodalite syenite

Mode

15% barkevikite
tr titanomagnetite
tr apatite

76% orthoclase laths
1% nepheline
2% albite
6% sodalite

Notes

Brown barkevikite has green amphibole at edges (arfveds?). Nepheline appears very fresh. Mod. kaolinization of fspar. Sodalite interstitial to feldspar laths.

Sample: SB-122
Location: summit, southwest corner
Elevation: 1707 meters
General Description: sodalite syenite

Mode

~8% barkevikite
tr apatite

88% orthoclase laths + zeolites
tr nepheline
4% sodalite

Notes

Slight zeolitization of fspar. Similar to SB-121.

Sample: SB-123
Location: summit, northwest corner
Elevation: 1732 meters
General Description: sodalite syenite

Mode

15% barkevikite
tr titanomagnetite

85% orthoclase laths
5% sodalite

Notes

Kspar slightly kaolinized, laths contain abundant fluid inclusions or glass fragments. Too small for identification.

Sample: SB-124
Location: above northeast comb
Elevation: 1634 meters
General Description: mottled transition rock

Mode

15% augite
2% biotite
1% titanomagnetite
2% barkevikite
1% apatite

80% orthoclase (10% laths, 70% interstitial)
tr cancrinite (?)

Notes

50% of augites replaced by barkevikite, remainder partially altered to green biotite. Orthoclase is perthitic.Cancrinite appears to be after nepheline.

Sample: SB-125
Location: between northeast and north combs
Elevation: 1524 meters
General Description: white globule

Mode

30% augite
4% biotite
4% titanomagnetite
2% apatite

tr albite
60% orthoclase + zeolites

Notes

Some augites going to green biotite, but most are relatively fresh. Magnetite crystals commonly rimmed by brown biotite. 30% of feldspar slightly zeolitized.

Sample: SB-126
Location: between northeast and north combs
Elevation: 1524 meters
General Description: dark rock surrounding SB-125

Mode

55% augite
4% biotite
3% titanomagnetite
4% apatite

tr pseudoleucite
35% orthoclase

Notes

Augites much fresher than those in SB-125. Kspar mostly interstitial, not optically continuous, moderately perthitic. Slight zeolitization of feldspar also.

Sample: SB-127
Location: northeast comb
Elevation: 1530 meters
General Description: white rock surrounding SB-128

Mode

20% augite
2% biotite
3% titanomagnetite
1% apatite
73% orthoclase + zeolites + glass/fluid inclusions

Notes

Most augites are fairly fresh, less than 10% replaced by green biotite. Some biotites are euhedral (brown) - formed at same time as augites? Very slight alteration of feldspar to zeolites - not common.

Sample: SB-128
Location: northeast comb
Elevation: 1530 meters
General Description: darker rock blob

Mode

17% augite
4% biotite
2% titanomagnetite
2% apatite
75% orthoclase

Notes

Very similar to SB-127 - color difference probably due to this sample's higher % of biotite, since biotite flakes cover large surface area for their percentage. 20% of feldspar kaolinized. Very little zeolitization.

Sample: SB-129
Location: base of northeast comb
Elevation: 1402 meters
General Description: shonkinite

Mode

30% augite
2% olivine
4% biotite
2% titanomagnetite
2% apatite
60% orthoclase (perthitic)

Notes

Olivine crystals cracked, with serp. and iddings. on cracks. Augite very fresh, rare alteration to green biotite. Most biotites appear primary - intergrown with augites. Kspar is anhedral, and occupies large interstitial patches up to 1 cm across.

Sample: SQB-1
Location: northeast comb
Elevation: 1552 meters
General Description: roof pendant

Mode	
50%	augite
5%	biotite
3%	titanomagnetite
2%	apatite
2%	pseudoleucite
2%	nepheline
36%	orthoclase

Notes

Some augite rimmed by green biotite - most is fresh. Some brown biotite is subhedral, and primary. Pseudoleucites are fan-shaped, radiating intergrowths of kspar and nepheline, not circular. Do not appear to be altered leucite crystals, more likely eutectic liquid.

Sample: SQB-2
Location: northeast comb
Elevation: 1554 meters
General Description: white selvedge on top of pendant

Mode	
20%	augite
3%	biotite
3%	titanomagnetite
2%	apatite
tr	pseudoleucite
70%	orthoclase

Notes

Augites rimmed by green biotite and partially replaced by brown biotite. Magnetite and apatite inclusions in augites and subhedral brown biotite crystals. Pseudoleucite not radiating, but looks more like parallel intergrowth - eutectic crystallization.

Sample: SQB-3
Location: summit, east side
Elevation: 1744 meters
General Description: sodalite syenite

Mode	
20%	barkevikite
tr	apatite
tr	nepheline
72%	orthoclase
8%	sodalite

Notes

Amphibole is mostly subhedral, but there are several euhedral crystals in this section.Euhedral barkevikite has brown-orange core and green borders - rims of arfvedsonite ? Apatite crystals contained in a few amphib. crystals - used to be augites ? Sodalite interstitial to fspar.

Sample: SQB-4
Location: between northeast and north combs
Elevation: 1530 meters
General Description: dark rock surrounding SQB-5

Mode

65%	augite
~2%	olivine
3%	biotite
2%	titanomagnetite
2%	apatite
1%	pseudoleucite
25%	orthoclase + zeolites

Notes

Olivine cracked, altered to serp. and iddings. on cracks. Augites quite fresh, some partly replaced by green biotite. Few euhedral biotite plates. One radiating pseudoleucite "crystal" ,rest is intergrown kspar and nepheline, interstitial to mafics.

Sample: SQB-5
Location: between northeast and north combs
Elevation: 1530 meters
General Description: white blob

Mode

27%	augite
2%	olivine
5%	biotite
3%	titanomagnetite
2%	apatite
tr	pseudoleucite
60%	orthoclase + nepheline

Notes

Olivines very corroded, mostly replaced by biotite. Augites also very corroded, enclosed by brown biotites. Magnetite commonly rimmed by brown biotite, and the brown biotite is rimmed by green biotite.Reflects the change of the "white" magma from Mg to Fe enriched ?

Sample: SQB-6
Location: between northeast and north combs
Elevation: 1530 meters
General Description: white blob east of SQB-5

Mode

16%	augite
1%	olivine
4%	biotite
2%	titanomagnetite
2%	apatite
5%	nepheline + zeolites
70%	orthoclase + kaolinite

Notes

Brown biotite rims on magnetite, green biotite on augites. Olivine inclusions in augite and biotite; augite inclusions in biotite; apatite inclusions in magnetite, augite, and biotite; biotite inclusions in augites. Microlites of apatite in kspar, and glass fragments or fluid inclusions in unaltered orthoclase.

Sample: SQB-7
Location: northeast comb
Elevation: 1536 meters
General Description: light globule surrounded by darker rock

Mode	Notes
35% augite 3% olivine 6% biotite 2% titanomagnetite 3% apatite tr pseudoleucite 50% orthoclase + nepheline	Corroded olivines with serp. and iddings. on cracks enclosed by augites. Green biotite at contact of olivine and kspar. Some augites partially replaced by green biotite also. Apatite inclusions in all phenocrysts. One small fan-shaped pseudoleucite cluster.

Sample: SQB-8
Location: northeast comb
Elevation: 1524 meters
General Description: pegmatite blob in shonkinite

Mode	Notes
tr augite 2% aegirine 2% biotite 1% titanomagnetite 1% apatite tr nepheline 5% albite 5% microcline tr sodalite 75% orthoclase	Aegirine is the dominant pyroxene. Only one crystal of augite found, and that had an aegirine rim. The existing aegirines may have been augites originally. Biotite forms long, needle-shaped crystals - probably secondary also.Appears to be a moderate amount of kaolinization in the feldspars.

Sample: SQB-9
Location: northeast comb
Elevation: 1524 meters
General Description: shonkinite surrounding pegmatitic material

Mode	Notes
40% augite 3% olivine 5% biotite 1% titanomagnetite 2% apatite 50% orthoclase	Augites may be cumulus,(local subparallel orientation) with intercumulus orthoclase which is optically continuous over 1 cm areas. This sample could be non-representative however, since most of the other shonkinite samples show no evidence of cumulus textures. Most of the minerals are quite fresh, with only the olivines mod. altered to serpentine + iddingsite.

Sample: SQB-10
Location: base of east-northeast comb
Elevation: 1402 meters
General Description: shonkinite

Mode

58% augite
3% olivine
4% biotite
1% titanomagnetite
3% apatite

tr pseudoleucite
30% orthoclase

Notes

All minerals are relatively fresh. Olivines are cracked, and slightly altered to serpentine and iddingsite. Augites are locally aligned (subparallel) but not as a rule. May be a cumulus texture, but not definite. Probably just a local feature.

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