To the Graduate Council:

I am submitting herewith a thesis written by Susan M. van Gelder entitled "Geology of the Bald Rock Granitic Batholith, South Carolina." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

Harry Y. McSween, Jr., Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:

Vice Chancellor
Graduate Studies and Research

GEOLOGY OF THE BALD ROCK GRANITIC BATHOLITH, SOUTH CAROLINA

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Susan M. van Gelder

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ABSTRACT

The Bald Rock Batholith is a postmetamorphic granitic pluton located in the southern Appalachian Piedmont. Granites and quartz monzonites of the Bald Rock consist mainly of microcline, plagioclase, quartz and biotite, with accessory amounts of allanite, epidote, titanite, muscovite, apatite, zircon, magnetite, ilmenite, pyrite and, locally, hornblende and garnet. Two major textural phases of the Bald Rock granite are distinguished: a medium- to coarse- grained porphyritic phase containing tabular microcline megacrysts up to 7 cm in length; and a fine-grained, equigranular phase that intrudes the former. The fine-grained granite is a more highly differentiated derivative of the porphyritic phase. Five variants of the porphyritic phase are recognized on the basis of modal and textural criteria. Most petrographic variation is concentrated near the margins of the batholith, suggesting that contamination occurred. Movement of magma is indicated by foliations of megacrysts and mafic xenoliths that are concentric about an area in the east-central portion of the batholith and are generally parallel to the margins. This alignment pattern may be attributed to resurgent deformation, whereby successive pulses of magma forced previously-intruded, plastic material radially outward from the center of upwelling. Deformed dikes and annealed protoclastic textures corroborate this model of synplutonic deformation. Swarms of elongated xenoliths are tapered in the same direction in any given pavement exposure near the margin of the

batholith. On a batholithic scale the sense of tapering is in a counterclockwise manner. Convection early in the emplacement history of the batholith is a likely cause of this inferred component of magma motion, but convective flow was not vigorous enough to homogenize the contaminated marginal facies.

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CHAPTER I

INTRODUCTION

Purpose of Study

The Bald Rock Batholith, located in northeastern Union and southern Cherokee Counties, South Carolina, is one of a string of related granitic intrusive bodies in the crystalline Southern Appalachians. Of particular interest here is the excellent preservation of certain internal textures and structures that are commonly interpreted as igneous flow features. Explanation of a concentric fabric pattern and documentation of an apparent systematic directional component to these flow features have been major objectives of this study. Other aspects of this study include:

1) Field description of the Bald Rock Batholith and its enveloping rocks;
2) Petrographic description of the Bald Rock granite and related rocks;
3) Synthesis of a petrologic model for the emplacement of the batholith.

Previous Work

The only geologic investigations of the Bald Rock Batholith to date include reconnaissance maps by Wagener and Price (1975), Wagener (1977) and Speer (unpub.), a building stone resource description (Wagener, 1977) and a limited petrologic study (Speer et al., 1980). Overstreet and Bell (1965) did not distinguish the body from the surrounding gneisses on the state geologic map.

The country rocks were mapped in a portion of Cherokee County by Wagener and Price (1975) and in York County by Butler (1966). No recent account of the geology of Union County has been published to date.

Regional Geologic Setting

The Bald Rock Batholith is located at the junction of the Charlotte and King's Mountain Belts of the Southern Appalachian Piedmont Physiographic Province. The northeasterly-striking belts of the Piedmont are delineated on the basis of lithologic character, age and structure. The spatial relationships between the batholith and these belts are shown in Figure 1.

The Charlotte Belt is a zone of medium- to high-grade metamorphic and plutonic igeneous rocks (Overstreet, 1970; Hatcher, 1972; Tull, 1980). The dominant lithologies are gneisses, schists and amphibolites, all of which are heavily intruded by plutons of varying compositions and ages (Butler and Ragland, 1969; Overstreet, 1970; Hatcher, 1972; Speer et al., 1980).

A mid-Paleozoic (ca. 400 m.y.) metamorphic event brought originally layered volcanic and sedimentary rocks of late Precambrian age to the albite-epidote amphibolite facies (Overstreet, 1970; Hatcher, 1972). This event overprinted an early Paleozoic event, accounting for the large volumes of metaigneous rock in the Charlotte Belt (Hatcher, 1972; Tull, 1980). By Devonian time, the two recognized deformational phases had produced an anticlinorium, cored by middle Precambrian basement, that contained a series of isoclinal folds with steeply-dipping axial planes (Hatcher, 1972; Tull, 1980).

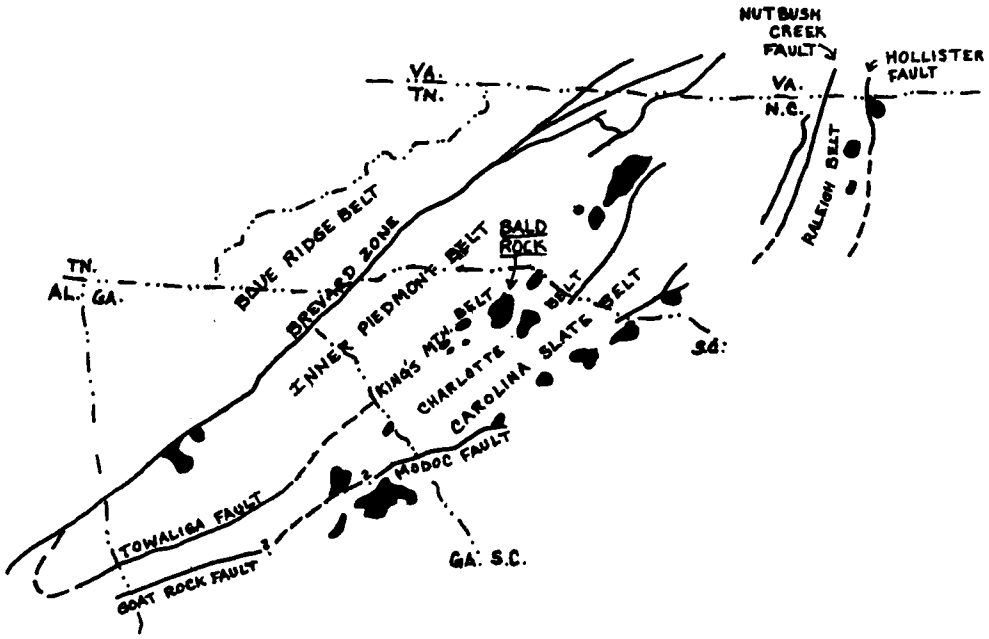


Figure 1. Map of the Southern Appalachians showing the location of the Bald Rock Batholith in relation to other postmetamorphic, coarse-grained granite plutons.

The King's Mountain Belt parallels the western margin of the Charlotte Belt in South Carolina. Rocks of the King's Mountain Belt are of lower metamorphic grade (biotite to garnet grade) than those of neighboring belts, and include amphibolite, quartzite, muscovite schist, metasiltstone, marble and intrusives of varying composition (Overstreet, 1970; Hatcher, 1972; Butler, 1966). The present study provides evidence that regional metamorphism probably reached sillimanite grade in the study area.

Structurally, the King's Mountain Belt is interpreted to be a synclinorium of late Precambrian to early Paleozoic metasedimentary and metavolcanic rocks, younger than those in immediately adjacent belts (Hatcher, 1972; Hatcher et al., 1980; Tull, 1980).

Details of relationships between most Piedmont belts are only peripherally known, but recent geophysical investigations suggest that the contact between the Charlotte and King's Mountain Belts, called the Central Piedmont Suture, is a "cryptic suture" separating the western allocthonous Inner Piedmont block from the autocthonous Charlotte Belt/Carolina Slate Belt block to the east (Hatcher and Zietz, 1980). The suturing event was either late Taconic or early Acadian, and predated the intrusion of the Bald Rock Batholith.

The Charlotte Belt has experienced the greatest amount of intrusive activity in the southern Piedmont. In northern South Carolina, about 75% of the exposed Charlotte Belt rocks are of apparent intrusive origin (Butler and Ragland, 1969). Rb-Sr whole-rock age determinations by Fullagar (1971) on samples from 25 plutons in the southern Piedmont corroborate field evidence that the plutons are of widely differing ages.

These ages tend to cluster into three groups with respect to the 400 m.y. peak of Charlotte Belt metamorphism: pre-, syn-, and postmetamorphic. It is important to note that the thermal peak of metamorphism was not the same in all areas of the Piedmont for any given metamorphic "event" (Tull, 1980); it is possible that thermal episodes were more sporadically distributed in time and space than previously thought (Butler and Ragland, 1969; Butler, 1972). At 388 m.y., the Bald Rock Batholith is one of the earliest post-metamorphic intrusions now recognized in the Piedmont (Speer et al., 1980). Other postmetamorphic granites are generally 325 to 265 m.y. old (Fullagar and Butler, 1979).

Compositions of the postmetamorphic group of plutons are variable (Speer et al., 1980), as are those of the other age groups (Butler and Ragland, 1969; Fullagar, 1971). Butler and Ragland (1969) recognized eastern and western subgroups among the postmetamorphic plutons that differ in terms of initial Sr^{87}/Sr^{86} ratios. A study of 24 post-metamorphic granitoid plutons in the southern Appalachians (including the Bald Rock) has demonstrated that, despite compositional differences, these granites bear similarities in texture, modal variation and in the nature of xenoliths, all of which may argue for a common intrusive history (Speer et al., 1980).

CHAPTER II

FIELD RELATIONSHIPS

Location of the Study Area

The study area occupies approximately 450 km^2 in portions of Union, Cherokee and York Counties in northwestern South Carolina. The Bald Rock Batholith has an outcrop area of 267 km^2 (see Geologic map, Plate I, in pocket). The area covers portions of the Pacolet Mills, Wilkinsville, Hickory Grove, Jonesville, Kelton, Lockhart, Union East and Union West U.S. Geological Survey 7.5 minute topographic quadrangles.

Physiography

The physiography of the study area is typical of this portion of the Piedmont. The area is severely dissected by a dendritic system of gullies. There appears to be a major drainage element in the direction of N20W, corresponding to an inferred fracture system noted in neighboring Newberry County by McCauley (1961). Relief in the study area is generally 100 to 200 feet.

Outcrops of fresh rock in this segment of the Piedmont are distressingly scarce (much less than 1% of the surface area) due to deep chemical weathering, which has produced thick mantles of lateritic soil and saprolite atop bedrock. The Bald Rock Batholith does not constitute a topographic high, but rather, has experienced the same degree of dissecton as its older enveloping rocks.

Sampling Method

Due to the aforementioned paucity of outcrops, systematic grid sampling techniques are impractical in this terrain. For this study, roadcuts, steamcuts and boulders in fields were equally important sources of samples as were the few quarries and flat-rock pavements in the area. South Carolina county road maps and U.S.G.S. 7.5 minute topographic quadrangles served as base maps.

Over 200 samples of Bald Rock granite and country rocks were collected in the study area. The locations of these samples, as well as a rough indication of the degree of weathering, are shown in Figure 2. More than one sample may have been taken at each station.

Samples of country rocks were collected to distances of a least 2 km in all directions from the margin of the batholith.

Description of the Country Rocks

King's Mountain Belt schists and gneisses flank the batholith on its western, northern and northeastern margins; to the east, south and southwest lie Charlotte Belt gneisses.

Foliation in rocks of both belts strike northeasterly. Although Wagener and Price's (1975) map of the Wilkinsville Quadrangle and Butler's (1966) map of York County deal with many of the same rock units at the northeastern margin of the batholith, their groupings of lithologies into map units is quite different, and hence difficult to correlate in the study area. Furthermore, it was not always possible to distinguish their units at the reconnaissance level. Therefore, I have devised a set of lithologic units that is similar to the usage of previous mappers

Figure 2. Localities of samples of Bald Rock granite and country rocks. Symbols indicate degree of weathering. Refer to geologic map (Plate I, in pocket) for explanation of units and for scale.

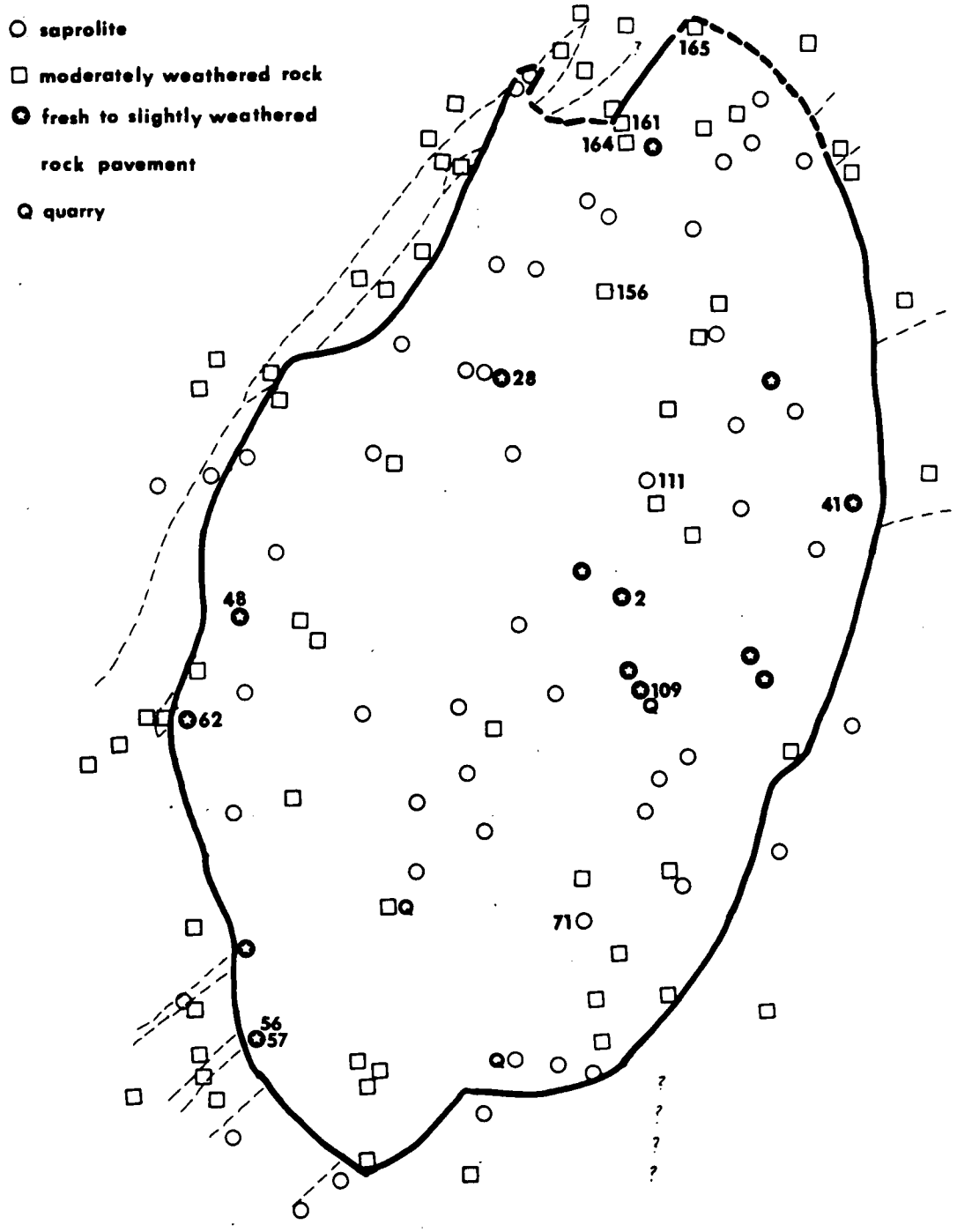

saprolite
moderately weathered rock
fresh to slightly weathered
rock pavement
Q quarry
165
161
164
156
28
111
41
48
2
109
62
71
56
57

Figure 2.

wherever possible, and arbitrarily combines some of the volumetrically less significant rock types into larger units that are appropriate to the map scale.

Most country rock lithologies were identifed in hand specimen only; however, 9 of the most common rock types, described below, were also examined in thin secton. Contacts between country rock units are based on sampling, and are only approximate since they are not exposed. Many lithologic determinations were made, of necessity, on samples of saprolite. A description of each map unit follows:

BRg Bald Rock granite

A light-gray, medium- to coarse-grained granite containing aligned K-feldspar megacrysts; described in greater detail in Chapter III.

amp amphibolite (Charlotte Belt)

A fine- to medium-grained, weakly foliated hornblende-plagioclase-microcline rock. This variety of amphibolite is probably metasedimentary. In contrast to the amphibolites of the mv unit described below, this type contains plagioclase grains that are larger than the hornblende grains, and lacks opaque minerals. In York County, this rock is interbedded with a very fine-grained, equigranular quartz-feldspar-hornblende rock which is probably a metasiltstone.

gn Granitic gneiss (Charlotte Belt)

A medium- to coarse-grained quartz-feldspar rock. Biotite, of significantly smaller grain size than quartz or feldspar, is common, usually in amounts less than 3 modal percent. Muscovite may or may not be present. Foliation is defined by mica grains

and by flattened grains of quartz and feldspar. Some gn may be metamorphosed intrusive rock.

dtn metamorphosed diorite and tonalite (Charlotte Belt)

These are speckled, medium-grained rocks of intermediate composition. Color index ranges from about 20 to 40. Major minerals are plagioclase, hornblende, biotite and quartz. Meta-diorite contains more plagioclase and hornblende, and less quartz than the meta-tonalite. As the names suggest, these units are probably metamorphosed intrusive rocks (Butler, 1966).

mv metavolcanic and related rocks (King's Mtn. Belt)

This unit comprises several distinct lithologies, which are finely interlayered (and probably folded) over the mapped area. The felsic members of this unit include a foliated leucocratic rock, a quartz-feldspar granofels interpreted by Wagener and Price (1975) as a metatuff, and a fine-grained, more obviously tuffaceous quartzofeldspathic rock with ferruginous cement. The mafic members of this unit include a microcline-free amphibolite that contains highly poikilitic, amoeboid hornblende in less abundance than the amp unit and is peppered with subhedral to euhedral magnetite grains; metagabbro and epidote-quartz veins. The igneous affiliation of these rocks is apparent.

qzt metaquartzite (Charlotte Belt)

Flattened grains of quartz constitute the bulk of this lithology. The rock is generally medium-grained and locally bears minor amounts of muscovite and hematite. The lack of feldspar suggests that this rock may be metasedimentary rather than metavolcanic.

Smg Santuck metagranite (Charlotte Belt)

A medium-grained, equigranular, massive to slightly sheared, leucocratic intrusive that grades imperceptibly into Charlotte Belt gneisses in the study area. The map boundary was taken directly from Wagener's (1977) map.

ms muscovite schist (King's Mtn. Belt)

This unit is characterized by strongly crenulated layers of muscovite separated by fine-grained segregations of quartz and feldspar. The rock has a distinctive bluish color in hand specimen. Trains of sillimanite needles and opaque rodlets preserve the crenulation of micaceous layers where cross-muscovite grains have grown in a later stress field. The quartzofeldspathic layers are infolded with the micaceous layers, indicating that they are of primary sedimentary (?) origin and not, as Wagener and Price (1975) suggest, the result of injection by the Bald Rock granite.

ss sillimanite schist (King's Mtn. Belt)

This strongly foliated unit contains quartz, muscovite and biotite as major constituents and is distinctive among the lithologies studied in its significant content of sillimanite. Quartz grains are flattened parallel to the foliation defined by the other minerals. Biotite, and more commonly, muscovite, cross the foliation as well as parallel it. Sillimanite in this and the adjacent ms unit is oriented parallel to foliation, and therefore was probably formed during regional metamorphism, possibly during the Paleozoic suturing event. This interpretation may provide

additional insight into the regional geologic picture, as studies of Overstreet (1970) and Hatcher (1972) restrict the occurrence of sillimanite in this portion of the Piedmont to the contact aureoles of large plutons. A temporary stress field may have been established during the intrusion of the Bald Rock Batholith, causing the recrystallization of some mica grains across the original foliation. If the sillimanite noted in the study area had also formed during contact metamorphism, then sillimanite grains would be expected to cross the foliation rather than parallel it.

Ugn undifferentiated gneisses (Charlotte Belt)

The major rocks of this unit include leucocratic (granitic to granodioritic) gneisses, hornblende gneisses (some of which may be more correctly designated dtn) and biotite gneiss. The classification of these various lithologies as a single "unit" is undeniably arbitrary and geologically unsound, but it is beyond the scope of this work to determine the complex relations among these Charlotte Belt rocks. Some contacts within this "unit" appear to be intrusive; others appear to be layered or folded, but intense weathering and paucity of outcrops make the relationships between lithologies difficult to determine at the reconnaissance level.

Description of the Bald Rock Batholith

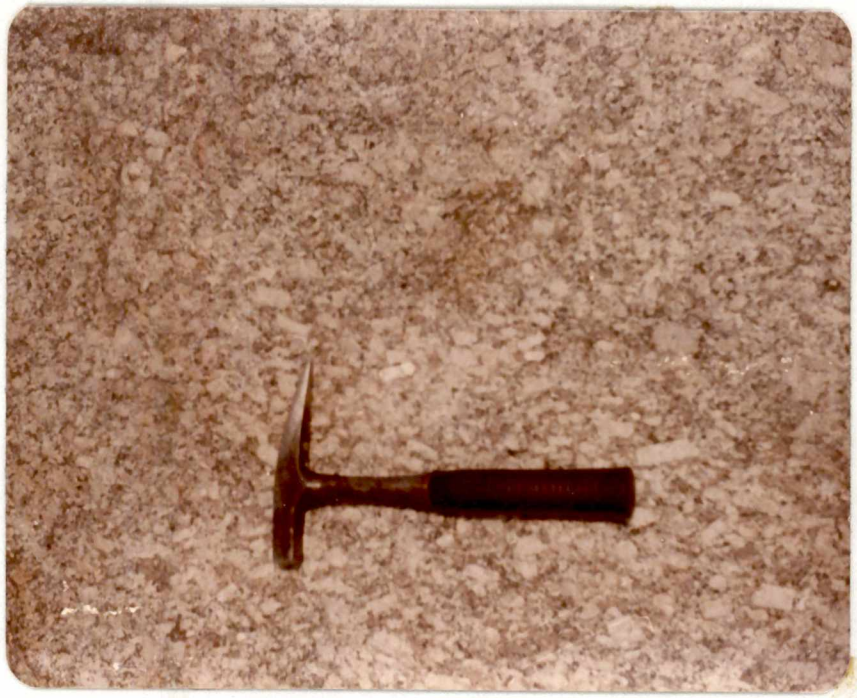
Exposures of Bald Rock granite range from large exposures of fresh rock through weathered boulders and saprolite to pebbly soil. The most

Figure 3. Pavement exposures of the Bald Rock granite.

a. Pavement exposure showing aligned megacrysts.

b. Tapered xenolith cut by a curved synplutonic alaskite dike.

a.



b.



Figure 3.

informative exposures are gently undulating pavements of fresh to slightly friable bedrock (Figure 3a and b). Pavements range in area from several square feet to about half an acre. Although they constitute only a fraction of the batholith's total outcrop area, 14 pavements provided an excellent two-dimensional view of most of the structures examined in this study.

Roadcuts expose numerous banks of saprolite, where the original fabric of the rock is preserved despite partial alteration of feldspars and mafic minerals to clays. Since K-feldspar megacrysts are usually only mildly altered in comparison to the groundmass minerals, their attitudes may be observed readily in the vertical dimension in roadcuts. Where weathering has been most severe, small, blocky pebbles of K-feldspar remain suspended in reddish-brown soil. These unweathered remnants of megacrysts impart a characteristic "knobby" texture to the soil and allow its identification, for mapping purposes, as Bald Rock residuum.

Contact Relations

The Bald Rock Batholith is a discordant intrusive body, as is evident from its map pattern (Plate I, in pocket). Nowhere is the contact between the batholith and country rock exposed in outcrop; however, some information is available from the rocks closest to the contact. Contact relations vary locally according to the type of lithology intruded. In most areas, contacts are inferred to be fairly sharp, as no exposures of transitional (partly assimilated) material were found. Dike swarms tend to be confined within the batholith and do not project into the country rocks, except perhaps at the northern margin. Anastomosing networks of felsic veinlets in biotite and hornblende gneisses near the southern and

southeastern margins are probably the result of thermally-induced granitization of the type noted by Bateman et al. (1963) at the margins of the Sierra Nevada Batholith. Since other country rock lithologies are not similarly affected, it is unlikely that these veinlets are injections of Bald Rock magma. The southwestern margin and portions of the eastern margin were particularly difficult to establish, as the intruded leucocratic gneisses are similar in appearance to the weakly porphyritic phase of the Bald Rock granite found locally.

Foliations in both country rocks and granite adjacent to the margin are parallel to the pluton boundary. Speer et al. (1980) observed this parallelism to be a general tendency among country rock fabrics immediately adjacent to other post-metamorphic plutons in the Piedmont. Granite samples from the margins of the batholith exhibit wider textural and compositional variety than samples from its interior, which suggests that there may have been some ion-exchange with the country rocks.

Enclaves

Elongate mafic xenoliths ranging in size from several centimeters to over 20 meters in length are distributed throughout the batholith (Figure 4, a and b). They are largest and most abundant nearest the margin. Xenoliths occur in swarms, with their apparent long axes aligned parallel to those of the megacrysts in the enclosing granite, and are generally tapered at one end. Biotite-rich schlieren are common in the interior of the batholith, and also parallel foliation.

Dikes

Several generations of dikes transect the granite, as is evidenced by crosscutting relationships. The oldest are felsic synplutonic dikes

Figure 4. Xenoliths in the Bald Rock Batholith.

a. Xenolith with rind and K-feldspar poikiloblasts.

b. Portion of a deformed xenolith showing disturbed internal foliation and impinging megacrysts.

a.



b.



Figure 4.

Figure 5. Dikes and xenoliths in the Bald Rock Batholith.

a. Ruptured synplutonic dike.

b. Xenolith offset by fracture.

c. Xenolith in wall of quarry, showing downward sense of tapering.

d. Deformed biotite schlieren.

e. Elongate xenoliths and schlieren from a location near the inferred center of upwelling.

f. Earlier-formed granite (dark) ruptured and deformed by later resurgent magma.

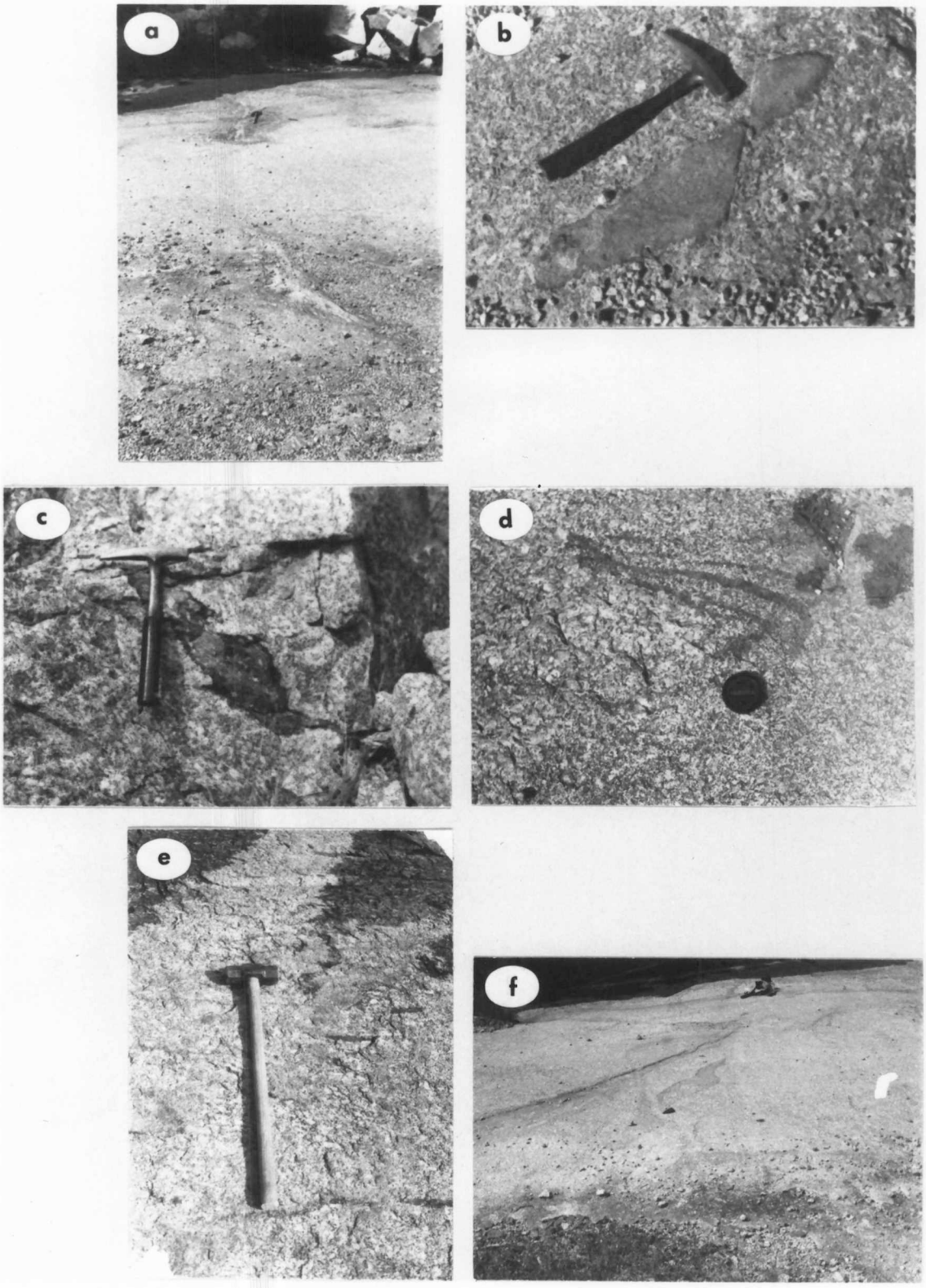


Figure 5.

(Figure 5a), recognized by irregular contacts, bending and interruptions. These dikes apparently intruded with sufficient force to rupture the semi-solid cooling granite, and were deformed by subsequent movement of the plastic granite. Similar occurrences were noted by Sylvester et al. (1978) in the Papoose Flat Pluton, California.

All other dikes have sharp, straight contacts (Figure 3b), suggesting that they were injected into fractures that formed after the Bald Rock magma had solidified. The dikes appear to be randomly oriented. The oldest of these dikes consist of fine-grained, equigranular granite, which is considered to be genetically related to the porphyritic facies of the Bald Rock granite. The dikes range in width from 0.5 m to about 8 m and have gentle to moderate dips. Concentrations of these dikes occur in the northern and southern portions of the batholith. These dikes may represent residual, vapor-rich Bald Rock magma that was deflected outward around a superincumbent plug of solidified porphyritic granite during injection, and found its way into existing marginal fractures (Speer, pers. comm., 1979). This model is supported by screens of coarse-grained granite that are partially or completely engulfed by this fine-grained phase.

A later series of medium-grained, hypidiomorphic granular alaskitic dikes is present throughout the batholith. These dikes are generally thinner (1 to 16 cm) than the granitic dikes and dip steeply. The broadest of these dikes often possess fine-grained chilled margins with pegmatitic centers, and sometimes have mafic-rich selvages. They rarely continue for more than a few tens of meters in pavement exposures. There is little or no offset of xenoliths cut by these dikes (Figure 3b).

The liquid that formed these dikes may be a later, more highly fractionated derivative of the residual Bald Rock magma.

Diabase dikes are the youngest generation recognized. They probably were intruded during the regional episode of tensional faulting that occurred in the late Triassic (Hatcher, 1972). Exposures are too poor to allow determination of their attutudes or continuity.

Fractures and Faults

Dikes are the most obvious evidence of fracturing. Thin fractures lined with alteration minerals were found in most pavements, but only in one instance (Figure 5b) could offset be observed. Since the fractures do not always intersect discrete structures such as xenoliths or dikes, in which case offsets would be obvious, minor offsets within the granite may actually be common.

Dilation joints, subparallel to the surface, cause the granite to weather into thin sheets in pavement exposures.

Geophysical Expression

Regional surveys of gravity, magnetics and radiation provide additional information concerning the shape of the batholith and relationships with the country rocks.

Gravity data of Hatcher and Zietz (1980) show a Bouguer anomaly of -19 to -39 mgal over the batholith (Figure 6a). A negative anomaly is expected for such a large granitic body, and the lack of steep gradients indicates that the batholith is intruded into rocks of similar densities. The pattern of deflected contours over the batholith is too weak to give an indication of the 3-dimensional shape of the body.

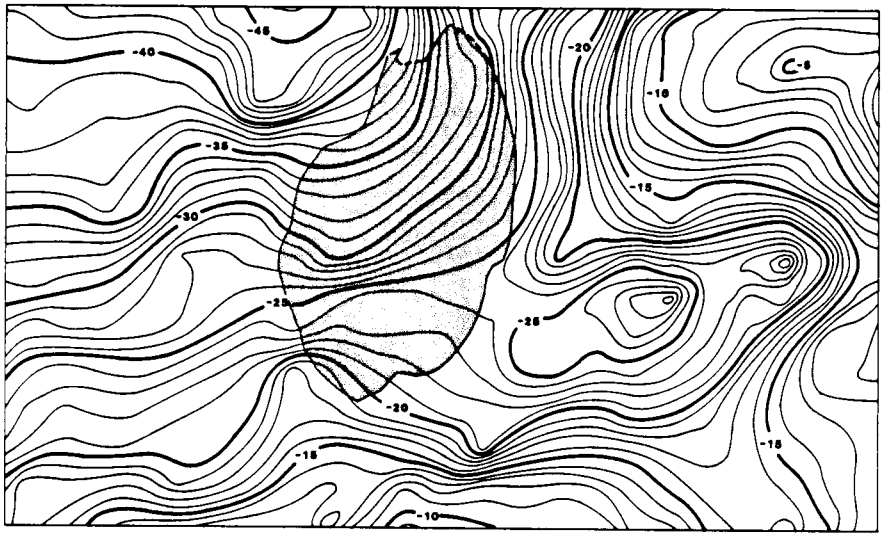
Figure 6. Geophysical data for the Bald Rock Batholith and environs. Shaded region represents outcrop area of the Bald Rock Batholith.

a. Gravity profile.
Contour interval = 5 mgal.
Data from Hatcher and Zietz (1980).

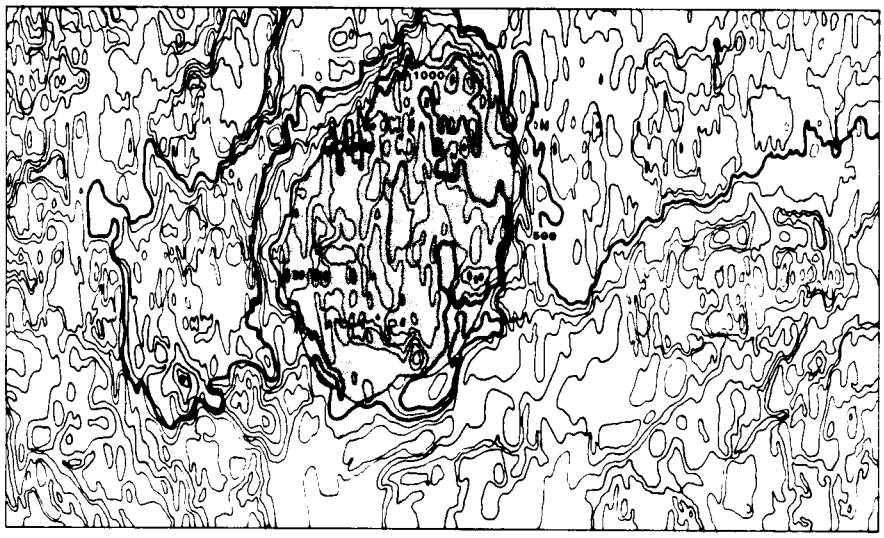
b. Aeromagnetic profile.
Contour interval = 100 gammas.
Data from U.S.G.S. Open File Report.

c. Aeroradiation profile.
Contour interval = cts. per sec.
Data from U.S.G.S. Open File Report.

A



B



C

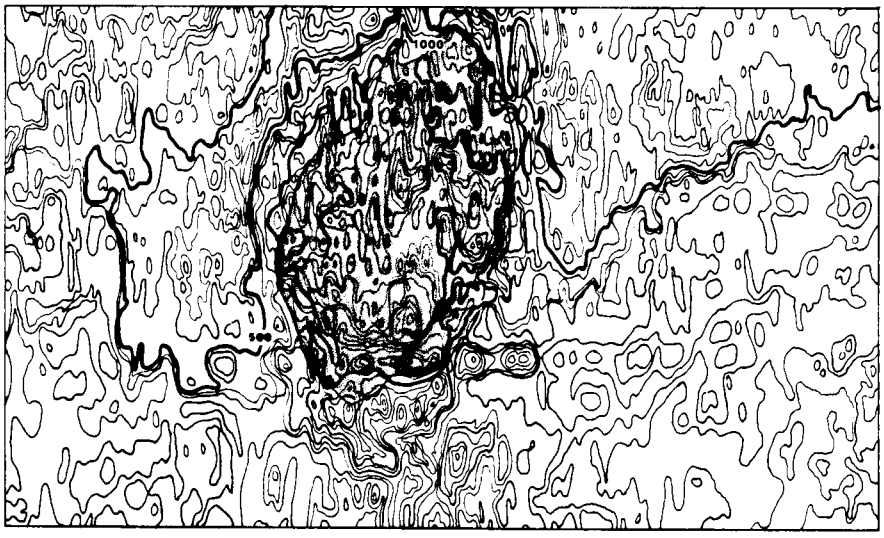


Figure 6.

Aeromagnetic and aeroradiation profiles for the Spartanburg 2° quadrangle from the U.S.G.S. open file report show more interesting patterns. A strong positive magnetic anomaly of about 600 gammas coincides rather well with the boundaries of the batholith mapped in this study (Figure 6b). This effect is presumably caused by the high content of magnetite in the Bald Rock granite relative to many of the country rock lithologies.

The aeroradiation profile also coincides well with the mapped contacts of the batholith. The body stands out as a radioactive high, generally about 500 cts. above the country rocks (Figure 6c). This positive anomaly is caused by the high content of radioactive accessory minerals (e.g., xenotime, thorite, monazite, allanite) in the granite as compared to the surrounding lithologies (Speer, pers. comm. 1979). Similarly high anomalies are associated with the other local, post-metamorphic granites due to the tendency for such highly differentiated magmas to be enriched in U, Th, etc.

From a combination of geohysical and field data, Speer et al., (1980) infer that the shape of the Bald Rock Batholith in three dimensions is a steep-walled elliptical pipe.

CHAPTER III

PETROGRAPHY OF THE BALD ROCK BATHOLITH AND ITS ENCLAVES

Mineralogy

Detailed examination of 14 thin sections and 6 slabs of the Bald Rock granite provided mineralogic and textural information. This is an admittedly small number of samples for a body of this size, but no other samples of fresh rock were available.

K-feldspar is the most abundant constituent of the Bald Rock granite, accounting for 25 to 50 modal percent of the anlyzed smaples. It has two habits: as euhedral to subhedral megacrysts ranging in size from about 0.5 to 7 cm in length and as anhedral groundmass grains averaging 0.4 mm in diameter.

Most K-feldspar grains exhibit microcline grid twinning. Megacrysts are usually twinned according to the Carlsbad law as well. Megacrysts are perthites and microperthites. Speer et al.(1980) also reported the presence of cryptoperthites in southern Appalachian postmetamorphic granites. Exsolved albite appears as anastomosing networks of stringers and blebs in the perthites and microperthites.

Tabular megacrysts are elongated parallel to their c axes. They tend to be poikilitic, enclosing grains of plagioclase, biotite, quartz and other microcline grains. Elongate inclusions tend to be arranged with their long axes parallel to the growth faces (generally 010) of the compositionally-zoned megacrysts (Figure 7a). Such inclusions, most commonly of plagioclase, tend to be concentrated in conentric zones.

Figure 7. Photomicrographs of Bald Rock granite.

a. Oriented inclusions of plagioclase in microcline.

b. Myrmekite fans projecting into microcline megacryst.

c. Mafic clot of biotite, titanite and epidote. Inclusions are apatite and zircon.

d. Two intergrown grains of allanite with epitaxial rim of epidote. The tiny round grain in center is zircon. {hk0} faces of biotite grains are intergrown with quartz.

e. Fine-grained granite.

f. Hornblende-biotite xenolith.

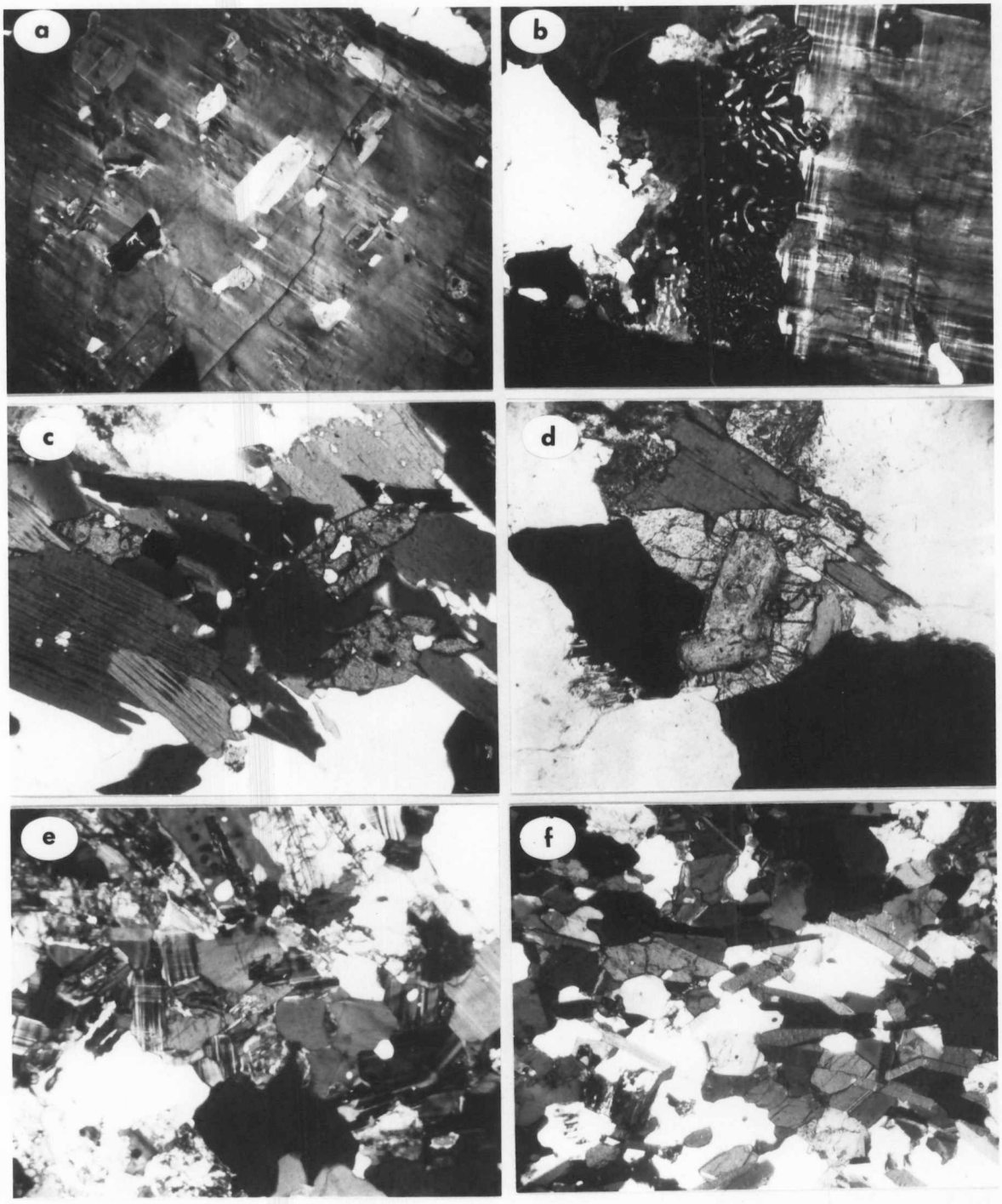


Figure 7.

Distances between zones within a single megacryst are variable, but are usually similar among megacrysts in a given slide. Such a distribution of inclusions is apparently common in megacrysts from rocks of granitic to intermediate compositions. Similar occurrences are documented in other postmetamorphic granites in the Piedmont (Speer et al., 1980), in the Sierra Nevada Batholith (Bateman et al., 1963; Kerrick, 1969) and in the Okanogan Range of Washington State (Hibbard, 1965).

Plagioclase generally constitutes 30 to 40 modal percent of each sample. It has 4 modes of occurrence: as subhedral to anhedral groundmass grains averaging 0.5 mm in diameter; as subhedral phenocrysts that are intermediate in size between groundmass grains and coexisting K-feldspar megacrysts; as euhedral to subhedral oriented inclusions in microcline megacrysts; and as the host phase to quartz blebs in myrmekite (Figure 7b).

Nearly all plagioclase grains are twinned according to the albite law; larger grains often combine the albite and Carlsbad laws. Pericline twinning is rare.

Compositional determinations by the Michel-Levy maximum extinction angle method reveal that the plagioclases are zoned. Oligoclase cores (An_{28-29}) grade normally or oscillate to less calcic (An_{10-15}) rims. Discontinuous rims of albite are common on plagioclase grains in the groundmass and as inclusions in microcline. These rims may be untwinned, twinned in continuity with the lamellae of the core, or twinned with lamellae offset with respect to those of the core.

Hibbard (1965) found that plagioclase inclusions in microcline megacrysts, while themselves normally zoned, were additionally more

calcic if located in megacryst cores and more sodic if located toward the rims. The model he proposed for this phenomenon is as follows: during the crystallization of the magma, growing plagioclase grains came into contact with K-feldspar grains and became attached when their growth faces (usually {010}) met. The more rapidly-growing K-feldspar grains entrapped the plagioclase grains resting along their growth surfaces. An alternate hypothesis for the origin of these plagioclase inclusions is that they are the result of sporadically-distributed epitaxial nucleation on the growth surfaces of microcline grains. In many cases, subsolidus reaction between the plagioclase and microcline has produced irregular albite rims around the inclusions.

There is evidence for saussuritization in almost all of the samples examined, but it is most advanced in the fine-grained facies, probably due to a higher water content in this late magmatic fluid. Flecks of sericite and epidote tend to be concentrated in the calcic cores of the plagioclase grains.

Quartz constitutes 16 to 31 modal percent of the Bald Rock samples. It typically occurs as anhedra in the groundmass. Grains range from 0.6 to 5 mm in diameter. Undulatory extinction is a common feature, ranging in intensity from sweeping extinction of 5° rotation or less to domained extinction, which is indicative of incipient polygonization. The number of crystallographic subindividuals within a deformed grain is difficult to determine, because the boundaries between sectors are diffuse, but when annealing recrystallization is complete the number of discrete new grains froming from a given parent grain is generally small. Inclusions of microcline and biotite are fairly common.

Biotite is the major mafic phase of the Bald Rock granite, forming up to 5 modal percent of the samples studied. Individual grains range from 0.5 to 2 mm in length. Biotite occurs interstitially to the feldspars and quartz, and as inclusions in these minerals.

Biotite {hk0} faces are ragged. Pleochroism ranges from wheat color to deep olive green. Microprobe analyses of Speer et al. (1980) show that compositions of Bald Rock biotites fall approximately midway between phlogopite and annite (molar Fe/Fe+Mg = 0.52) and exhibit a range of tetrahedral aluminum contents (2.1 to 2.4 mole percent) that is somewhat lower than those of other Southern Appalachian postmetamorphic granites. Unlike most of the related plutons studied by Speer et al. (1980), biotites show no systematic compositional variations from the core to the rim of the batholith.

The most common form of biotite alteration is a symplectitic intergrowth with quartz and muscovite, involving the {hk0} faces of both mica species. Muscovite forms from biotite concomitant with the release of mafic ions, which contribute to the formation of secondary epidote and chlorite in the slides studied. Chlorite tends to remain interleaved with biotite in situ, while epidote forms either webby or discrete grains in close proximity to the parent biotite.

Amphibole is present in only a few samples and is volumetrically trivial. The possiblity that all of the amphibole found in the Bald Rock granite is secondary is discussed in a later section of this chapter. Subhedral prismatic grains are approximately the same length as coexisting rains of biotite. An occasional grain is twinned on {100}.

The pleochroic scheme is in shades of green, usually with a bluish tinge as compared to biotite. Analyses of Speer et al. (1980) indicate compositions in the ferroedenitic hornblende range of Leake (1978). Molar Fe/Fe+Mg for the amphiboles (0.56) is nearly the same as the ratio for coexisting biotites. The absence of amphibole in most samples may be due to the presence of sufficient fluid during crystallization to stabilize biotite at the expense of hornblende (Speer et al., 1980; Fyfe, 1970).

Two generations of titanite are found in Bald Rock specimens. Where it occurs as a primary phase, titanite forms subhedral to euhedral wedge-shaped grains that average 1 mm in length. These are often included within individual biotite grains. Secondary titanite forms anhedral to subhedral poikilitic grains and smaller, rounded granules. Granular titanite occasionally forms a beaded rim on magnetite and ilmenite grains. These oxides probably provided the Ti necessary for titanite formation throught precipitation. Another possible source of Ti is biotite, which contains between 1.04 and 2.27 weight percent TiO_2 (Speer et al., 1980). Titanite occurs most frequently in mafic clots, where it is in close proximity to biotite (Figure 7c). Apatite, zircon, allanite and opaque minerals occur as inclusions in primary titanite. Secondary titanite also encloses biotite and epidote.

Two generations of epidote exist. Matrix epidote occurs in irregular (webby) intergrowths with biotite in mafic clots and as epitaxial rims around allanite (Figure 7d). Speer (pers. comm., 1979) contends that the formation of this generation of epidote is a post-consolidation reaction, or possibly occurs at a very late magmatic stage.

The second paragenesis is as a saussuritization product of plagioclase, and is recognizable as small flecks in the cores of plagioclase grains. Analyses of Speer et al. (1980) show that saussurite epidotes are consistently lower in Fe (9 to 19 mole percent pistacite) than matrix epidotes, which average 30 mole percent pistacite.

Muscovite has the same two parageneses as epidote. In the first, discrete poikilitic or skeletal grains of muscovite either partly surround biotite grains or interfinger with biotite and quartz in the aforementioned symplectitic intergrowth. Muscovite of this generation is spatially associated with its parent biotite and is similar in size.

Shreds of sericite in the cores of plagioclase grains clearly belong to the second paragenesis. The term sericite is used here because the composition of this fine-grained material departs significantly from that of ideal muscovite in terms of its high Na content (Speer et al., 1980)

Allanite is a ubiquitous primary accessory phase. Its grain size varies markedly, from tiny inclusions in biotite to grains which are several millimeters in length. Allanite is typically euhedral. Color varies from deep reddish orange to pale yellow, and grains are often cloudy. Concentric compositional zoning is common, as are concentric epitaxial overgrowths of matrix epidote (Figure 7d). The epidote structure of allanite apparently provided favorable nucleation sites for the later-forming epidote, aided by the typical spatial association of allanite and biotite.

Zircon and opaque minerals occur as inclusions in allanite (Figure 7d). It is possible that some of the rimless yellowish grains of high relief,

particularly those that form inclusions in other minerals, are actually monazite. The presence of monazite has been confirmed in related plutons (Speer et al., 1980), but it is difficult to identify positively by optical methods.

Zircon is easily recognized by its high relief and birefringence. It forms rounded or pellet-shaped grains that are generally smaller than 0.05 mm. Most zircons occur as inclusions in biotite, where they are surrounded by pleochroic haloes, and in epidote and allanite. Some of the so-called zircons may actually be radioactive accessory minerals such as thorite and xenotime, but they could not be distinguished optically. These and several U-bearing minerals are fairly common as accessories in other postmetamorphic granites (Speer et al., 1980).

Another accessory mineral associated with biotite is apatite. It occurs as subhedral to euhedral grains from 0.01 to 0.1 mm in length. An early crystallizing phase, apatite forms inclusions in all of the aforementioned minerals except allanite.

Rounded opaque grains are relatively scarce in the coarse phase of the granite, and are typically in spatial association with other mafic minerals. Specks of opaques in chlorite may be ilmenite that precipitated from the breakdown of biotite. Hematite and rutile are also byproducts of biotite breakdown. Tiny opaque inclusions in allanite and zircon are probably esoteric rare-earth or uranium minerals such as coffinite (Speer, pers. comm., 1979).

Magnetite is the predominant opaque phase, although ilmenite, pyrite and chalcopyrite were also found. Opaque minerals are more abundant in the fine-grained granite. Fine-grained, intrusive granite phases in

other postmetamorphic plutons of South Carolina contain molybdenite (Speer, 1978), and its presence in the Bald Rock is suspected due to the similarity of the Bald Rock's fine-grained phase to those of the other plutons. No molybdenite was found in the samples studied; however, the volume of fine-grained material was insufficient to rule the presence of molybdenite in the batholith.

Isolated subhedral pink garnets were found in two of the fine-grained specimens. The garnet is a spessartine-almandine solid solution (Speer et al., 1980) that is stable under late-magmatic, fluid-enriched conditions due to its high Mn content.

Textures

Coarse-grained Granitic Rocks

Microcline megacrysts up to 7 cm in length characterize this textural phase of granite. The broad {010} faces of the tabular megacrysts usually define a foliation. Megacrysts are embedded in a hypidiomorphic-granular to seriate matrix of microcline, plagioclase, quartz and ferromagnesian minerals. The overall texture is porphyritic. The average grain size of the groundmass is 1.5 to 2 mm. Megacrysts account for 5 to 33 percent by volume of the rock.

In samples with high color indices, biotite and hornblende grains are oriented parallel to the megacrysts. These samples are generally from the margins of the body. In rocks with moderate to low color indices, the ferromagnesian minerals are either randomly oriented or weakly foliated sub-parallel to the long (c) axes of neighboring megacrysts. Bateman et al. (1963) suggest that this phenomenon results from the

systematic expulsion of existing biotite grains away from the growing faces of the megacrysts; this process would tend to concentrate biotite (and all other matrix minerals) at the peripheries of the megacrysts and cause some alignment of elongate phases. If this process was indeed active, then Hibbard's (1965) model for the origin of plagioclase inclusions in megacrysts is unlikely.

Where alignment is absent, subsequent movement of liquid between the megacrysts may have occurred prior to complete solidification of the magma.

Ferromagnesian phases and the accessory minerals (e.g., apatite and zircon) that tend to be associated with them are generally found together in mafic clots (Figure 7c, d, p.29). Alteration products (muscovite, epidote, titanite) are frequently found intergrown with biotite, as discussed earlier. Rare chlorite is found partly rimming or interleaved with biotites from the central portion of the batholith only. Putman and Alfors (1969) noted a similar restriction of chlorite to the core of the Rocky Hill Stock, and attributed it to the protracted presence of residual fluids in the core.

Contacts between grains of microcline and plagioclase are irregular, and those between quartz and feldspar grains are even more so, often sutured in a lobate manner. Quartz-quartz contacts are more often serrate, controlled by the tendency of quartz to polygonize in response to directed stress.

Evidence of protoclasis (clastic deformation of grains in an incompletely solidified magma) is present to various degrees in all coarse-grained samples examined. Granulated matrix material is common

throughout the batholith, but granulation was either more intense or better preserved at marginal localities 56 and 41 (Figure 2, p. 9). Quartz grains show the most evidence of granulation, but any fractures that may have formed were healed by annealing recrystallization. The cause of protoclasis in the Bald Rock Batholith is discussed in Chapter IV.

Other protoclastic structures include slight kinking of twin lamellae in plagioclase and slight bending of a few biotite grains. Strained minerals that have not recrystallized (or recrystallized minerals that have experienced subsequent stress) exhibit undulatory extinction. Almost all of the quartz grains and many of the matrix feldspars are undulose to some degree. Curiously enough, microcine megacrysts are never undulose. Deformation of incompletely solidified interstitial material during protoclasis may have dissipated the applied stress sufficiently so that the megacrysts were effectively cushioned from much of the shear.

Myrmekite is most widely developed in samples with well-preserved protoclastic texture. Plug-like projections of myrmekite radiate into microcline grains (usually megacrysts) from the sheared groundmass (Figure 7b, p. 29). Many of the plugs have thin albite rims. Host plagioclase grains are sometimes mechanically twinned. The spatial association K-feldspar and myrmekite, and the affinity of myrmekite for sheared rocks was described by Shelley (1964), who maintained that the albite exsolved from perthitic microcline under stress, and quartz grains in the granulated groundmass were incorporated into and deformed by recrystallizing albite patches. In a more recent and comprehensive review, Phillips (1974) supported the idea that myrmekite results from

the solid state exsolution of quartz and plagioclase from the hypothetical $CaAl_2Si_6O_{16}$ molecule, which is presumed to be present in perthitic K-feldspar. Finger-like outgrowths of biotite into microcline and symplectitic intergrowths of biotite and quartz are present in all myrmekite-bearing specimens, in an association described by Williams et al. (1954).

There is strong evidence for thermal recrystallization (annealing) in the east-central portion of the batholith. Incipient development of granoblastic texture in samples 2C and 111 (Figure 2, p. 9) is indicated by an overall poikilitic matrix in which groundmass grains enclose rounded blebs of other groundmass phases. Triple junctions are present, but the texture has not developed to the point where they are common. Reheating from resurgent magma in this area is probably responsible for this texture; however, the thermal effects are not so great as to obscure evidence of earlier protoclasis.

Fine-grained Granitic Rocks

The fine-grained phase of the Bald Rock granite is richer in quartz and plagioclase and concomitantly poorer in K-feldspar than its coarse relative. Color index is also generally lower (3). Accessory minerals, particularly allanite, are more abundant (partly at the expense of titanite, which is nearly absent in the fine-grained phase), as are alteration minerals and textures. Speer et al. (1980) attribute these differences to higher concentrations of fluid associated with the intrusion of the late (fine-grained) phase. The presence of garnet indicates that the later magma was also relatively enriched in Mn and Al.

Textures are hypidiomorphic-granular to slightly seriate (Figure 7e, p. 29). Average grain size is 0.8 mm.

Plagioclase and some microcline grains are subhedral. Quartz is always anhedral and sometimes amoeboid. Intergranular contacts are often finely sutured, indicating localized post-consolidation recrystallization. Migration of components during the restructuring process was probably facilitated by the coexisting post-magmatic fluids.

Alteration features include the widespread saussuritization of plagioclase (oligoclase), the development of epidote rims on allanite and the formation of poikilitic muscovite.

Order of Crystallization

Textures in the coarse-grained phase indicate that the earliest minerals to crystallize were apatite, zircon and some magnetite, which are found as inclusions in all other minerals. Allanite and primary titanite began to crystallize shortly thereafter. The first major phase to crystallize may have been plagioclase, as suggested by its subhedral outlines where it borders quartz and microcline. Formation of K-feldspar (orthoclase, which underwent subsolidus inversion to microcline) began shortly (?) after that of plagioclase. It is not necessary to postulate early crystallization of K-feldspar to explain the presence of megacrysts: in a granitic system, K-feldspar has a nucleation rate roughly equivalent to those of other phases, but its growth rate is two orders of magnitude greater than comagmatic phases (Swanson, 1977). Hence, it may be expected to form larger grains than would other phases under normal conditions of crystallization. The inclusions of plagioclase within the megacrysts demonstrate that there was a large number of slowly-growing plagioclase nuclei coexisting in the magma with a few

rapidly-growing K-feldspar grains (Hibbard, 1965). The compositional zoning of both feldspars, in combination with the zonal distribution of plagioclase inclusions on all growth faces of microcline megacrysts may be construed as evidence for the involvement of liquid (magma) in the formation of this texture and, in a broader sense, in the formation of the Bald Rock granite. The presence of two discrete feldspar phases indicates that this is a sub-solvus granite (Tuttle and Bowen, 1958). Biotite began to crystallize next, as it forms inclusions only in the outer zones of megacrysts. The paragenesis of amphibole is discussed later in this chapter.

The timing of the appearance of quartz on the liquidus is difficult to pinpoint. The tendency for quartz to recrystallize into smaller grains is so great that any evidence of quartz phenocrysts such as the bipyramids found in the Rocky Hill granodiorite of California (Putman and Alfors, 1969) would have been destroyed by protoclasis and annealing. Quartz inclusions are found in the outer zones of microcline megacrysts and in some groundmass plagioclase and microcline, indicating that the three minerals co-crystallized at least in the final stages of solidification.

Muscovite, epidote and poikilitic titanite are all late-magmatic and secondary in paragenesis. Chlorite is secondary, as are the opaque minerals associated with the micas.

The crystallization order of the fine-grained phase was similar to that of the coarse-grained phase.

Mafic Inclusions

Discrete enclaves of mafic-rich rock are distributed throughout the batholith. Petrographic information from two samples (I56D, 57; Figure 2, p. 9) suggest that these are pieces of country rock that were thermally metamorphosed as a consequence of their entrapment by the intruding magma.

Sample 57, from the southwestern margin of the batholith, contains about 45 modal percent plagioclase (oligoclase), 33% hornblende, 17% biotite, 1% microcline and 4% minor and accessory minerals (allanite, epidote, zircon, apatite, opaques). Average grain size is 0.7 mm.

Biotite and hornblende have a preferred orientation (Figure 7, p. 29) that is too weak to call a foliation. Both biotite and hornblende have idioblastic margins against plagioclase. Microcline forms poikiloblasts that are megascopically similar to the megacrysts in the surrounding granite, and might be misconstrued as xenocrysts in the field. The poikiloblasts, however, are smaller, blocky rather than tabular, and are not aligned. Titanite forms smaller, subhedral to amoeboid poikiloblasts. A large amount of apatite is associated with biotite. The occurrence of epidote as epitaxial rims on allanite and as discrete grains is the same as in the granite, but epidote in this inclusion tends to be in contact with hornblende rather than with biotite.

Deformation textures include undulose and crackled plagioclase as well as slightly kinked biotite and plagioclase twin lamellae.

Examination of hand specimens of xenolithic material from pavement localities 48 and 49 (Figure 2, p. 9) reveals that both biotite and

hornblende are present. It is likely that the protolith for this type of xenolith was an amphibolite derived from the adjacent King's Mountain Belt.

Sample 156D, a xenolith form the north-central portion of the batholith, is distinctly different from 57. It contains 34% biotite, 23% oligoclase, 15% quartz, 8% epidote, 8% titanite, 5% microcline, 4% muscovite and 3% accessory hornblende, zircon, allanite and opaque minerals. Mineral habits are similar to those of the biotite-hornblende xenolith, 57.

A moderate foliation is defined by biotite. K-feldspar poikiloblasts are larger and more tabular than those of 57. Foliation is deflected around large (up to 1 cm), lenticular aggregates of quartz and of quartz+plagioclase+microcline. These are, respectively, deformed pebbles of quartzite and a felsic igneous rock, indicating that the protolith was a clastic rock, probably a graywacke. Xenoliths from the northern, eastern and central portions of the batholith are all of this type.

Although no meta-graywackes are found among the country rocks, the xenoliths may have been derived from some depth or from the (now eroded) roof zone.

Metasomatism introduced potassium into both types of xenoliths, producing biotite and K-feldspar. Addition of sodium to the xenoliths is probably responsible for the oligoclase composition of the plagioclase, as this is an unusally sodic composition for such mafic rocks. Depletion of felsic components from the magma immediately surrounding the xenoliths produced a residual mafic rind around them (Figure 4 a, b, p. 19).

Modal Data and Classification

Modal analyses were performed on 9 fresh samples from the batholith. Locations of samples are shown in Figure 2 (p. 9). Six of these samples (2C, 48B, 41, 56A, 56B, 109), from the porphyritic phase of the batholith, were so coarse-grained that reasonable modes could be obtained only from stained slabs. Slabs were stained for K-feldspar with sodium cobaltinitrite and for plagioclase with amaranth red according to procedures outlined by Hutchison (1974). The smallest slab area was about 9000 mm^2, more than large enough to minimize error according to Chayes (1956). A 3 mm grid was penciled directly onto the slab surface and at least 1000 points were counted on each slab with the aid of a binocular microscope. To further reduce error caused by misidentification of some poorly-stained minerals, each point count was performed twice on each slab and the results were averaged.

The presence of myrmekite and granulated matrix material certainly introduced some error into the slab analyses. As mafic minerals could not be distinguished from one another in the slabs, only estimates of color index could be determined. Relative abundances of dark minerals were, however, estimated from thin sections of the same samples.

The remaining three samples (71, 164, 165) were sufficiently fine-grained that their modes could be tallied from thin sections. At least 1000 points were counted on each thin section.

Complications due to alteration were partially circumvented by counting grains of secondary minerals as their unaltered precursors where

the secondary minerals were present within the grain boundaries of the original mineral. For example, grains of sericite and epidote in suassuritized plagioclase were counted as plagioclase.

Modes for all 9 samples are presented in Table 1. Estimated analytical errors average 3% relative 2σ, according to the graph of Van der Plas and Tobi (1965). The use of this graph, however, is not strictly applicable to the analyses of the porphyritic samples since its use requires that the size of the grid used in the point count is larger than the largest grain in the samples counted. This procedure was not followed in this study due to the large size of the megacrysts with respect to the groundmass grains. Such a technique would require prohibitively large slab areas. Therefore, the error estimate given is at best a minimum estimate.

The amounts of quartz, alkali feldspar and plagioclase, normalized to a total of 100%, were plotted on the Q-A-P triangle shown in Figure 8. Following the I.U.G.S. system of nomenclature for plutonic rocks developed by Streckeisen (1975), the majority of these samples may correctly be termed granites. The fine-grained samples consistently appear to be more quartz- and plagioclase-rich than the porphyritic phase, at the expense of K-feldspar. It is possible that the magma was depleted of K-feldspar components during the crystallization of the porphyritic phase. Two samples, both from marginal locations adjacent to mafic country rocks, fall into the quartz monzonite field. These compositions are similar to the bulk of analyses from other granite plutons in the Piedmont (shaded area of Figure 8). The relationship between the mode of a rock and its location is discussed in the next section.

TABLE I

Modes of Selected Samples

Sample No.	% Ksp	Pl	Qtz	Bio	Hbl	Ttn	Msc	Acc	
41	41	35	15	4	1	2		2	all, epi, apa, zir, opq
2C	41	29	25	4		1		1	all, epi, apa, zir, opq
48B	33	36	27	3		1		1	all, epi, apa, opq, zir
56A	50	30	13	4	tr	2	1	tr	apa, opq, zir
56B	43	31	20	3	tr	2		1	apa, opq, zir
109	38	34	22	4		1	1	1	all, epi, apa, opq, zir
71	25	41	30	2			1	1	all, epi, opq, zir, apa
164	27	38	25	6			3	1	all, epi, opq, zir, apa
165	29	29	31	6			3	2	all, epi, opq, gar, apa, zir

Figure 8. Compositional classification of Bald Rock samples using the I.U.G.S.-approved nomenclature for plutonic rocks (Streckeisen, 1975). Apices of triangle are quartz (Q), alkali feldspar (A) and plagioclase (P). Locations of samples are shown in Figure 2 and complete modal analyses are presented in Table 1. Shaded area reprsents the compositional range for 24 Southern Appalachian postmetamorphic plutons studied by Speer et al. (1980).

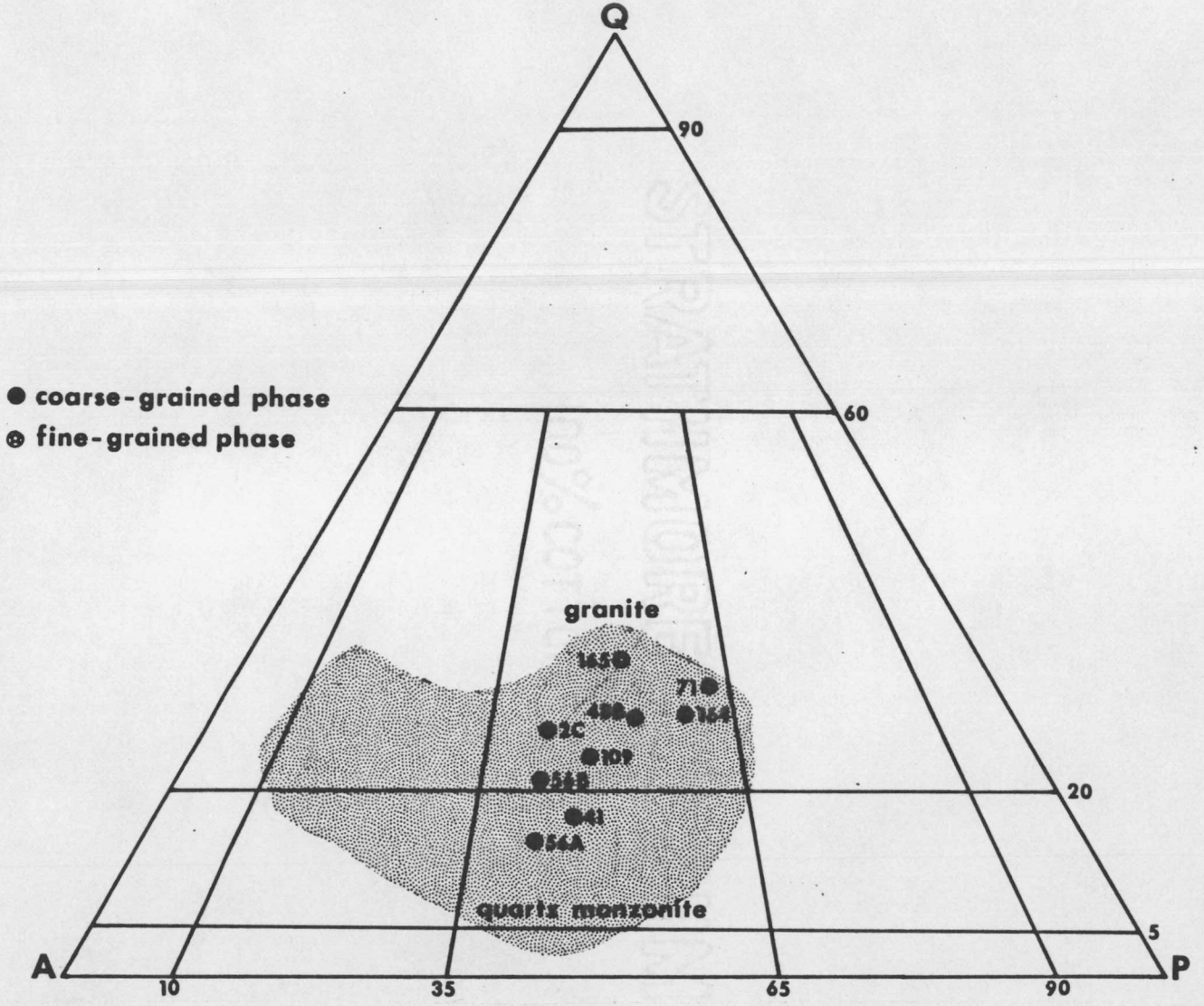

Q
90
60
20
5
A
P
10
35
65
90
● coarse-grained phase
⊛ fine-grained phase
granite
quartz monzonite

Figure 8.

Identification and Distribution of Textural Variants

Examination of hand specimens from locations throughout the batholith reveals textural and compositional inhomogeneities, seen as variation in grain size and in the relative amounts of megacrysts and dark minerals. Five mappable divisions were made in the coarse-grained, porphyritic facies. These are as follows:

I) 5-33% large (>2 cm) tabular megacrysts of varying size in a medium- to coarse-grained hypidiomorphic-granular groundmass. Color index (C.I.) ranges from 1 to 5. This is the most common textural type in the batholith;

II) 17-20% small (<2 cm) subequant megacrysts of equal size in a dark, foliated and granulated groundmass, C.I. = 6-7;

III) 10-15% large (≥3 cm), tabular megacrysts in a very coarse-grained, blocky groundmass. C.I. = 1-2;

IV) 5% medium-sized (≅2 cm), tabular megacrysts in a fine- to medium-grained, equigranular groundmass. C.I. = 0-3;

V) 15-30% large (≥2 cm), tabular megacrysts in a strongly foliated, dark groundmass. C.I. = 8-10.

Areal distributions of these petrographic types within the pluton are shown in Figure 9. Contacts between the various phases were not found; they are either gradational or obscured by lack of outcrop.

It is noteworthy that the samples with the highest color indices (the only quartz monzonites) are found at the margins immediately adjacent to mafic country rocks. The only amphibole-bearing samples (41, 56, 62 and 161) are found contiguous to amphibole-bearing country rocks. Assimilation of ferromagnesian components from the country rocks by the

granite magma, in the presence of insufficient water to stabilize biotite exclusively might result in the formation of some hornblende. The possibility that the hornblende grains in these samples are xenocrysts from the country rocks seems doubtful, as the hornblende grains show no evidence of resorption and are evenly distributed in mafic clots. The high content of platy and prismatic minerals accentuates the marginal foliation of these samples.

Low color indices and a paucity of megacrysts characterize the granite samples from the southern and southeastern margins of the batholith. This portion of the body is largely in contact with quartzofeldspathic gneisses, which may have donated felsic components through assimilation of xenoliths. Felsic xenoliths were not recognized in the Bald Rock Batholith, but their existence may be inferred by analogy to the mafic xenolith occurrences. If sufficient felsic xenolithic material were assimilated by the magma, the color index might be lowered (or if raised, then imperceptibly so) and the concentration of megacrysts per unit volume of coalesced material would be diluted.

The exceptionally coarse-grained variety (III) in the north-central portion of the batholith (Figure 9) may have resulted from prolonged contact with residual, water-rich fluids that remained trapped in the core after the margins had solidified.

The tendency for most petrographic variation to be concentrated at the margins suggests that the intruding magma in many cases interacted with the adjacent country rocks. It is unlikely that diffusion of components was the sole altering process since diffusion in a magma is a

Figure 9. Map showing the distribution of petrographic variants in the Bald Rock granite. Sizes of circles indicate approximate color indices. See text for descriptions of the variants. No data are available from the unshaded areas.

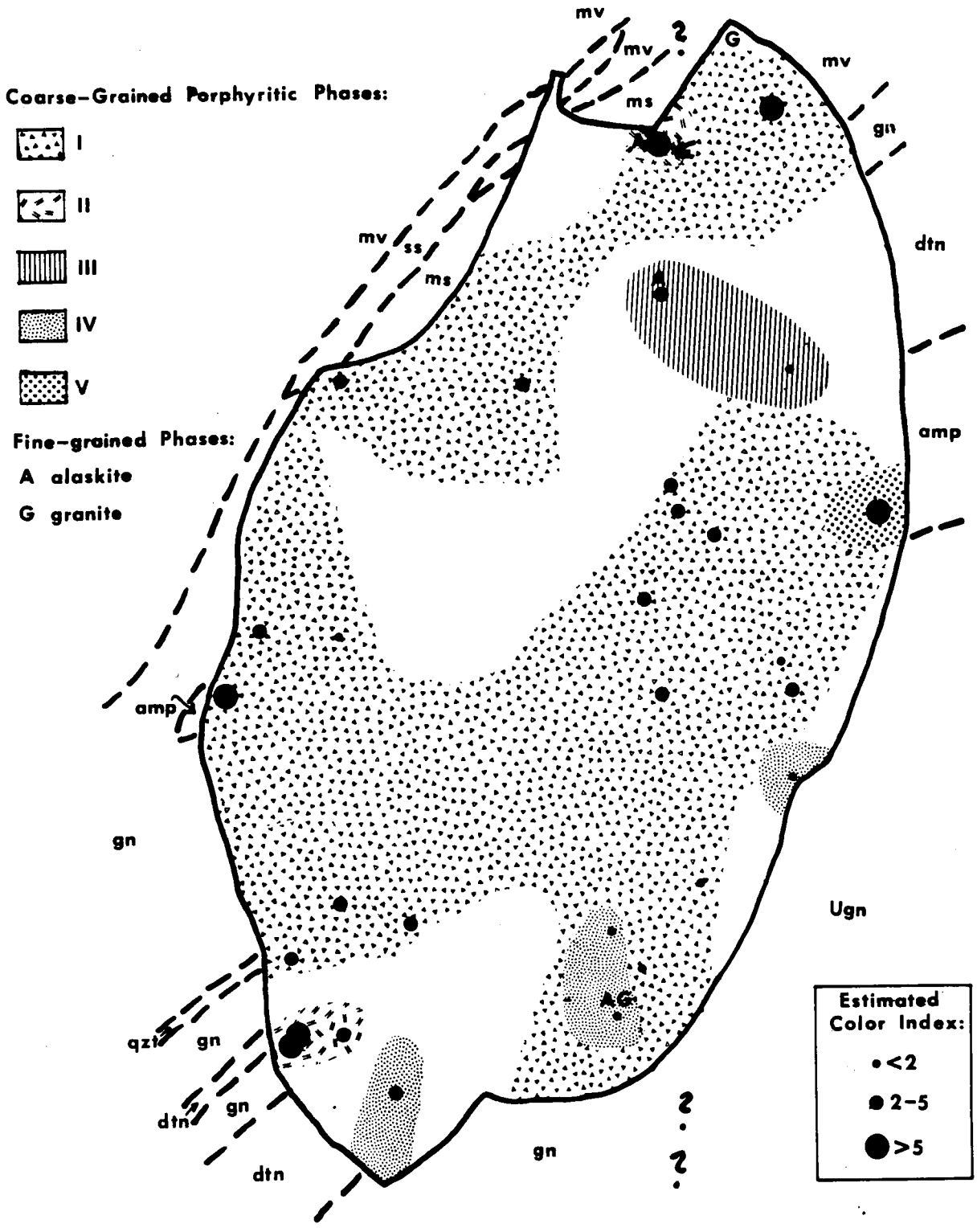

Coarse-Grained Porphyritic Phases:
I
II
III
IV
V
Fine-grained Phases:
A alaskite
G granite
mv
mv
?
G
mv
ms
gn
mv
ss
ms
dtn
amp
amp
gn
Ugn
AG
qzt
gn
dtn
gn
dtn
gn
?
?
Estimated Color Index:
<2
2-5
>5

Figure 9.

very slow process and does not propagate over great distances (Pitcher, 1979). Fluid exchange and assimilation of xenoliths were probably more important processes. The small amount of petrographic variation that occurs in the central portion of the batholith is thought to be the result of internal processes discussed in Chapter IV.

Evidence for movement of magma subsequent to its intrusion is discussed in the next chapter, but some constraints on the extent of this motion, imposed by the pattern of textural variation, deserve mention. First, the limited areal extent of the variants and their immediate proximity to their presumed country rock contaminants indicates that the magma did not move significant lateral distances subsequent to its modification. Second, the existence of the variants demonstrates that flow was not vigorous enough to produce homogenization. An alternative hypothesis is that the variants are remnants of successive pulses of related but compositionally different magma. The strong field evidence in support of the former hypothesis, however, makes this a poor second choice.

Two varieties of dike material were observed: the fine-grained granite (G) and alaskite (A) described in Chapter II. Areas of the batholith where these dikes are concentrated are shown in Figure 9.

CHAPTER IV

INTERNAL FABRIC AND STRUCTURAL ELEMENTS

Field Methods

The characterization of major fabric elements (alignment of megacrysts, xenoliths and schlieren) required both conventional and specially adapted methods of field measurements.

Determination of megacryst orientations was accomplished in saprolite banks exposed in roadcuts. At each station (Plate 1, in pocket), the broad {010} faces of several megacrysts were carefully unearthed so as not to disturb their original positions. Strikes and dips of the {010} faces were measured with a Brunton compass, and the average of several measurements was recorded for each station. Plunges of c-axes were not measured, although it should be pointed out that they can vary about an axis perpendicular to the {010} planes of the megacrysts without significantly affecting the fabric. In pavement exposures, strikes of the apparent c-axes of the megacrysts were measured. Vertical dips were inferred where the 010 Carlsbad twin plane cut the exposed portions of the megacrysts exactly in half. These data appear in Plate I (in pocket).

Strikes of xenoliths could only be measured on pavement surfaces. Direction of tapering and length:width ratios were also determined. A large pavement at station 28 (Figure 2, p. 9) was the subject of detailed fabric study. An area of approximately 3680 m^2 was taped off into a 4 m grid. Within each square, average apparent strikes of megacrysts, xenoliths and dikes were measured. One typical xenolith per square (there

were usually several) was chosen and its shape recorded schematically with the width exaggerated. These data appear in Plate II (in pocket).

Presentation of Fabric Data

Perhaps the most striking feature of the Bald Rock Batholith is the marked parallelism of megacrysts in most exposures. The map pattern of foliations (Figure 10) of generally steeply-dipping megacrysts is parallel to the margins and concentric about an area of random orientations in the east-central portion of the batholith.

Xenoliths and biotite-rich schlieren follow the same pattern. Xenoliths are elongated and internally foliated parallel to the megacryst orientations. Those in the center of the pluton tend to have high length to width ratios, up to 19:1 (Figure 5e, p. 21), while xenoliths from the margins are more equant, usually about 6:1 (Figure 5b). Megacrysts habitually impinge on the xenoliths, suggesting that the xenoliths were plastic at one time; as a result, most xenoliths have highly irregular shapes and disturbed internal foliations. Xenoliths located near the margins nearly always have one tapered end, and in any one exposure, swarms of xenoliths are generally tapered in the same direction (Plate II, in pocket). Six large exposures in various parts of the pluton indicate that the sense of tapering is counterclockwise on a batholithic scale (Figure 10). Three vertical exposures show that the xenoliths dip toward the margins and possess a downward component of tapering as well (Figure 5c, p. 21).

Small-scale perturbations of the fabric occur in pavements at various locations (Figure 5d), and larger-scale fabric deflections exist at some marginal localities (Figure 10).

Figure 10. Fabric map of the Bald Rock Batholith. Symbols indicate orientations of tabular megacrysts and xenoliths. Arrows indicate sense of xenolith tapering. The same data appear on a topographic base in Plate I (in pocket).

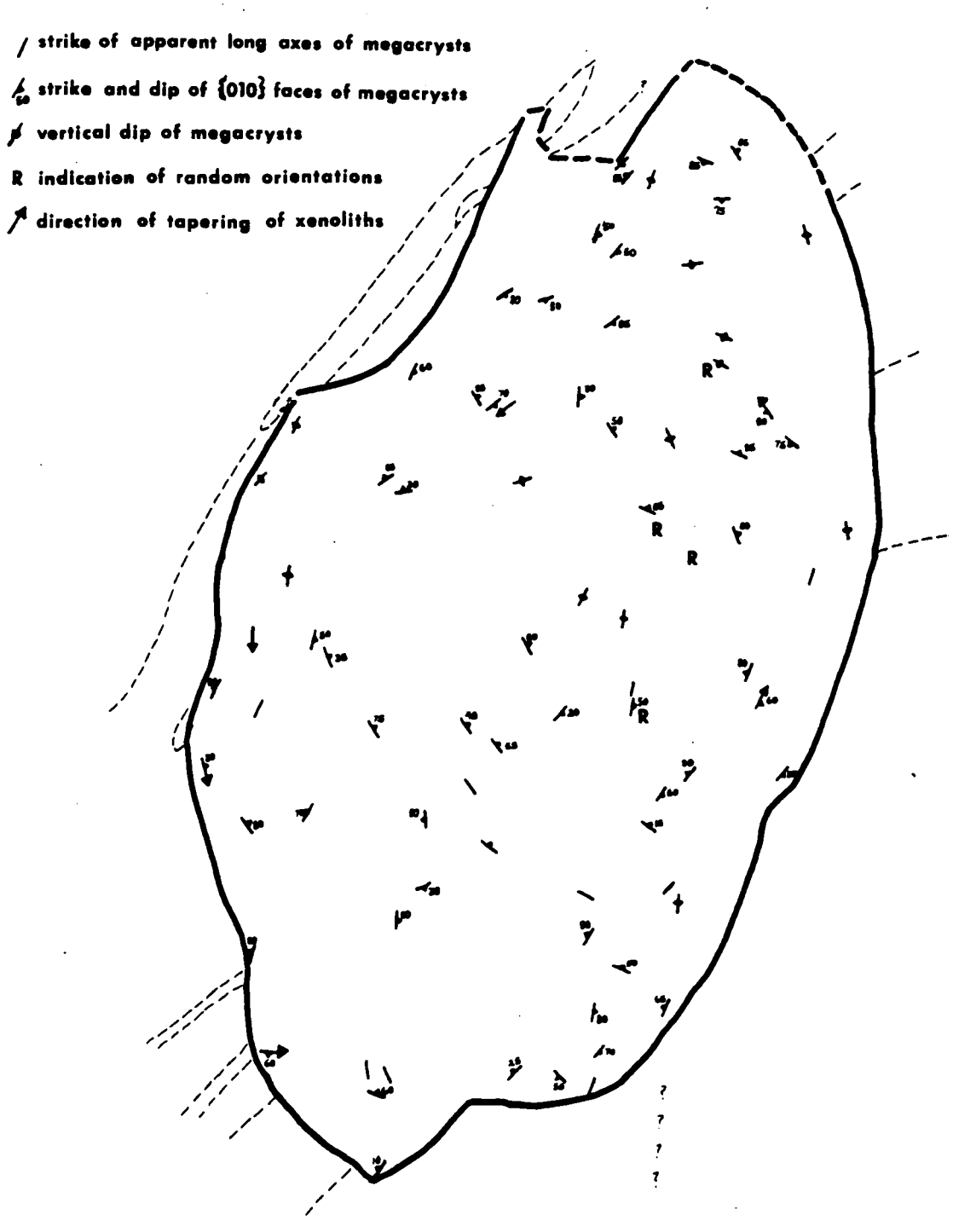

/ strike of apparent long axes of megacrysts
strike and dip of {010} faces of megacrysts
vertical dip of megacrysts
R indication of random orientations
direction of tapering of xenoliths

Figure 10.

Fabric Formation as the Result of Internal Processes

It would seem that such systematic fabrics could not develop fortuitously. They are probably not metamorphic in origin, since in places the fabric lies across the regional metamorphic trend. Therefore, it is assumed that the structures preserved in the Bald Rock granite manifest the interaction of a variety of processes that operated during the intrusion and crystallization history of the batholith. An attempt will be made to interpret the Bald Rock data in terms of current supposition about the nature of granitic batholiths.

In preface to the following discussion, several assumptions must be made:

1) The Bald Rock magma was capable of movement subsequent to its emplacement;
2) Magma movement was caused by one or more forces;
3) The present fabric preserves evidence of the directional nature of these forces.

Intuitively, the production of a concentric foliation pattern such as that of the Bald Rock might be accomplished by concentric laminar flow about a vortex, by a combination of radial-outward motion followed by downward motion, or by radial-outward forces from a central point. In the first two cases, entrained tabular solids such as megacrysts would tend to be oriented with their broadest faces parallel to the flow direction, and in the latter case, the broad faces would lie perpendicular to the direction of principal stress (Reiner, 1959).

In developing a model that describes motion within a body of granitic magma, it is first necessary to consider certain properties of that magma and how they govern its movement.

The most important constraint on the movement of magma is viscosity. It is well-established that granites that are emplaced at moderate levels in the crust will intrude at sub-liquidus temperatures and hence will be crystal-bearing to some degree (Pitcher, 1979). The presence of crystals at intrusion temperatures raises the effective viscosity of the magma (Shaw, 1965). Viscosity estimates of 10^6 to 10^8 poise have been obtained for granitic magmas (Shaw, 1965; Bartlett, 1969; Pitcher, 1979). Although granite magmas do contain water and other volatile components, the de-polymerizing effect of water cannot lower the viscosity, as most granitic batholiths are considered to contain less than 1.5 wt. percent water when they intrude (Wyllie et al., 1976). These effects cause crystal-bearing granite magmas to behave generally as Bingham ("pseudo-plastic") bodies (Shaw, 1965; Pitcher, 1979), in which flow is possible only after a critical shear value is exceeded (Carmichael et al., 1974). Therefore, the behavior of the Bald Rock magma cannot be considered in terms of simple (Newtonian) fluid behavior. The actual viscosity contrast between the Bald Rock granite magma and solid Bald Rock granite was probably extremely small.

Upon first examination of a pavement exposure, it may appear that the alignment of platy features is the result of primary laminar flow of a crystal-bearing fluid, as described by Balk (1937). In light of the foregoing theoretical and experimental work, however, it becomes apparent

that this is too simplistic a model. Nickel et al. (1967, in Pitcher, 1979) conclude that laminar flow within a large body of granitic magma is an improbable cause of particle orientations (although it is capable of moving the particles within the magma), since the required flow layers cannot be produced except at much higher flow rates than are encountered in granite magmas.

Crystal settling is also ruled out as an orienting mechanism, for the following reasons:

1) In a Bingham body, the density contrast between the solid crystals and interstitial material would be negligible, hence settling would not occur.
2) Gravitational settling would not produce the concentric pattern of steeply-dipping tabular and platy features observed in the Bald Rock.
3) Convection, if it occurred, would tend to redistribute settling crystals (Bartlett, 1969).

Logically, the next possiblity to consider is convection. Convection is believed to be an effective mechanism for heat dissipation in many intrusions. Shaw (1965) and Bartlett (1969) contend that convection can occur in bodies of magma with viscosities up to about 10^8 poise, provided the magma chamber is large enough. In Shaw's model, upwelling occurs (ideally) at the center of the mass and downcurrents operate radially outward toward the margins.

Convection would tend to plaster crystals against the margins of the body, as seen in the Bald Rock Batholith, and could also explain the

downward and outward drag on the xenoliths. Other field evidence places limitations on the role of convection in producing the Bald Rock fabric.

The outward force of the convective cell would preferentially flatten those xenoliths closest to the walls of the magma chamber (if the force of convection indeed had the capacity to deform the xenoliths) and leave those in the center relatively undeformed. The exact opposite of this is observed in the Bald Rock Batholith.

The apparent counterclockwise component of xenolith tapering cannot be caused by a simple upward-outward-downward convection cell; however, if a concentric counterclockwise component to the downcurrents operated, the plastic xenoliths might have been able to be stretched in such a manner. The cause of such a component of motion is difficult to imagine.

The Coriolis Effect was initially considered as a possible cause of the counterclockwise component of flow. At the time of intrusion, the batholith was located between 10° and 15° south latitude (Bambach et al., 1980) so that the Coriolis Effect on a liquid would have been in a counterclockwise direction. Assuming a generous convection velocity of 1 mm per second, the force of gravity on a magma would have been at least 10^8 times greater than Coriolis Effect. Since gravity has already been eliminated as an effective cause of motion in such viscous magmas, it seems certain that a force that is 8 orders of magnitude weaker could not affect flow. One other conceivable cause of the counterclockwise flow might be deflection by irregularities in the walls of the magma chamber.

Convection could not have produced protoclastic textures throughout the batholith. The granulation of crystalline material requires that it

was solid or very nearly so. Convection would have ceased long before the magma reached the degree of rigidity necessary for protoclastic deformation. It is also unlikely that protoclasis was induced from outside the magma chamber, because the batholith does not lie along any major faults, and regional studies (Hatcher, 1972) indicate that there has been no significant compressional tectonic activity in the area since the emplacement of the batholith. Therefore, an internal source of stress must be identified.

A model that could account for the concentric fabric as well as protoclasis, while adhering to viscosity constraints, has been discussed by Pitcher (1979) and Spry (1979). In this model, particle orientation is achieved by deformation in a near-solid state resulting from sequential intrusion. During emplacement, repeated surges (used in the sense of Pitcher, 1979) of magma forced previously-intruded, nearly-solidified mush away from the center of upwelling in all directions, toward the margins of the pluton. The outer carapace cooled but remained plastic while continued magmatism plastered crystals and xenoliths against the previously-intruded material. Platy and tabular particles became oriented with their broad faces perpendicular to the direction of principal stress. Xenoliths were flattened parallel to the margins and additionally deformed by the impingement of megacrysts. The outward force of the resurgent magma on the confined, nearly-solidified surrounding material induced protoclasis, and was intense enough to rupture and deform the previously-intruded material (Figure 5f, p. 20) and disrupt synplutonic dikes (Figure 5a).

One limitation of this model is that it cannot account for the tapering of xenoliths, as there are no systematic downward or concentric components to the radial-outward stress system.

The best model for the emplacement history of the Bald Rock Batholith involves a combination of the convection and resurgence models.

Shortly after emplacement, a convection cell was established in the magma chamber. Originally blocky xenoliths were tapered in the directions of major flow components. As cooling ensued, presumably from the margins inward, convection was progressively damped out as the viscosity of the magma increased. Migration of fluids into the core from the solidifying carapace kept the core mobile and receptive to resurgent pulses. The radial-outward force of resurgent pulses deformed previously-intruded material while orienting tabular bodies in a concentric manner around the center of upwelling. Continued resurgence induced protoclasis of the nearly-solidified material.

The center of upwelling is inferred to be the area of random orientations in the east-central portion of the batholith, about which foliations are concentric. Incipient granoblastic texture in this area suggests that the local magma was subjected to reheating, and the extreme deformation of xenoliths indicates that magma in this area experienced the effects of stress for a longer period of time than marginal areas.

Localized deflections of the fabric may be due to irregularities in the shape of the magma chamber or to vagaries in the propagation of stresses.

CHAPTER V

SUMMARY

Although empirical observations have been made about the field relations, petrography and fabric of the Bald Rock Batholith, the lack of quantitative information obtained in this study makes it unsafe to draw many conclusions regarding its history. The following geologic synopsis is based on analogies to the studies of others and is highly speculative.

The Bald Rock Batholith originated as a lower crustal melt (Fullagar and Butler, 1979) that was generated above a subduction zone in the mid-Paleozoic and rose without significant crustal contamination (as deduced from Sr isotopic data by Fullagar, 1971) after the cessation of subduction-related regional metamorphism.

Depth of emplacement cannot be determined due to lack of suitable pressure-indicating metamorphic assemblages in the country rocks; however, studies on a cogenetic pluton to the east of the Bald Rock indicate intrusion temperatures in the range of 670°-740°C and pressures on the order of 4.5 to 5.5 kb, corresponding to a depth of 15 to 18 km (Speer et al., 1980). It is not known whether the Bald Rock magma rose diapirically by density contrast (Pitcher, 1979) or by channeling along deep-seated fractures. The fact that the batholith is emplaced on the boundary between the Charlotte and King's Mountain Belts is probably fortuitous, as related plutons are discordantly intruded without regard to regional structure. Additionally, the morphology and extent of the Central Piedmont Suture is unknown, hence its potential as a magma conduit cannot be evaluated.

At the inferred depth of emplacement, disturbance of the country rocks was moderate, consisting mainly of the engulfment of many small xenoliths and a few larger screens of distressed country rock by the magma. Assimilation of xenolithic material and exchange of fluids with the country rocks caused local contamination of the granite at the margins.

Upward movement of the magma was arrested when sufficient water had dissipated through pressure-release to cause rapid, though incomplete, crystallization. The resulting crystal-charged mush behaved as a Bingham body. Stirring and heat dissipation may have occurred in the early post-intrusion stage, and was progressively damped out during cooling. Successive surges of magma caused deformation of nearly-solid marginal rocks to create a concentric foliation of megacrysts and xenoliths around the center of upwelling. A counterclockwise component of flow appears to have been present, but its source and possible role in aligning megacrysts and xenoliths is unknown.

Concentration of volatiles in the residual magma led to the forcible emplacement of fine-grained granite dikes. Later-formed fractures were intruded by alaskite and diabase dikes.

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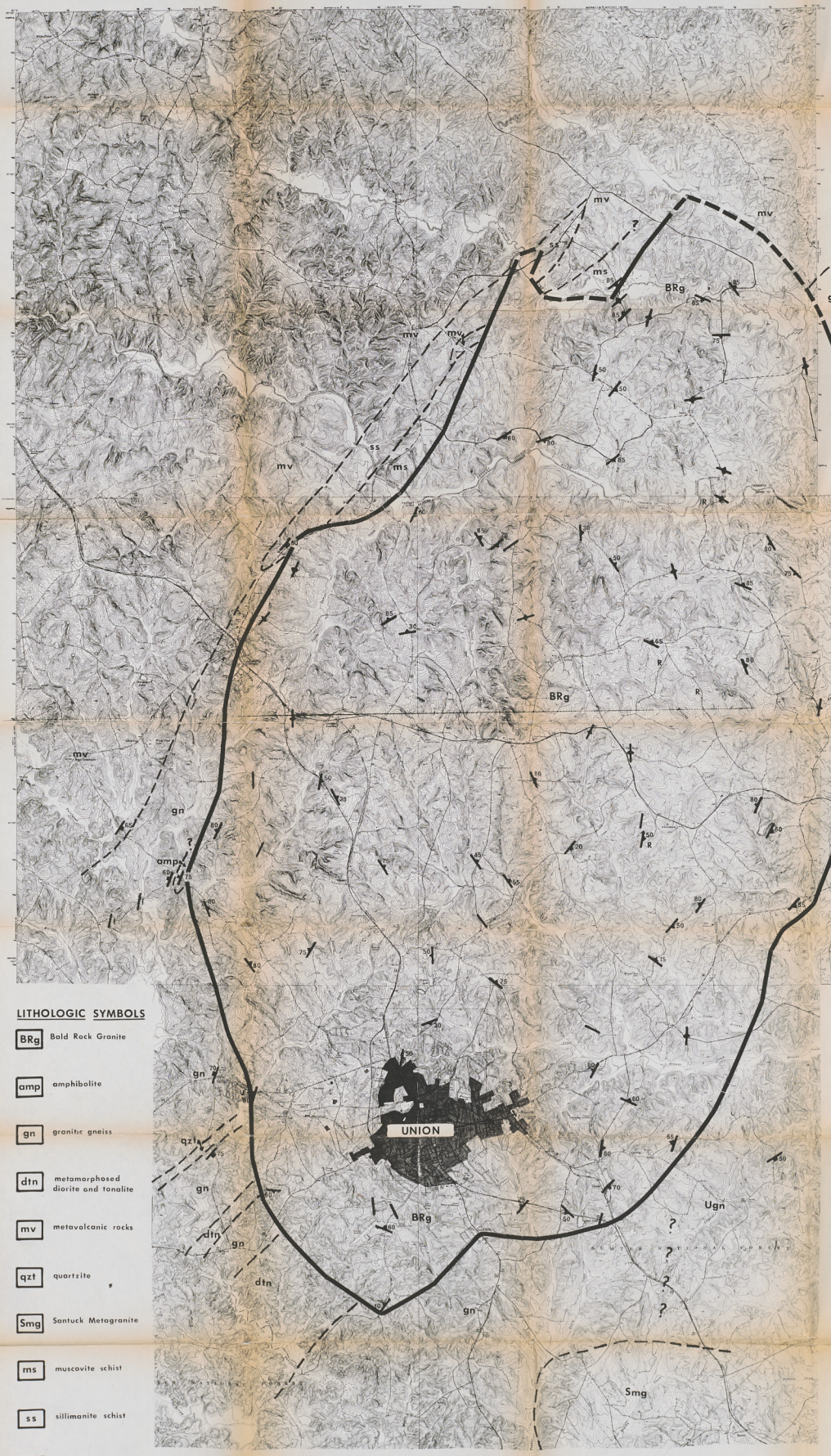
VITA

Susan M. van Gelder was born on May 6, 1955, in Plainfield, New Jersey. She attended the Cranford, New Jersey, Public Schools and graduated from Cranford High School in 1973.

She attended Franklin and Marshall College, Lancaster, Pennsylvania and received a Bachelor of Arts degree in Geology in May, 1977. In September, 1977, she began graduate studies at the University of Tennessee, Knoxville, where she was a graduate assistant, and received her Master of Science degree in Geology in December, 1980.

Susan began working for Mobil Exploration and Producing Services, Inc. in September, 1980.

GEOLOGIC MAP of the BALD ROCK BATHOLITH, Union and Cherokee Counties, S.C.



MAP SYMBOLS

- margin of Bald Rock Batholith (dashed where inferred)
- approximate contacts of country rocks
- strike and dip of country rock foliation
- strike of country rock foliation

MICROCLINE MEGACRYST ORIENTATIONS

- strike and dip of (010) faces
- vertical dip of (010) faces
- strike of c-axis projections
- R indication of random orientations

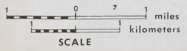
LITHOLOGIC SYMBOLS

- BRg Bald Rock Granite
- amp amphibolite
- gn granitic gneiss
- dtn metamorphosed diorite and tonalite
- mv metavolcanic rocks
- qzt quartzite
- Smg Santuck Metagranite
- ms muscovite schist
- ss sillimanite schist
- Ugn undifferentiated granitic and hornblende gneisses

Location of Study Area:







U.S. Geological Survey 7.5' Quadrangles used as base map. Contour interval 10 feet

PLATE 1.

PLATE 2.

FABRIC OUTCROP MAP

