

Abstract

Christopher S. Schiappa. PETROLOGY AND GEOCHEMISTRY OF THE CORONACA PLUTON, GREENWOOD COUNTY, SOUTH CAROLINA. (Under the direction of David P. Lawrence) Department of Geology, March, 1988.

The Coronaca pluton is a late Paleozoic, postkinematic composite stock which intrudes regionally metamorphosed meta-igneous rocks of the Charlotte belt. Lithologies include granite, quartz syenite, monzonite, monzodiorite, syenite, quartz monzonite, quartz monzodiorite, norite and small, alaskite satellite stocks. Field evidence suggests that contacts are gradational. The Coronaca suite can be divided into three phases on the basis of chemistry and petrology: 1) a felsic phase (granite, quartz syenite); 2) an intermediate phase (quartz monzonite, quartz monzodiorite, syenite, monzonite and monzodiorite) and 3) a mafic phase (norite).

Whole-rock chemical analysis of major and trace elements of 30 samples show SiO₂ concentrations from 46-75 weight percent. Harker plots of CaO, MgO, Fe₂O₃, Sr, Rb and Y show curvilinear trends. Aluminum, TiO₂, MnO, Zr and the alkalis do not show curvilinear trends, but the plots for these

elements are biased by rocks of intermediate composition (53-62 wt. % SiO₂). Curvilinear trends are enhanced in variation diagrams where major and trace elements are plotted against the Differentiation Index. Modal and normative mineralogical data suggest an I-type parent magma. Petrological and geochemical data suggest that the diverse lithologies are comagmatic.

Gravity, magnetic and radioactivity anomalies associated with the pluton suggest that the felsic lithologies of the Coronaca may be a cap, covering a larger, more mafic body at depth.

Petrology and Geochemistry
of the Coronaca Pluton,
Greenwood County, South Carolina

A Thesis

Presented to
the Faculty of the Geology Department
East Carolina University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Geology

by
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March 1988

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of the Coronaca Pluton,
Greenwood County, South Carolina

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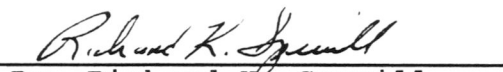
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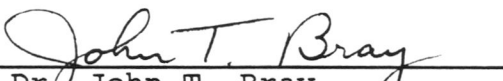
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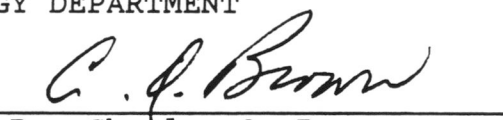
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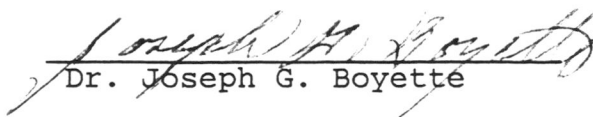
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Acknowledgements

My sincere thanks goes to my thesis committee members Drs. Dave Lawrence, Richard Mauger and Richard Spruill for their insightful advice, discussion and encouragement throughout the duration of this project. I am deeply indebted to them for teaching me geology. I would also like to thank Dr. John Bray for some of the trace element analyses and for reading the manuscript. Chris Corbitt and Pete Moncla deserve special mention for their long hours of help during the geochemical work. Many thanks to Tom Danahy, Tammy Andrade, Van, Lucy and Burt for assistance and support in the field.

My parents, Sam and Betty Schiappa and my best friend Tammy Andrade gave me the encouragement, advice and financial support without which I would have never made it through graduate school. Many thanks to my brother and sister, Dave Schiappa Judy Weiss, for their suggestion to start and encouragement to finish graduate school.

The acknowledgements would not be complete without mention of the faculty, students and friends (you know who you are) at the geology department during my tenure as a graduate student. Our friendly discussions and fun times made graduate school a truly worthwhile endeavor. To you, I dedicate this thesis.

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Introduction

The Coronaca pluton surrounds the town of Coronaca in Greenwood County, South Carolina. The area investigated lies within the Waterloo, Cokesbury, Ninety-Six and Greenwood 7.5' quadrangles and covers an area of approximately 35 square kilometers. Topography is typical of the southern Piedmont, with gently rolling hills (local relief 15-40 m) and a dense vegetative cover interspersed with open cultivated fields (Plate 1).

The purpose of this study is to examine the petrology, rock chemistry and geophysical expression of the Late Paleozoic (278 $\pm$ 2 Ma) (Fullager and Butler, 1979) Coronaca pluton. Objectives of the project are to: 1) characterize the various lithologies and describe their interrelationships using petrological and geochemical data; 2) quantify variations in major and trace element content within the different lithologies of the pluton; 3) use geophysical data (gravity, radioactivity and magnetics) and field interpretations to estimate the areal extent of the pluton, and 4) suggest a possible petrogenetic history based on petrological and geochemical trends for the Coronaca suite.



Plate 1. Topography and outcrop typical of the Coronaca area.

Previous Work

Most of the previous analytical and descriptive petrologic studies of the Coronaca Pluton have been limited to the granite and quartz syenite from the main Coronaca quarry (Figure 2). The first published chemical analysis of the Coronaca granite was by Sloane (1908), who analyzed a sample from the Benjamin quarry, located behind the present Springfield Church. McSween (1969) studied the general petrography and geochemistry of rocks within the Coronaca pluton and the surrounding metamorphic country rock and also noted a variation in lithology of the rocks within the pluton. Later, McSween (1970) presented a reconnaissance map of the area. In an investigation of potential crushed and dimension stone resources of the granitic rocks of South Carolina, Wagener (1977) described macroscopic features of the Coronaca granite and quartz syenite and provided a map of small quarries and outcrop locations. A mineral-whole rock Rb-Sr isochron for the granite-quartz syenite by Fullager and Butler (1979) suggests a minimum age of 278 ± 2 Ma.

Sando (1979) investigated trace element variations in twenty-five 325-265 Ma granitoid plutons, including the Coronaca. Chemically, the plutons follow two distinct trends similar to the groupings of Fullager and Butler (1979). The Charlotte belt granites (western group) define a distinct chemical suite which is petrologically and chemically more

homogeneous than the eastern group granites (Raleigh, Carolina Slate and Kiokee belts). In general, western group plutons (except Coronaca) show higher Mg/Fe, CaO, Ba, V/Fe and Ce/Yb than eastern group plutons. Europium anomalies for Charlotte belt plutons are small to absent. The eastern group plutons have irregular trace element patterns and display significant variations between individual plutons. Overall, Charlotte belt plutons appear to form a related group based on patterns of trace element variations; however the Coronaca shows a tendency to diverge from this major trend.

Geologic Setting

The Coronaca pluton is a postkinematic composite stock intruded into plutonic meta-igneous rocks of the Charlotte belt. The Charlotte belt is one of a series of northeast- to southwest-trending lithotectonic belts or terranes within the Piedmont of the southeastern United States (Figure 1). Each belt or terrane has distinctive characteristics and is bounded by cataclastic zones or steep metamorphic gradients. In South Carolina, belts characterized by low- to medium-grade regional metamorphism (Belair, Carolina Slate, Kings Mountain and Chauga) alternate with medium- to high-grade belts (Kiokee, Charlotte and Inner Piedmont) (Secor and others, 1986b; see also Crickmay, 1952; King, 1955; Overstreet and Bell, 1965a; Overstreet and Bell, 1965b and Hatcher, 1972. Deep seismic reflection studies across the Piedmont by COCORP (Consortium for Continental Reflection Profiling) suggest an allochthonous origin for the belts by westward imbricate thrusting after a collisional event (Cook and others, 1979) or microplate accretion (Zen, 1981). A discovery of Atlantic faunal province trilobites in the Carolina Slate belt may confirm an exotic origin for the Slate and Charlotte belts (Carolina terrane) which, during the Cambrian, was not part of the North American craton (Secor and others, 1983).

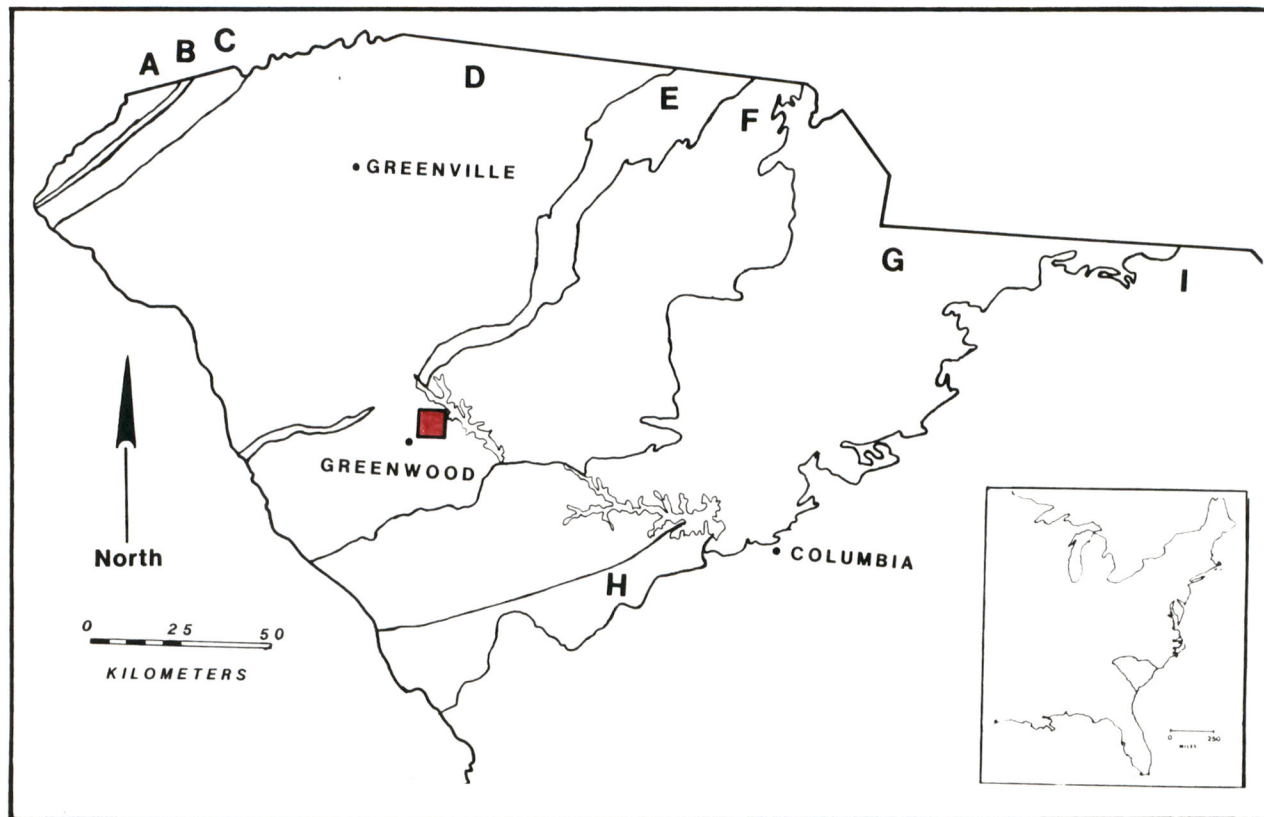


Figure 1. Lithotectonic belts of the South Carolina Piedmont. Approximate study area location is shown in red.
 A= Blue Ridge Province, B= Brevard Zone, C= Chauga Belt
 D= Inner Piedmont Belt, E= Kings Mountain Belt
 F= Charlotte Belt, G= Carolina Slate Belt, H= Kiokee Belt
 I= Coastal Plain
 (Modified from Overstreet and Bell, 1965b)

A series of granitic to gabbroic intrusives, paralleling the belts, occurs within the Piedmont and beneath Cretaceous/Tertiary Coastal Plain sediments. Geophysical data and core holes through Coastal Plain sediment indicate a distribution of igneous rocks similar to that in the exposed portions of the Piedmont (Costain and others, 1980). A petrological and geochemical study by Butler and Ragland (1969) divided the Piedmont plutons into two groups: 1) post- and syn-metamorphic and 2) pre-metamorphic. Whole-rock Rb-Sr ages for twenty-five intrusions (Fullager, 1971) showed that pulses of igneous activity occurred between 595-520 Ma, 415-385 Ma and approximately 300 Ma. The latest period of igneous activity is defined by a group of 325-265 Ma plutons in the central and eastern Piedmont (Fullager and Butler, 1979). These plutons have been subdivided into eastern and western (Charlotte belt) groups. Charlotte belt plutons have higher Sr contents than eastern Piedmont plutons. Most of these plutons postdate regional metamorphism. However, plutonic rocks of the Kiokee belt exhibit foliation which may have formed contemporaneously with late Paleozoic regional metamorphism in that belt (Kish and others, 1978). The Kiokee belt is thought to have originated as an exotic terrane (Secor and others, 1978) or may be part of the larger Avalon terrane (Williams and Hatcher, 1983). Sinha and Zeitz (1982) used chemical and geophysical characteristics to define an arcuate regional distribution of the Hercynian plutons, suggesting emplacement in a magmatic-arc environment. Field relations

and petrologic characteristics were described by Speer and others (1980) for twenty-four post-metamorphic Piedmont granitoids. These plutons possess similarities in age, texture, degree of modal variation, mineral composition and type of xenoliths. A comparison of Paleozoic Piedmont gabbroic plutons by McSween (1987) also reveals petrologic similarities between mafic intrusions. Mafic intrusives of the Charlotte belt occur in two linear segments separated by an intervening zone without mafic plutons (Fronabarger and McSween, 1985).

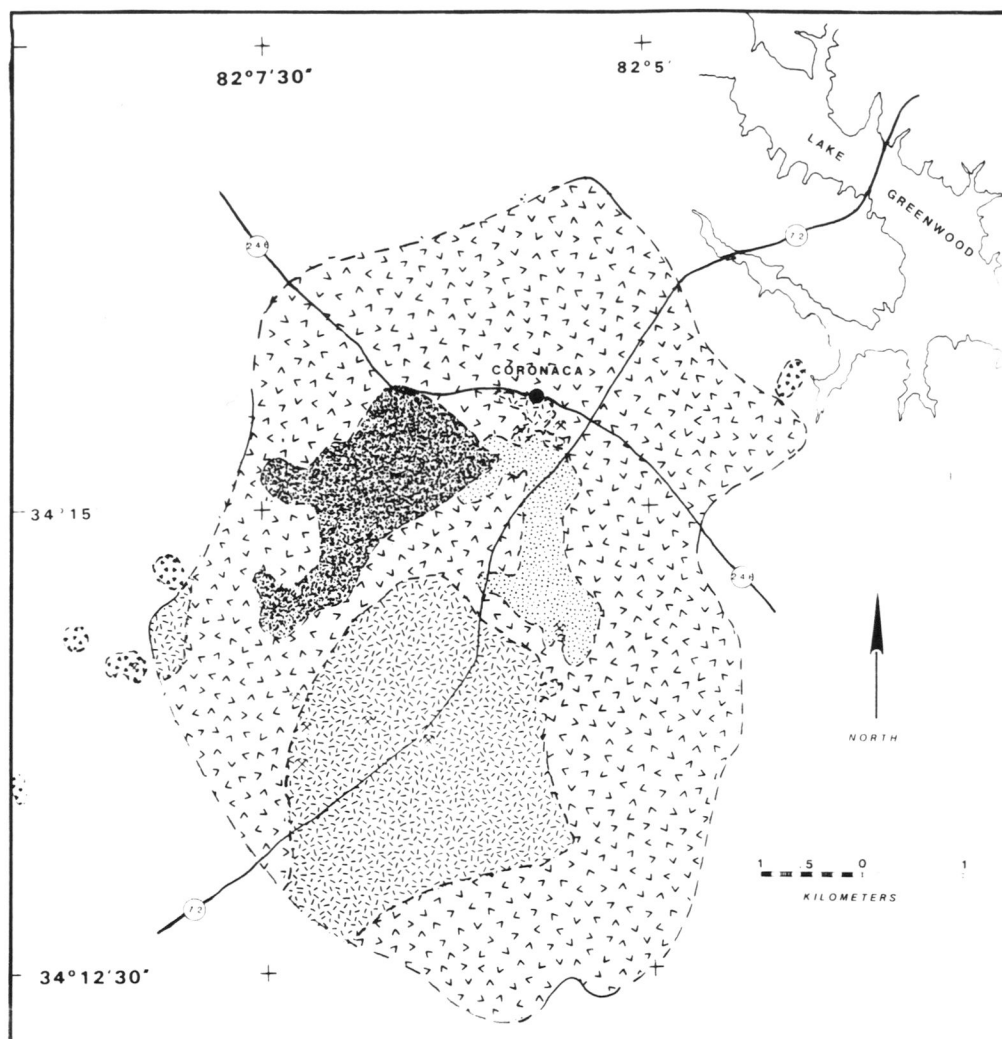
Petrology

Classification

The Coronaca pluton exhibits three compositional phases: 1) a felsic phase of granite (Plate 2) and quartz syenite (Plate 3); 2) a heterogeneous intermediate phase of gradational lithologies (Plate 4) and, 3) a mafic phase of norite and leuconorite. Figure 2 shows the distribution of these phases within the pluton. A suite of lithologies with similar composition and field occurrence characterize each of the three phases. Lithologies are classified according to the recommended IUGS (International Union of Geological Sciences) classification for granitoid rocks (Streckiesen, 1976) (Figure 3). Rocks with a mafic mineral content of greater than 90% are classified by mafic mineralogy using the IUGS classification for gabbroic rocks (Figure 4). Petrological and chemical data on an alaskite are presented but the alaskite is not regarded as belonging to the Coronaca plutonic suite. The alaskite (Plate 5) occurs as small, elliptical stocks roughly 500 meters in diameter.

Field Relations

Geologic mapping of the Coronaca pluton is based on limited outcrop exposures and, to a minor extent, on soil



EXPLANATION



Granite



Quartz Syenite



Intermediate Rocks
(Syenite, Monzonite,
Monzodiorite)



Norite



Alaskite

Figure 2. Geologic map of the Coronaca composite stock, Greenwood County, South Carolina.

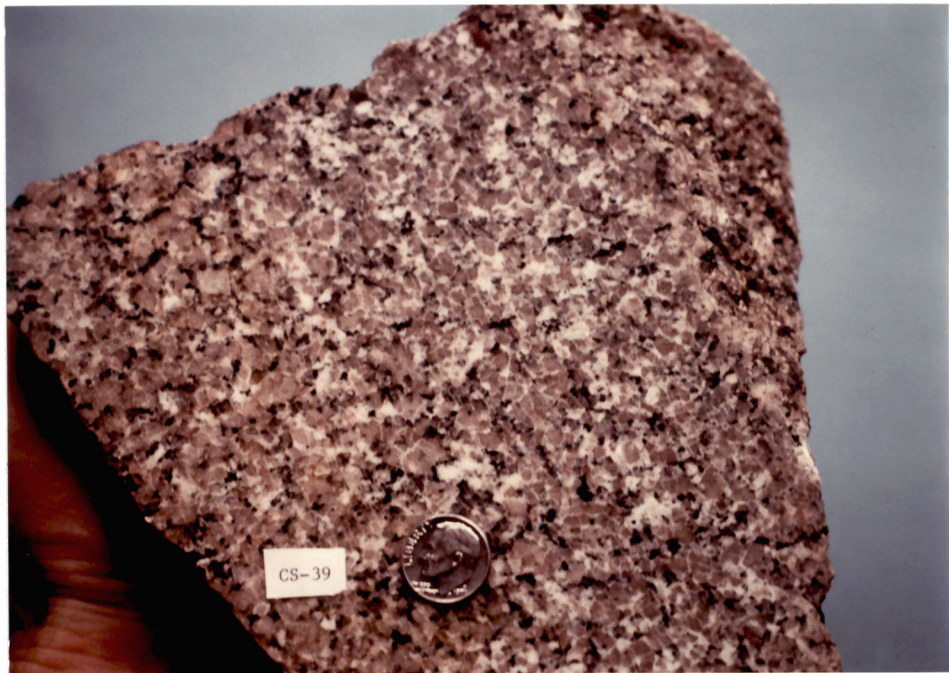


Plate 2. Hand specimen of granite. Sample CS-39



Plate 3. Hand specimen of quartz syenite. The fine-grained red mineral is sphene. Sample CS-43

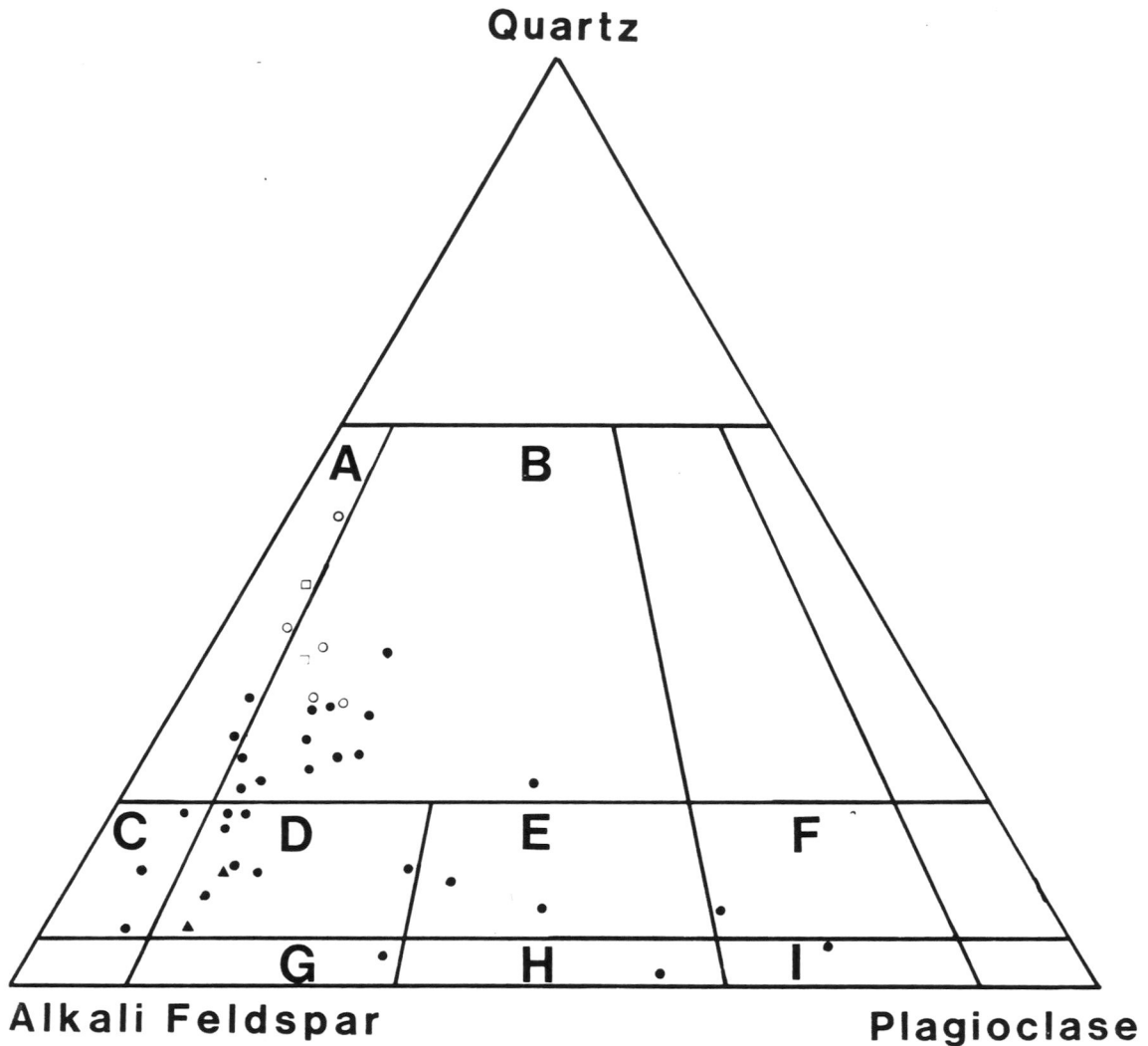


Figure 3. IUGS diagram for classification of granitoid rocks.
 (•)= Coronaca plutonic rocks (◻)= Inclusions
 (◦)= Satellite stock rocks (▲)= pegmatite/aplite

A= alkali feldspar granite B= granite
 C= alkali feldspar quartz syenite
 D= quartz syenite E= quartz monzonite
 F= quartz monzodiorite G= syenite H= monzonite
 I= monzodiorite

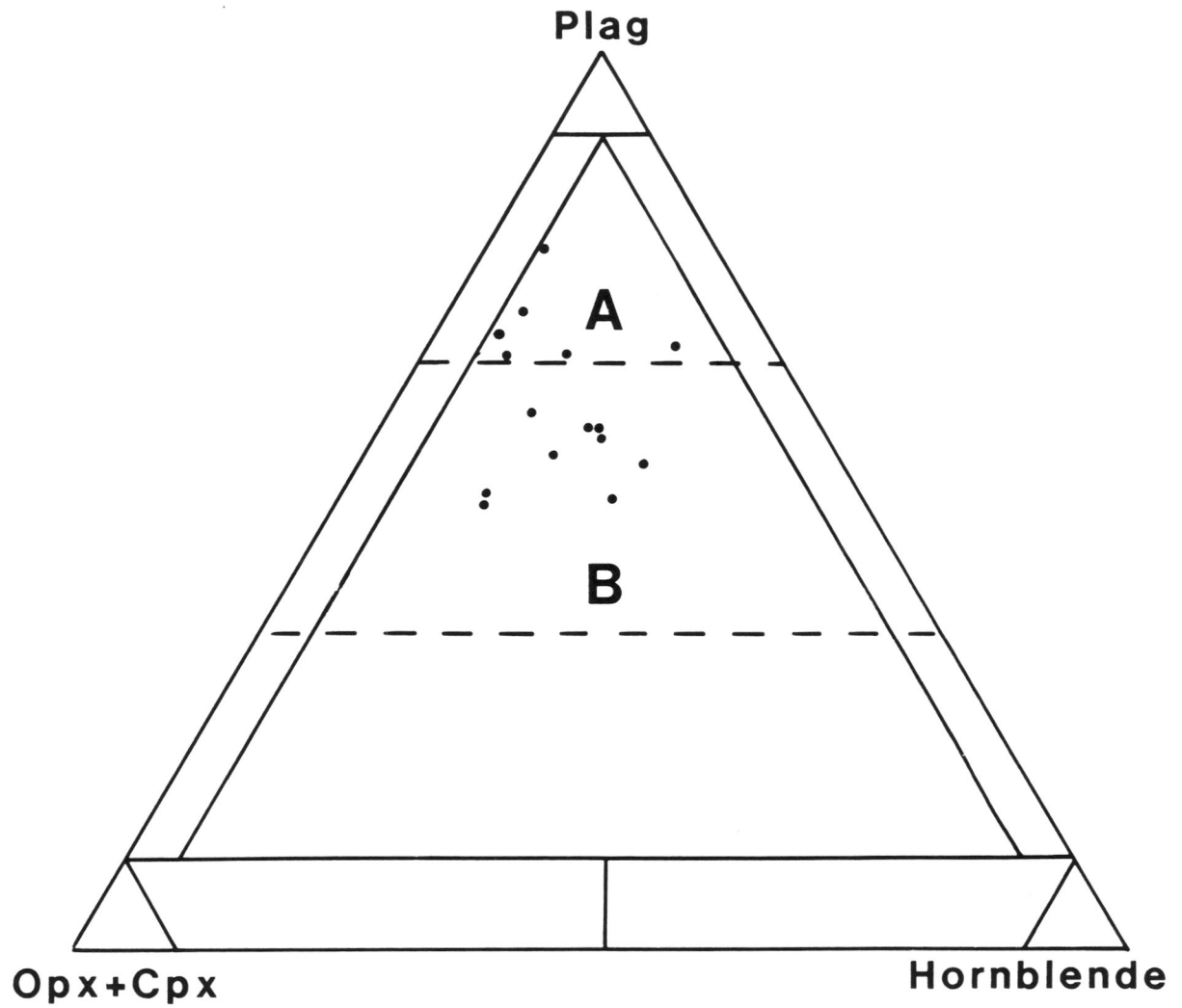


Figure 4. IUGS diagram for classification of gabbroic rocks.
A= leuconorite B= norite

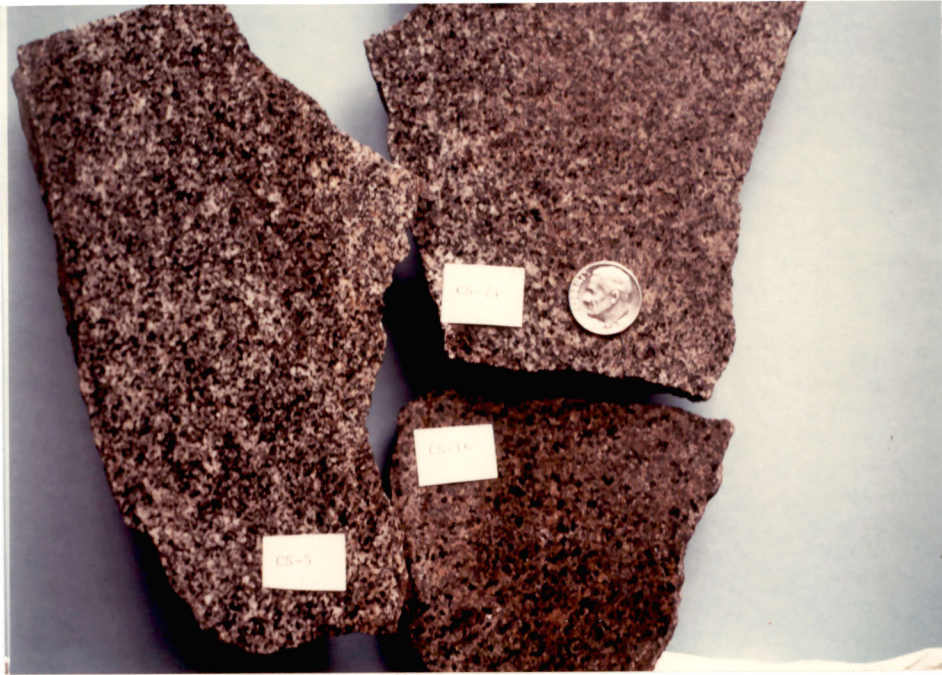


Plate 4. Hand specimens of intermediate composition rocks. Sample CS-5 (syenite), CS-16 (quartz monzodiorite) and CS-74 (quartz monzonite).



Plate 5. Hand specimen of alaskite. Sample CS-62

type. Field maps were produced on USGS 1:24000 topographic maps. Soils were used for mapping purposes in the absence of exposed rock. The soils are residual and have weathered in place from the underlying bedrock. The soils have morphological, chemical and textural characteristics directly related to the underlying bedrock (Camp and Herren, 1980). Felsic lithologies tend to underlie Appling or Helena series soils, and mafic rocks underlie Mecklenburg or Iredell series. Outcrops are best seen along stream channels, flat-rock areas and small quarries. Samples were collected at all accessible exposures (see Figure 10 for sample locations), but because of variable lithologic weathering rates and thick soil cover, felsic lithologies are better exposed than more mafic lithologies.

Spheroidal boulders are common throughout the pluton and are characteristically different for felsic and mafic compositions. Felsic boulders are deeply weathered and range from 1 to 10 meters in diameter (Plate 6). Mafic boulders average 1 to 2 meters in diameter, but have only thin (3-4 cm.) weathered rinds (Plate 7).

The main Coronaca quarry is the best exposure within the pluton (Plate 8). Numerous small quarries, 10 meters or less in diameter and 2 meters in depth, occur irregularly throughout the pluton and provide a source for fresh samples suitable for chemical analysis (Plate 9).

Contacts are obscured by thick soil cover and agricultural



Plate 6. Deeply weathered spheroidal boulder of granite. Exposed near Greenwood, South Carolina.



Plate 7. Spheroidal boulder of norite. Note the fresh appearance on the surface of the boulder.



Plate 8. East wall of the abandoned main Coronaca quarry. Wall height is about 4 m. above water line.



Plate 9. Small abandoned granite quarry adjacent to a cemetery, near Coronaca, South Carolina.

development. Saprolite, residual boulders and variability in soil type were used to approximate contact locations. Field evidence suggests that boundaries between phases are sharp and that lithologic variations within each phase are gradational. All phases are massive and lack the regional foliation that is typical of the surrounding Charlotte belt rocks. Small pegmatites, aplites and less abundant diabase dikes intrude all lithologies in the pluton.

Rocks mapped within the felsic phase include granite and quartz syenite. Variable quartz content in felsic phase rocks results in an irregular distribution of granite and quartz syenite. Felsic phase rocks constitute about 85% of the surficial exposure and occupy all but the central portion of the pluton (Figure 2). There is no evidence of a contact aureole between the felsic phase and country rock. Aligned schlieren (N45W) are common in the granite and quartz syenite. These are lens-shaped concentrations of mafic minerals and range from 4 to 20 cm. in length.

Intermediate phases are composed of syenite, quartz monzonite, monzonite, monzodiorite and quartz monzodiorite. The compositions of these intermediate lithologies may imply that they are transitional between the mafic and felsic end members.

Rocks mapped as mafic phases are norites grading to leuconorites. The norites occupy a topographic low in the west-central portion of the pluton.

Geophysics

Gravity, magnetic and radioactivity data provide a visual aid which is useful in delineating the boundaries of the Coronaca pluton and for interpreting the geology of the pluton at depth. The geophysically determined contacts agree well with the field interpretations (Figure 5).

Gravity

The gravity survey of the Coronaca pluton presented in this report supplemented earlier regional studies of the area by Duc and others (1979), Chalcraft and others (1979), Chalcraft and others (1981), Horrocks and Chalcraft (1981), Lawrence and Chalcraft (1981), Chalcraft (1981) and Lawrence (1985). The data were reduced to Bouguer values using an assumed average density of 2.67 gms/cm³. A contour map of the observed Bouguer anomalies was produced using 175 gravity stations measured at road intersections with known elevations (Figure 6). The map was produced using the TOPO Contouring Program (version 2.00; Golden software, 1985) with a search radius of 300 map grid units and a curve smoothing factor of 0.95.

The gravity map displays a NE-trending positive anomaly superimposed on a major northward decreasing regional gradient. The gradient is attributed to the zone of transition between felsic plutons and gneiss to the north and relatively

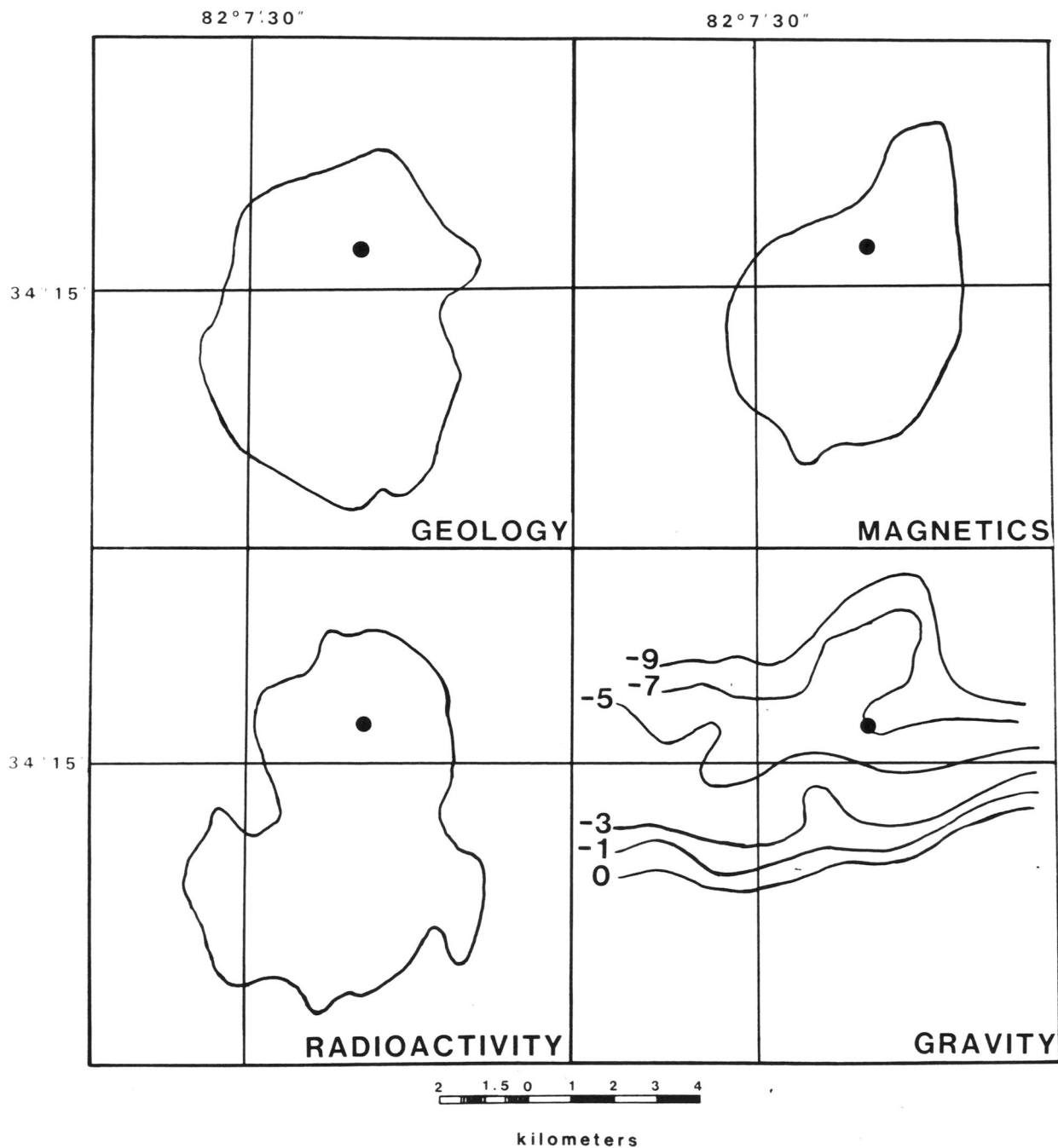


Figure 5. Comparison of pluton limits from field and geophysical data.
 (●) = Town of Coronaca

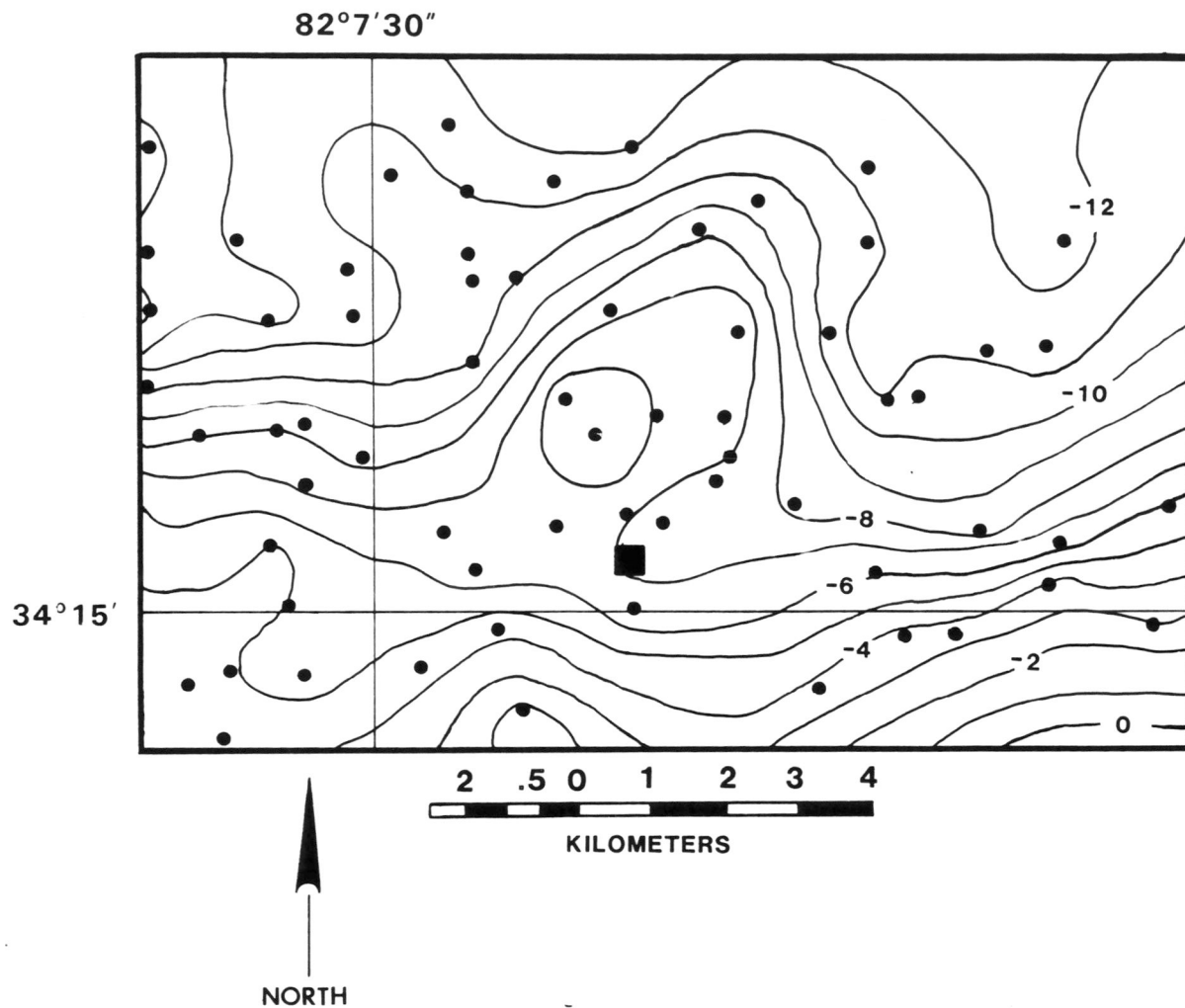


Figure 6. Contour map of observed Bouguer anomalies based on measured gravity stations (●). (■) = Town of Coronaca. Contour Interval = 1 mgal.

mafic rock of the Charlotte belt to the south (D. P. Lawrence, personal comm.).

Figure 7 is a 3-dimensional representation of the gravity map showing the location of the pluton with respect to the regional gradient. This diagram was produced using SURF 3-d Surface Program (version 1.00; Golden Software, 1984).

Magnetics

An aeromagnetic survey of South Carolina (US Geological Survey, 1978a) displays the Coronaca pluton as a magnetic high (Figure 8). The survey lines were flown east-west at an altitude of 500' and a line spacing of one mile. The magnetic high associated with the pluton reflects an underlying mass of magnetic rock. The anomaly suggests that mafic rocks are laterally more extensive at depth than at the surface.

Radioactivity

Aeroradioactivity surveys measure emissions from radioactive minerals in soil and bedrock, but unlike other geophysical methods, they are a measure of essentially a surface phenomenon (Pemberton, 1967). Soil type is a major controlling factor in that residual soils and saprolite tend to concentrate many radioactive elements. The Piedmont is an ideal region for interpretive aerorad studies because of the gently rolling topography, varied lithologies and residual

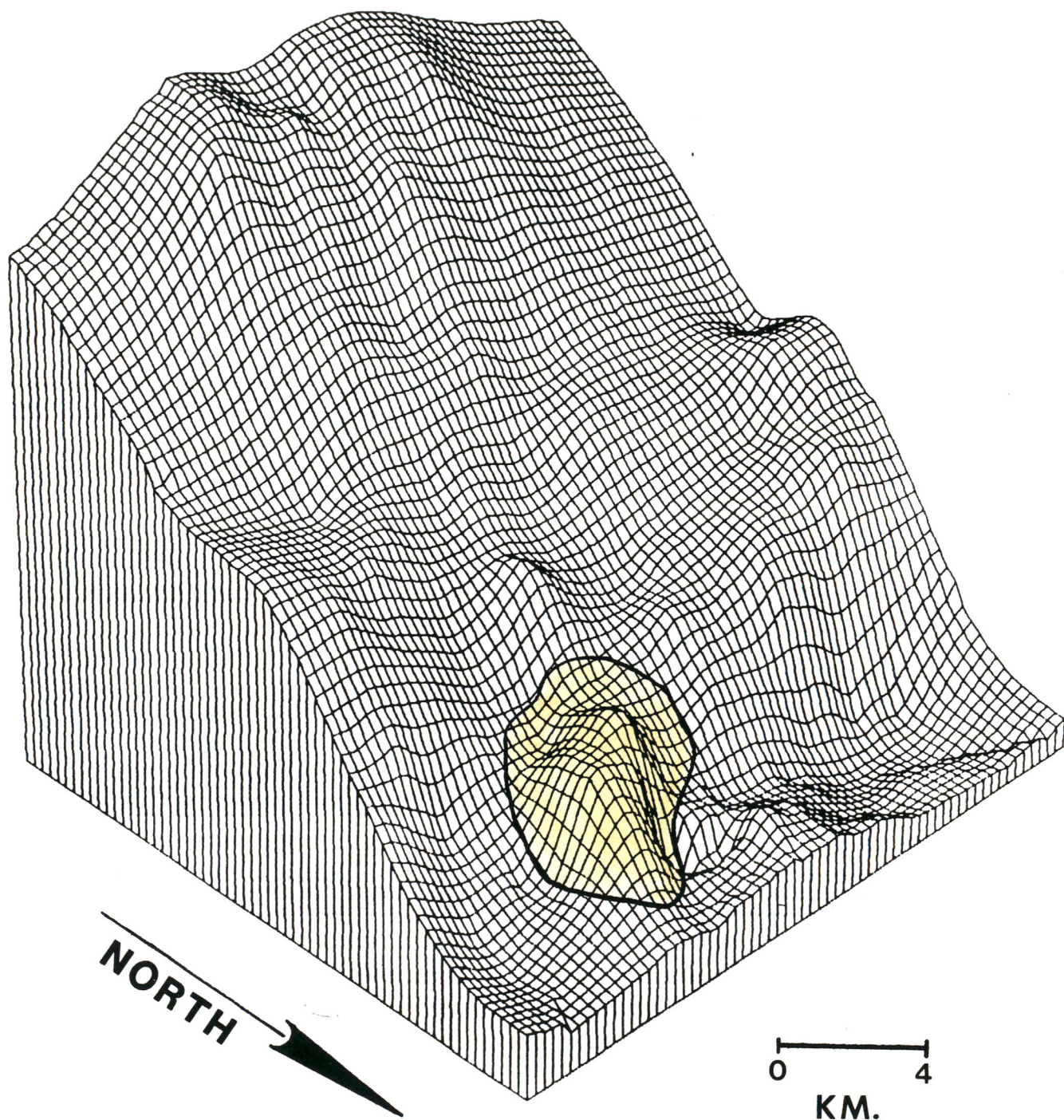


Figure 7. Three dimensional representation of the localized gravity high associated with the Coronaca pluton. The approximate pluton limits based on the geology are shown in yellow.

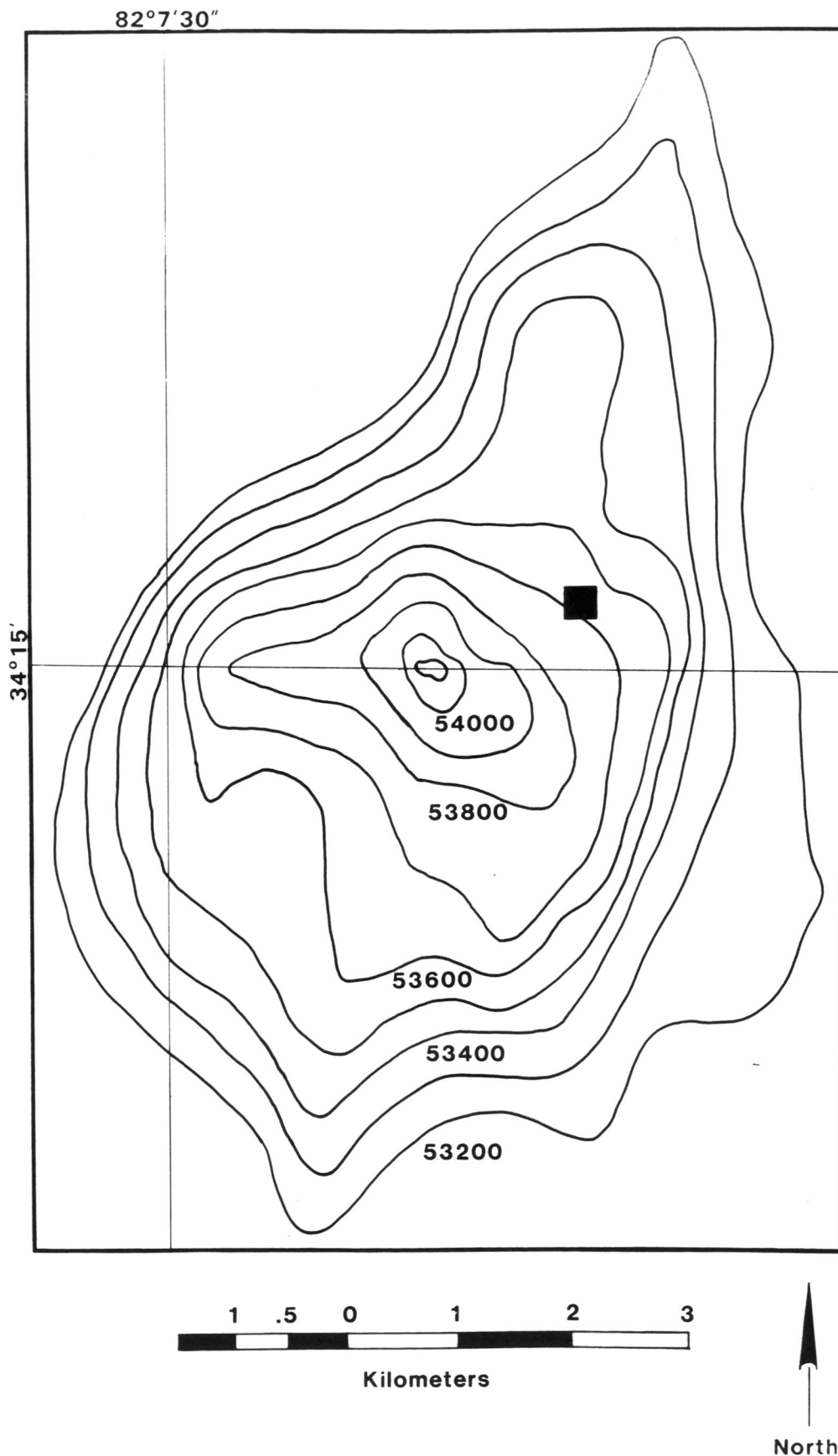


Figure 8. Aeromagnetic map displaying the magnetic high associated with the Coronaca pluton.
(■) = Town of Coronaca
Contour Interval = 100 gammas

soils (Pitken, 1968). Most of the gamma radiation measured is from cosmic rays, airborne radioisotopes (Rn and Ar40), surface radioisotopes (U, Th and K40) and extraneous aircraft radiation. The U, Th and K40 occur in K-feldspars and other minerals (ie. allanite, zircon and sphene) which tend to concentrate in felsic rocks.

The aeroradioactivity map used in this report was part of the South Carolina survey made by the USGS (1978b) (Figure 9). The purpose of the survey was to determine background gamma radiation in the regions adjacent to the Savannah River facility.

The aeroradioactivity map for the Coronaca area shows a radioactive high coincident with the pluton that reflects the surficial extent of felsic rocks. The contours are somewhat distorted due to the orientation of the east-west flight path utilized during the survey.

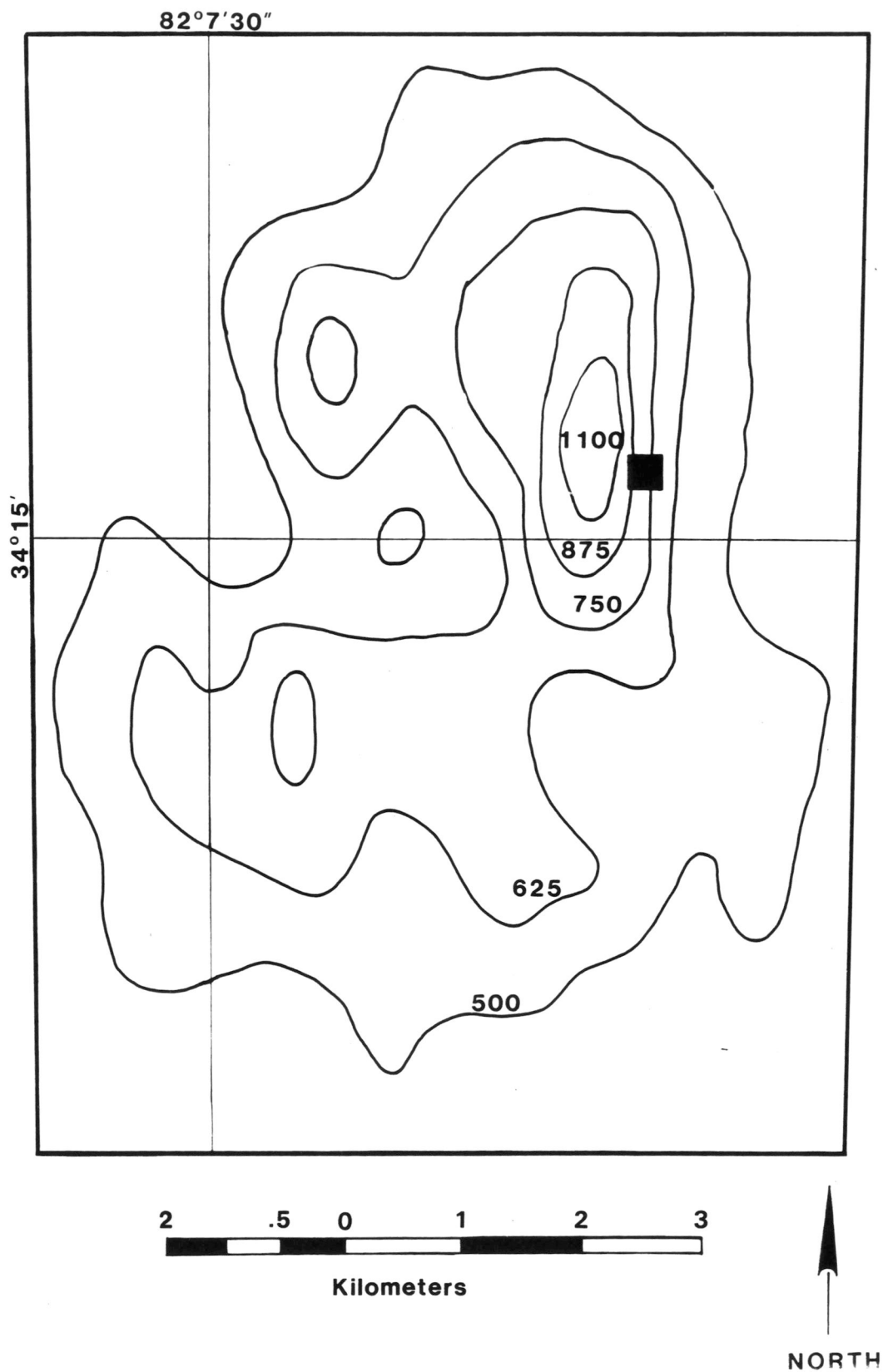


Figure 9. Aeroradioactivity map displaying the radioactive high associated with the Coronaca pluton. (■) = Town of Coronaca
Contour Interval = 125 cps

Petrography

Modal compositions of 57 samples are given in Appendix A. A minimum of 400 points were counted for each thin section. Thin sections were stained with sodium cobaltinitrite to differentiate potassium from sodium feldspars, and mafic rocks were stained with Trypan blue for cordierite detection. Plagioclase compositions were determined using the Michel-Levy method.

Felsic Rocks

Granites and quartz syenites display a coarse-grained, subhedral granular texture (Plate 10). Principal minerals include alkali feldspar (microperthite and microcline), plagioclase (An₂₀-An₂₄), quartz, biotite with associated hornblende and euhedral sphene. Microcline varies from pink to white in hand specimen; in some samples it occurs as megacrysts. Microperthitic textures are represented by sinuous lamellae of albite that cross-cut the tartan-twined microcline and by patches of exsolved albite within coarser K-feldspar grains (Plates 11 and 12). Finer grained, subhedral plagioclase commonly grades into a bulbous myrmekitic texture when in contact with microcline. Plagioclase grains may exhibit a faint discontinuous normal zoning with rare oscillatory zoning. Some grains display rims

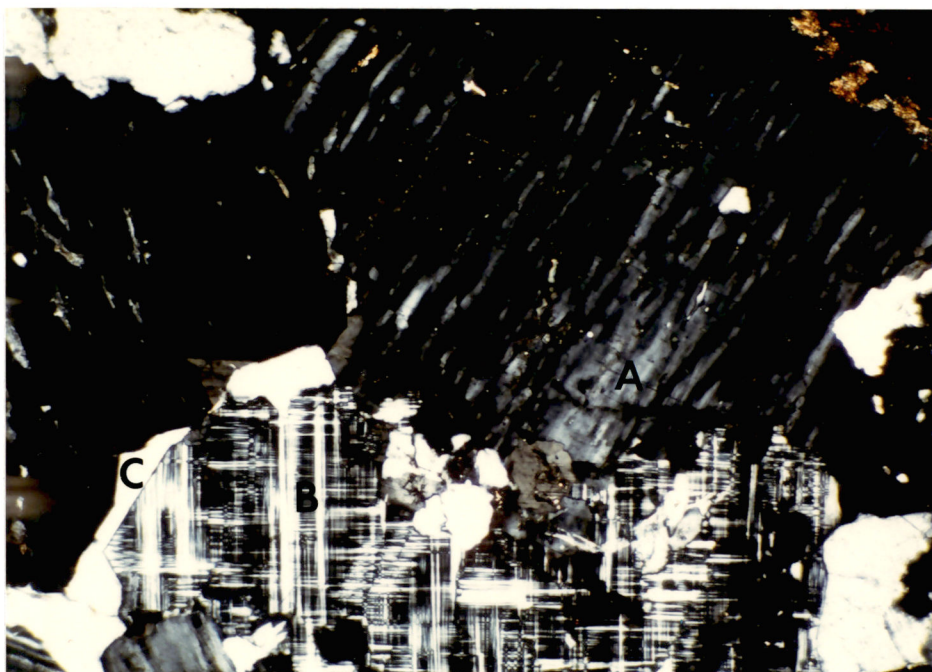


Plate 10. Granular texture of quartz syenite. Note the well developed perthitic texture (A), tartan twins (B) and interstitial quartz (C). Photo width = 3.08 mm.

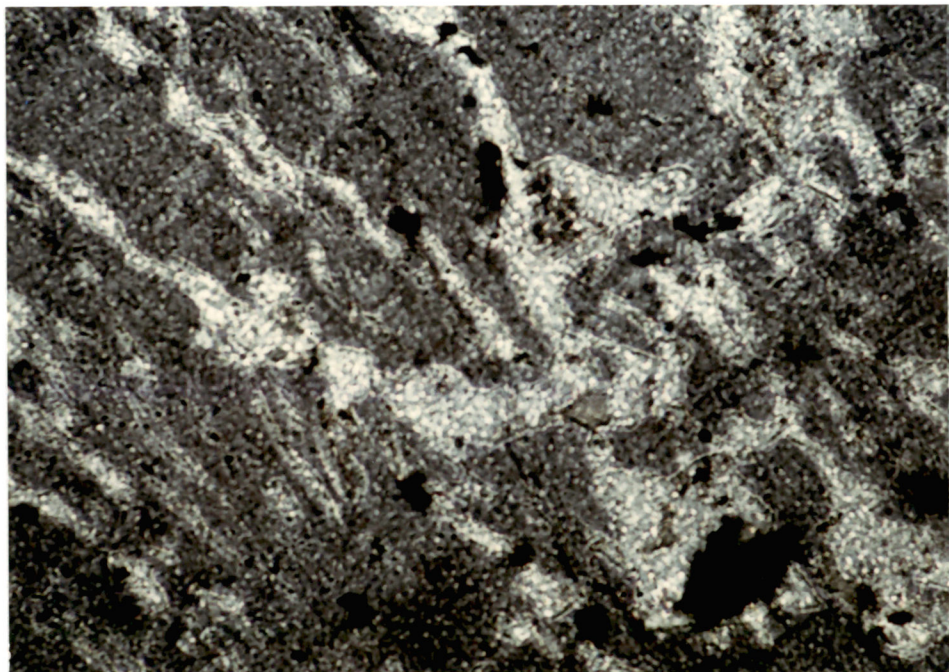


Plate 11. Microperthitic texture illustrating sinuous lamellae of Na-rich feldspar (light colored).
Sample CS-17
Photo width = 1.24 mm.

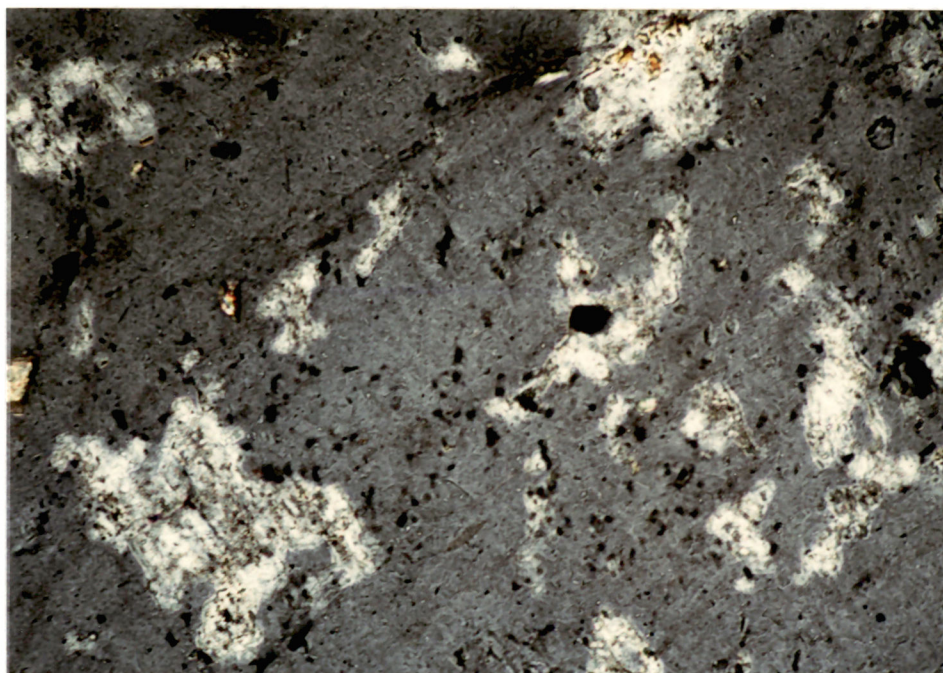


Plate 12. Microperthitic texture. Patchy intergrowths of Na-rich feldspar (light colored). Sample CS-38
Photo width = 1.24 mm.

of albite, especially those in contact with microcline. Quartz is found as fine- to medium-grained interstitial masses and as coarse anhedral grains. Coarse-grained biotite is the most common mafic phase and is found in association with hornblende. Biotite also forms occasional thin rims around opaque minerals. Allanite, zircon, apatite, pyrite, ilmenite, magnetite and fine-grained chalcopyrite are minor constituents.

Schlieren are fine-grained and mainly composed of biotite with alkali feldspar, plagioclase, hornblende and disseminated blebs of magnetite with intergrown lamellae of ilmenite (Plate 13).

The aplites and pegmatites are mineralogically identical. Common minerals include alkali feldspar (microcline), plagioclase, coarse-grained quartz, biotite and minor muscovite. Euhedral tourmaline is a rare phase in the aplites. Aplites display a micrographic texture and pegmatites are coarse-grained with an anhedral texture. Pegmatites also display fractures (indicative of brittle deformation) that are lined with microcrystalline quartz (Plate 14).

Alaskites are compositionally alkali feldspar granites displaying a coarse-grained, subhedral equigranular texture (Plate 15). Major minerals include alkali feldspar, quartz, plagioclase and biotite. The alkali feldspar is microcline and plagioclase is predominantly albite with minor oligoclase. Bulbous myrmekite and micrographic intergrowths between alkali feldspar and plagioclase are common

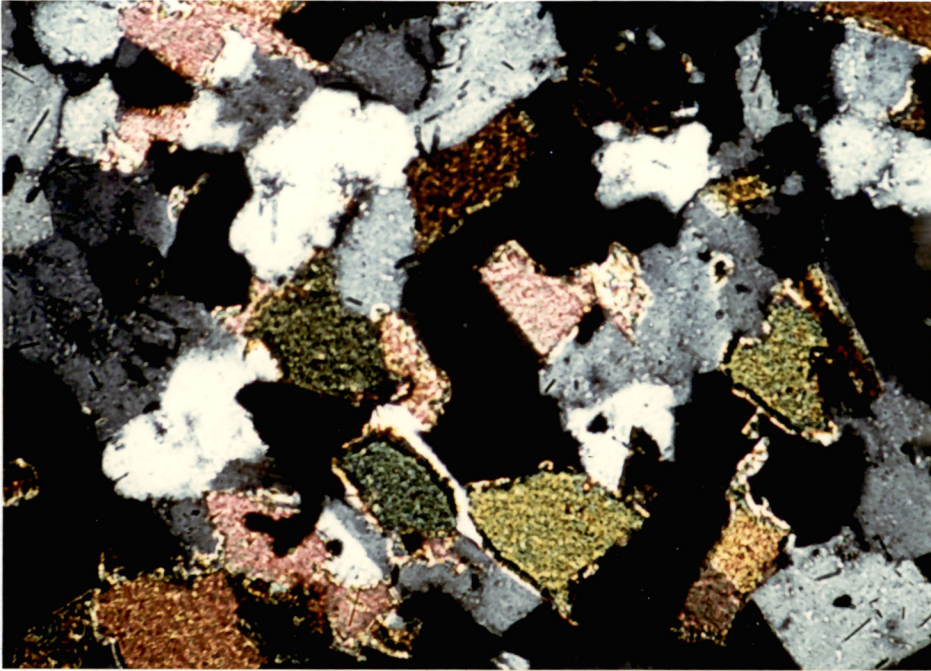


Plate 13. Fine-grained texture of schlieren. Birefringent grains are biotite and polygonal grains are alkali feldspar
Sample CS-6
Photo width = 1.24 mm.

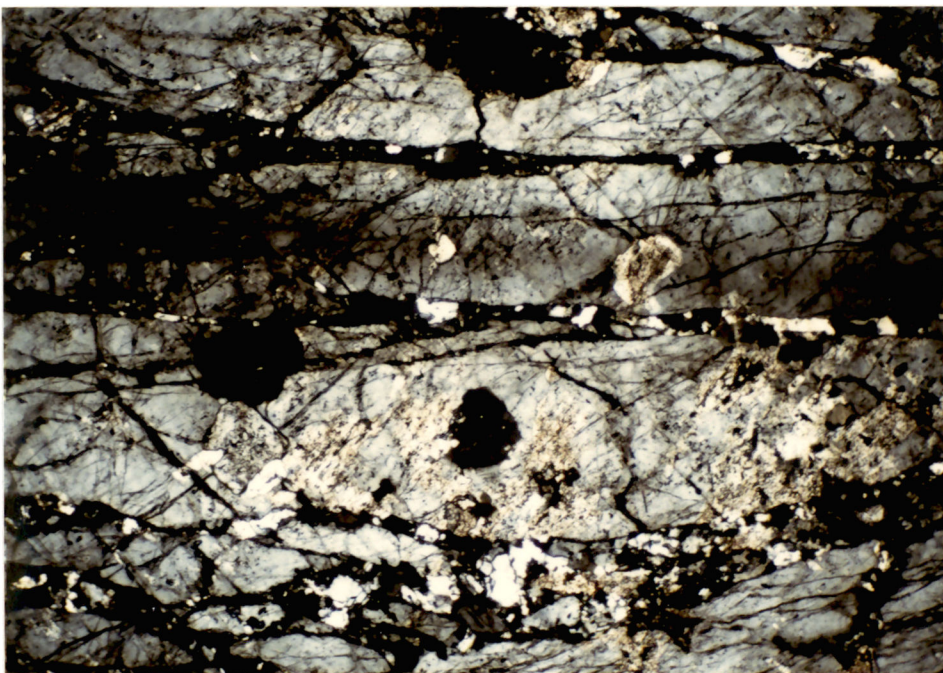


Plate 14. Quartz lined microfractures in pegmatite.
Sample CS-13. Photo width = 3.08 mm.

microtextural features. Minor constituents include allanite, zircon, tourmaline and apatite.

Intermediate Rocks

Intermediate rocks display more variability in texture and composition than do the felsic and mafic rocks. Grain sizes range from medium- to coarse-grained and textures are equigranular to porphyritic.

Monzonite and quartz monzonite are medium-grained and have a subhedral granular texture (Plate 16). Major mineral phases include plagioclase (average An₃₀), alkali feldspar (microcline and microperthite), biotite, clinopyroxene, hornblende, interstitial quartz, and anhedral sphene. Minor constituents include magnetite, ilmenite, chalcopyrite, pyrite, zircon and apatite. Myrmekitic textures between alkali feldspars and plagioclase are common. Occasional alkali feldspar grains display a weak normal zoning. Monzonite contains fine grains of clinopyroxene which poikilitically enclose hornblende and biotite.

Quartz monzodiorite has a coarse-grained, subhedral poikilitic texture with coarse biotite enclosing plagioclase, quartz, microcline and clinopyroxene (Plate 17). Modal mineral compositions are similar to monzonite except for a higher percentage of clinopyroxene. Small grains of intergrown magnetite-ilmenite, pyrite and chalcopyrite are evenly disseminated throughout the rock.

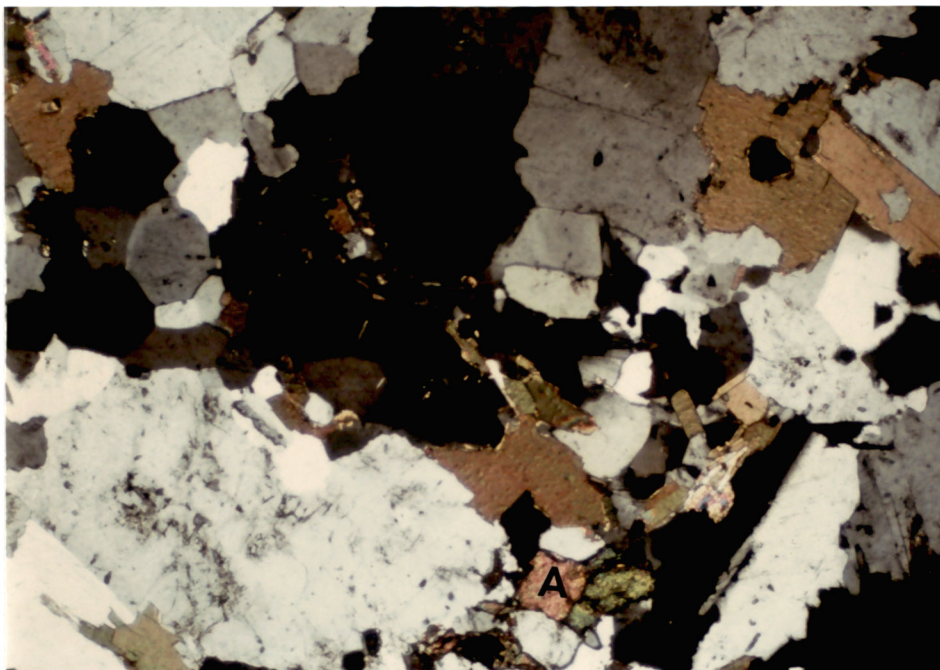


Plate 15. Coarse-grained, granular alaskite composed of alkali feldspar, quartz and biotite. Grain labeled A is allanite. Sample CS-62 Photo width = 3.08 mm.

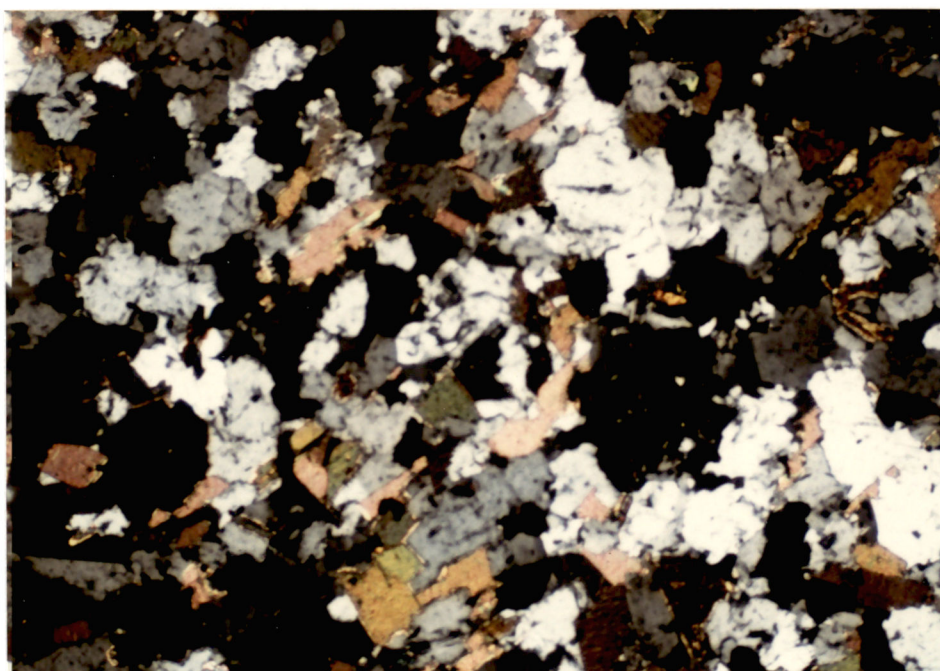


Plate 16. Typical medium-grained, subhedral texture of monzonite. Sample CS-9 Photo width = 3.08 mm.

Monzodiorite is fine grained and glomeroporphyritic with clumps of zoned alkali feldspar and biotite (Plate 18). Major minerals include plagioclase (An30-An35), biotite, hornblende, clinopyroxene, orthopyroxene, alkali feldspar (microcline), quartz and opaque minerals. The opaques include intergrown lamellar magnetite-ilmenite, pyrite, chalcopyrite and pyrrhotite (?). Epidote, hematite, zircon and apatite are minor phases.

Mineralogical and textural features common to the syenites, monzonites and monzodiorites include fine- to medium-grained clinopyroxene associated and/or intergrown with biotite, hornblende and opaque minerals. Myrmekitic intergrowths of plagioclase, quartz and alkali feldspar are common microtextural features. Biotite is coarse grained, commonly poikilitic and contains irregular intergrowths of hornblende.

Mafic rocks

Norites and leuconorites are subophitic, subhedral and coarse grained (Plate 19). Principal minerals include plagioclase (An40 to An60), biotite, orthopyroxene, hornblende, clinopyroxene, alkali feldspar and numerous opaque phases. Subhedral orthopyroxene ranges from medium to coarse grained with fibrous, thread-like inclusions (Plate 20). Plagioclase occurs as medium to coarse subhedral laths and as finer-grained interstitial masses. The coarser grains

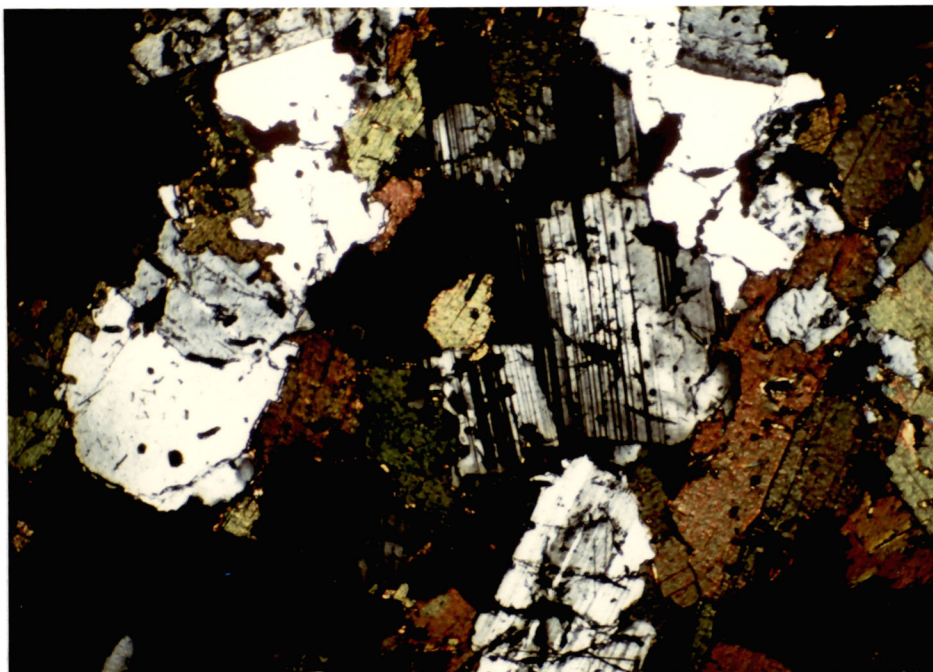


Plate 17. Quartz monzodiorite displaying poikilitic texture in biotite. Sample CS-16 Photo width = 3.08 mm.

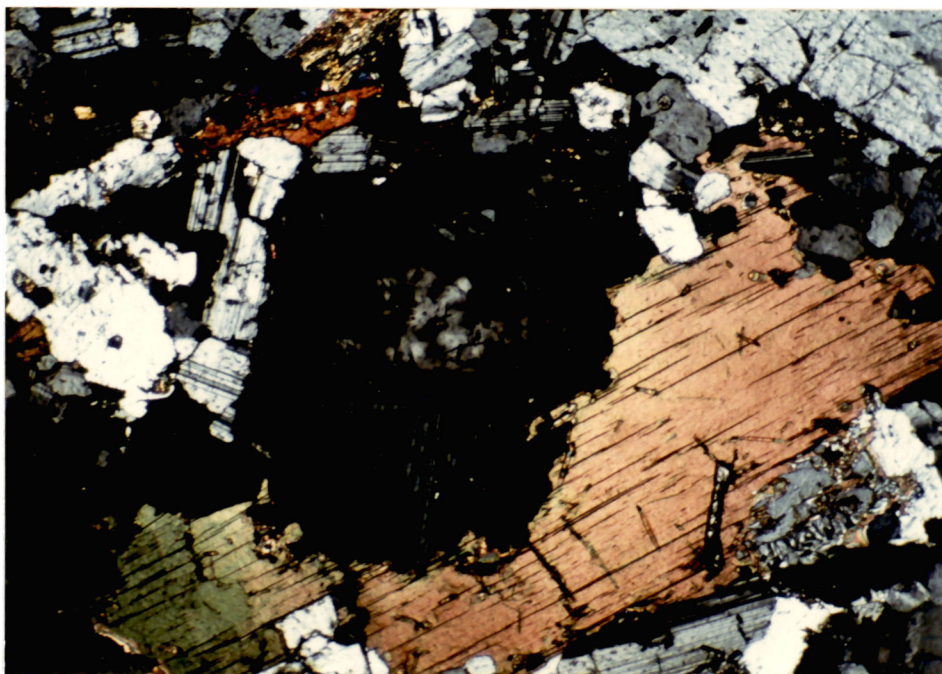


Plate 18. Monzodiorite- Glomerocryst of biotite and zoned alkali feldspar in a finer grained groundmass. Sample CS-34 Photo width = 3.08 mm.

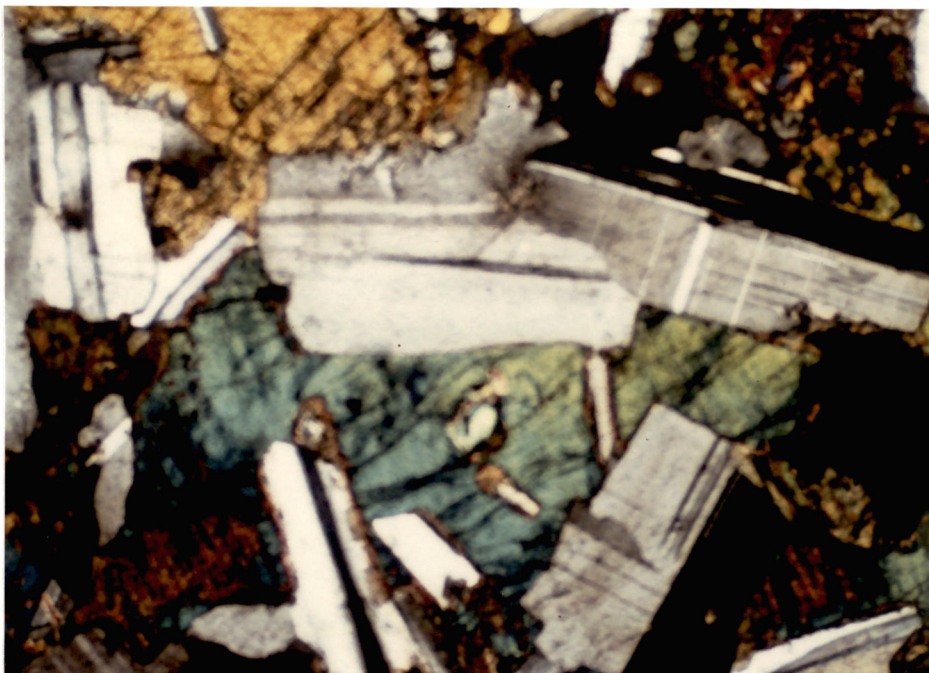


Plate 19. Subophitic texture in norite. Sample CS-17a
Photo width = 3.08 mm.

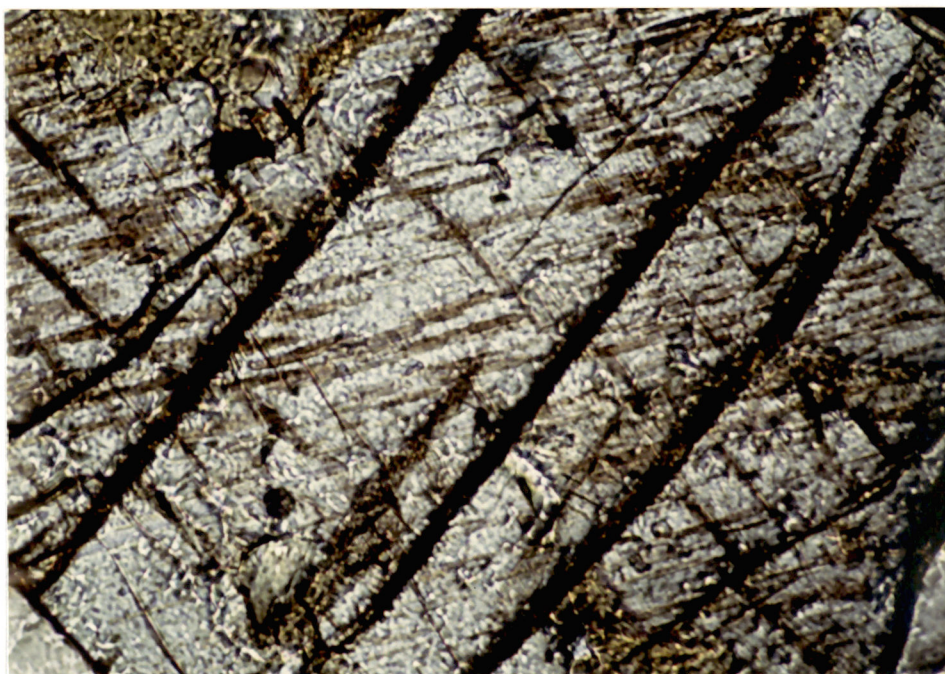


Plate 20. Thread-like inclusions in orthopyroxene from
norite. Sample CS-49
Photo width = 1.24 mm.

commonly display a discontinuous normal zoning. Plagioclase laths and clinopyroxene are occasionally enclosed or partially enclosed by larger orthopyroxene grains (Plate 21). Biotite is medium to coarse grained and is occasionally rimmed by hornblende. Biotite also displays a consertal texture in association with plagioclase and hornblende. Fine-grained sulfides and Fe-Ti oxides are associated with biotite-hornblende intergrowths, and coarser grains occur alone. Determination of opaque minerals is based on reflected light methods as described in Craig and Vaughn (1981). These minerals include intergrown magnetite-ilmenite, pyrite and chalcopyrite. X-ray diffraction analyses reveal the presence of pyrrhotite. An unidentified opaque phase is thought to be pentlandite based on the unusually high Ni concentrations in some norite samples. Minor minerals include interstitial quartz, epidote, and calcite. Small-scale textural features include symplectic intergrowths of magnetite and orthopyroxene (See Plate 21).

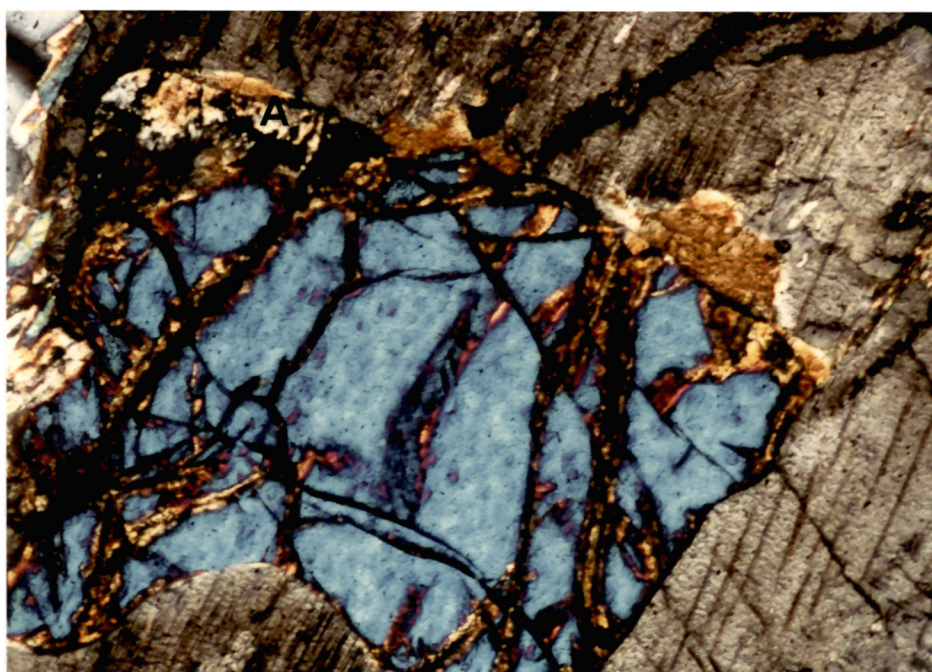


Plate 21. Clinopyroxene grain (blue) enclosed by orthopyroxene from norite. Note symplectic intergrowth (A)
Photo width = 1.24 mm.

Sample Preparation and Analytical Procedures

Samples for geochemical analysis were selected on the basis of size, degree of weathering, lithology and spatial location (Figure 10). The samples selected were the least weathered samples which were approximately 1000 times greater in volume than the average grain volume. At least one sample was analyzed for each exposed lithology. Appendix E gives estimated precision and accuracy for each analysis.

Samples were slabbed (5 x 7 cm.) to remove any weathered material and mechanically fragmented using a Type VD Bico-Braun chipmunk crusher. Fragmented samples were ground to sand size using a ceramic disc Bico-Braun UD pulverizer. Three samples (10% of total unknown samples) were randomly selected for replicates to determine analytical precision. The replicates were separated and treated as discrete samples. An approximately 50 gm. representative subsample was obtained from each pulverized sample. A split of the subsample was milled for 10 minutes to a powder, using a Spex #8000 mixer/mill. Standards were received as powders and prepared identically to samples.

Approximately 3 grams of the milled sample were used to produce a pressed-powder rock disc with a boric acid backing for XRF analysis as described by Hutchison (1974).

Silica, TiO_2 , MnO , CaO , P_2O_5 , Ba, Rb, Sr, Y and Zr concentrations were determined using a General Electric XRD-6

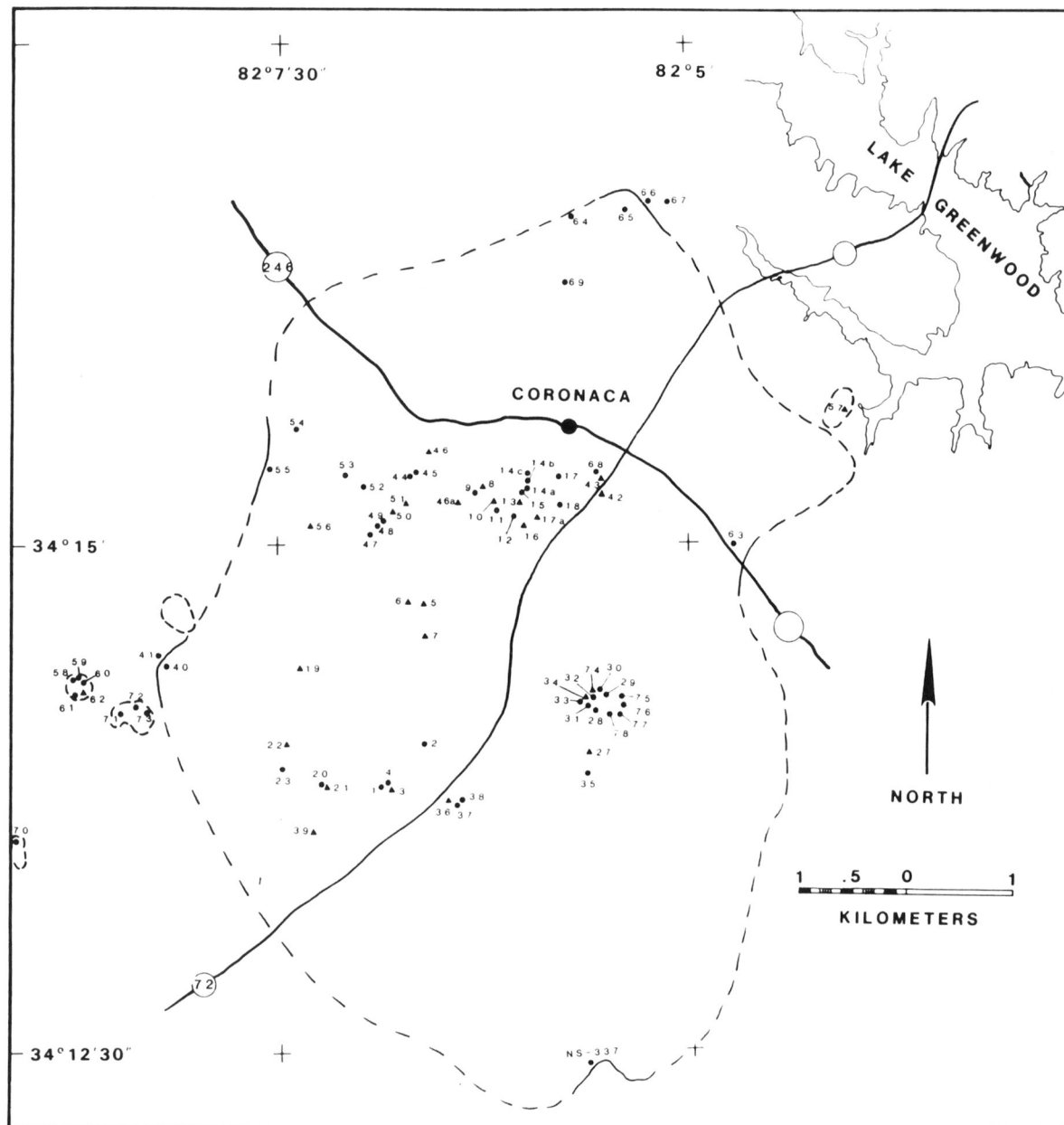


Figure 10. Locations of samples used in the study.
 (•) = geochemical sample

spectrometer. Operating conditions used for each element are listed in appendix C. Standard curves produced from analyzed rock standards were plotted as counts per second versus weight percent (or ppm). Standards were measured randomly during the sample run. Compensation for instrumental drift was made by plotting counts per second versus relative time position of sample during the run. Rubidium, Sr, Y and Zr concentrations were measured by the method of Drez (1977) using the Mo Compton (Mokac) scattering intensity measurement. Reynolds (1967) demonstrated that the Mo Compton peak is indicative of mass absorption and true background for the Rb, Sr, Y and Zr Ka peaks. Calibration curves were produced for spectrographically pure salts (which do not contain one or more of the elements to be analyzed) by measuring Ka for each element and Mokac. The calibration curves are used to estimate the background correction for each sample using Mokac as the background indicator.

Samples for spectrophotometric analysis were decomposed and diluted to 500 ppm solutions (Bernas, 1968) using a polypropylene bomb and 125 mg. of sample. Blanks were prepared in the same manner.

Magnesium, K₂O, Fe₂O₃, Al₂O₃ and Na₂O analyses were performed on an Instrumental Laboratories Model 457 atomic absorption spectrophotometer. The fuel and oxidant flow rates, flame type and operating conditions are those specified in the instruction manual (Instrumental Laboratories 457). Operating conditions for each element are listed in Appendix C. Standard

curves are plotted as absorbance versus weight percent. Due to the wide range in MgO (0.05-12.6 wt. %) and Fe₂O₃ (0.21-12.39 wt. %) concentrations, separate analyses were made of high and low concentration groups of samples for each element. This procedure produced standards curves with a lower compositional range and therefore increased accuracy for each analysis.

In addition to XRF determinations of SiO₂, analyses were also performed on a Hitachi Model 100-60 U-V visible spectrophotometer. Shapiro (1975) describes the titration procedure and reagents for analysis. The SiO₂ weight percentage values in Appendix D are averages of the XRF and U-V visible analyses.

Formvar solutions (2% formvar solution in 1,2 dichloroethane) were used for mounting samples for energy dispersive x-ray analysis. The solution forms a thin film on the surface of water which is mounted on the inner surface of a 35mm photographic slide mount. A dry, powdered sample is sprinkled on the inner surface of the slide. This infinitely thin film eliminates mass absorption corrections.

Chromium, Cu, Ni, Pb and Zn were determined using a KEVEX Model 0600 energy-dispersive XRF. Instrument settings are presented in Appendix C. Concentrations were determined using best-fit computer generated linear standards curves. Literature values of standards concentrations and instrument readings of EDXRF data were used to determine sample concentrations.

Loss on ignition (LOI) and H₂O- were determined gravimetrically on 1 gram subsamples with measurements taken after heating one hour at 110° C for H₂O- and after 8 hours at 1000° C for LOI.

Rock Chemistry

Locations of the 29 geochemical samples are shown in Figure 10. Geochemical and CIPW normative data are presented in appendix D. In calculating CIPW norms, total iron was partitioned to FeO and Fe₂O₃ using the methods of Carmichael and others (1975). Chromium, Cu, Pb and Ni concentrations for the Coronaca suite are very near the detection limit of the analytical methods.

General Chemistry of the Main Rock Types

On the basis of major and trace element chemistry, the Coronaca suite is divided into three distinct groups. Mafic rocks fall into a group with SiO₂ concentrations between 46 and 52 wt. %. Felsic rocks have SiO₂ concentrations between 62 and 73 wt. % and intermediate rocks fall between 53 and 61 wt. %. Intermediate composition rocks show the most chemical variability and display complex major and trace element variations with respect to SiO₂ (Figure 11).

Modal anorthite content (An) ranges from An₂₄ (granitic) to An₅₄ (noritic) and decreases with increasing SiO₂ content throughout the suite of rocks. The increase in An content correlates ($r = 0.82$) with a similar observed increase in CaO concentration.

Rocks of granitic composition commonly plot together on variation diagrams. Compared to average granites worldwide (Le Maitre, 1976), Coronaca granites contain a higher K₂O content,

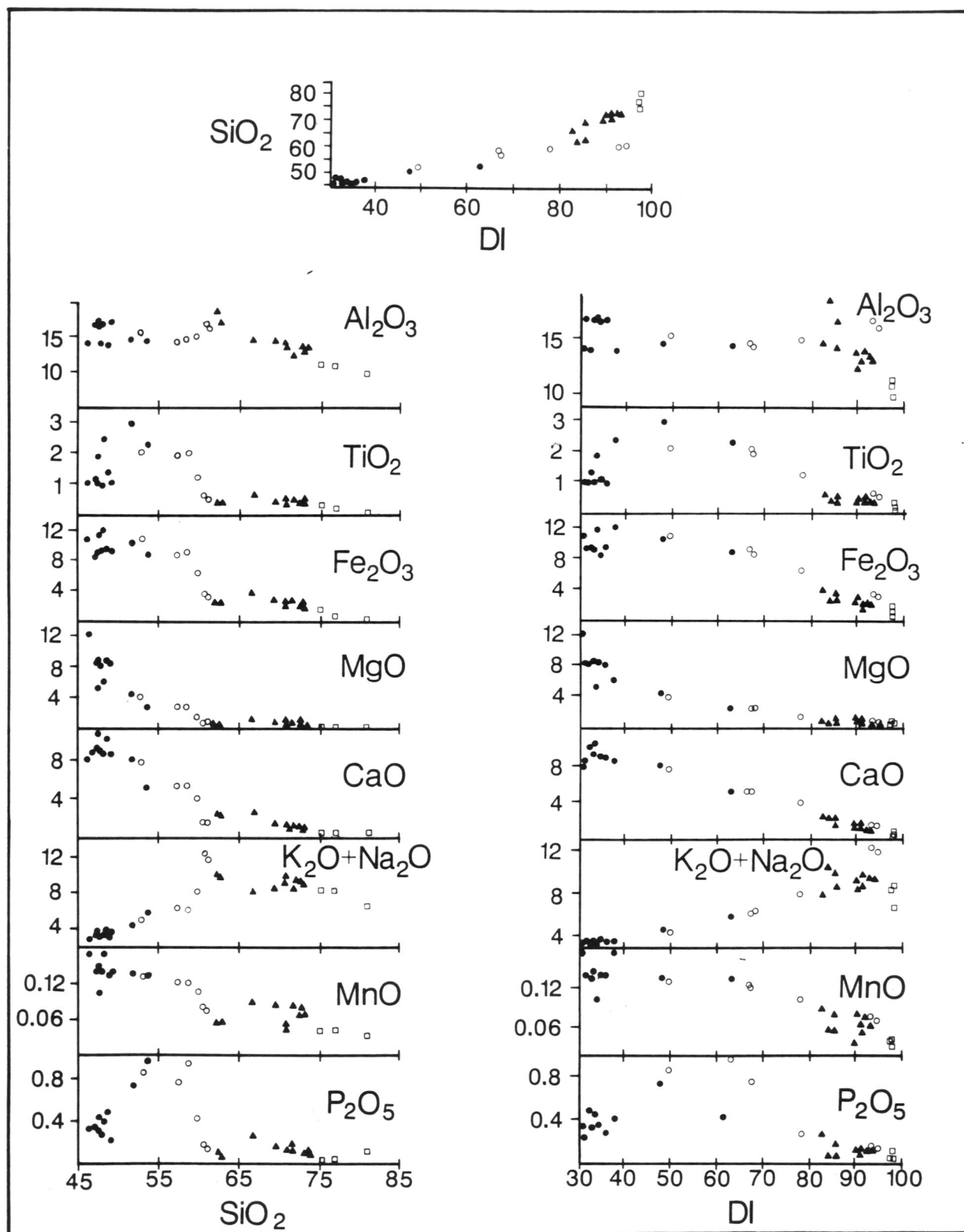


Figure 11. Major element variation diagrams for Coronaca rocks.
 (•) = mafic rocks, (◦) = intermediate rocks,
 (▲) = felsic rocks, (◻) = alaskites

but display similar major element characteristics. K_2O is greater than Na_2O for all analyzed Coronaca granites. An expected enrichment in LIL elements (Rb, Y and Zr) is also present in felsic composition Coronaca rocks.

Intermediate composition rocks (53-62 wt. % SiO_2) display the most variable chemical behavior. The two syenite samples (CS-5 and CS-32) have SiO_2 concentrations (58.5 and 59.8 wt. %) similar to world average syenites (59 wt. %). CS-32 and CS-5 also have higher TiO_2 content (1.31 and 2.08 wt. %, respectively) than world syenites (0.84 wt. %).

Quartz monzonites of the Coronaca range in SiO_2 content from 53 to 57 wt. % (compared to world average of 63 wt. %). Other major element concentrations are comparable to world average values.

Quartz syenite samples CS-42 and CS-42m are grouped with intermediate composition rocks because of their anomalous chemical behavior. These two samples plot consistently off trend for most major and trace elements. Compared with world average adamellites, these samples have low SiO_2 , CaO and K_2O concentrations and higher Al_2O_3 and Na_2O content.

Intermediate rocks tend to show enrichment in elements associated with opaque oxides and sulfides (TiO_2 and Zn), non-silicate minerals (P_2O_5) and incompatible elements (Zr and Ba). The abundances of P_2O_5 and Zr may correlate with high modal percentage of apatite in intermediate composition rocks. Wager and Mitchell (1951) found that Zr and Y increase in concentration in the residual liquid with differentiation and may preferentially substitute for Ca in apatite.

The norites are the most chemically homogeneous rocks of the pluton. Concentrations of major and trace elements are comparable to world average norites, except for a relative enrichment in the transition metals Fe, Mn, and Ni.

Differentiation Index

The differentiation index can be used to estimate the position of a sample in a differentiation sequence. The differentiation index (DI) reflects the tendency of magmatic differentiation to enrich residual fluids in the felsic minerals (petrogeny's residua system) (Best, 1983). The DI is defined as the sum of normative quartz + orthoclase + albite + nepheline + kaliophilite + leucite (Thornton and Tuttle, 1960). A plot of SiO₂ versus the differentiation index for Coronaca rocks is shown in Figure 11.

Major Elements

The three chemical groups of Coronaca rocks are represented on Harker diagrams with different symbols.

Calcium, MgO and Fe₂O₃ display the most coherent trends with respect to SiO₂. Points from mafic rocks plot more in clusters and show less direct correlation with DI or SiO₂ than do the more felsic lithologies.

Aluminum, TiO_2 , MnO and the alkalis display relative enrichments in the intermediate composition syenites and quartz syenites. These rocks, however, bias the Harker plots because they are relatively low in SiO_2 but highly differentiated. When the same elements are plotted versus the DI, more linear trends result because the highly differentiated syenites and quartz syenites plot more on trend and eliminate the apparent enrichment.

P_2O_5 analysis produced low values that approached the detection limit; therefore the data provide little value for geochemical interpretation. Variation diagrams of P_2O_5 versus SiO_2 and P_2O_5 versus DI display an apparent enrichment in rocks of intermediate composition.

Compositionally, Coronaca suite rocks fall in the calc-alkaline field on an AFM diagram but show a slight trend toward iron enrichment (Figure 12). The Coronaca suite can also be characterized as calc-alkaline according to the alkali-lime index (Peacock, 1931) (Figure 13).

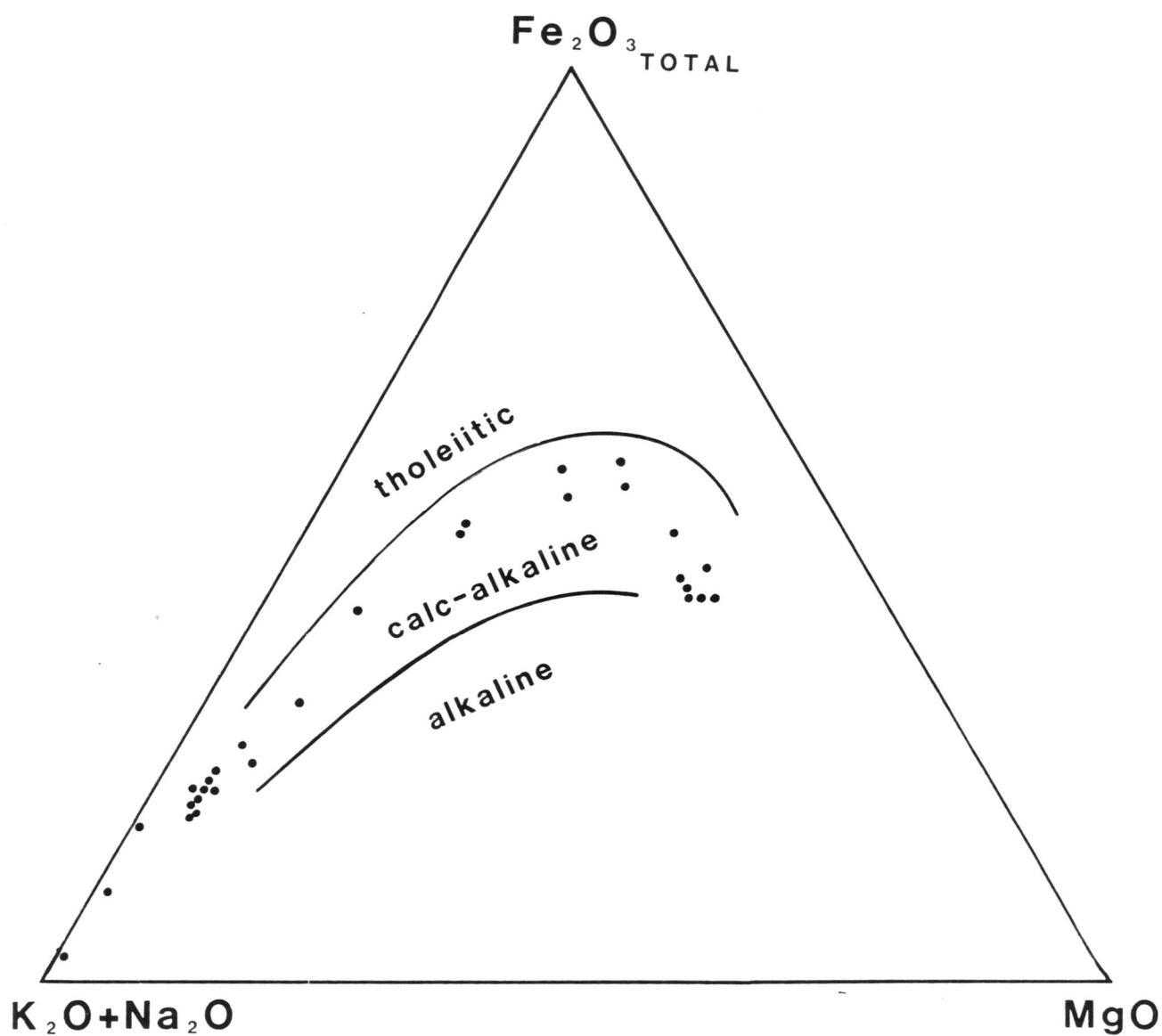


Figure 12. AFM diagram for Coronaca suite. Solid curves separate fields of tholeiitic, calc-alkaline and alkaline rocks.

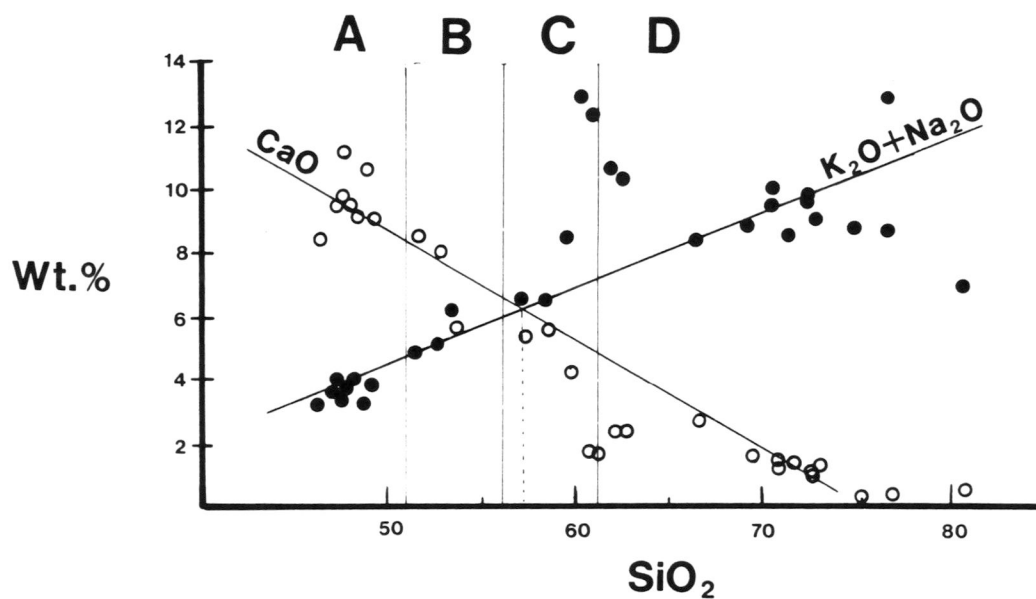


Figure 13. Peacock plot for Coronaca suite rocks. These fields are labeled A= alkalic, B= alkali-calcic, C= calc-alkaline, D= calcic. Dashed line represents SiO₂ value (57%) for intersection of CaO and K₂O + Na₂O best-fit line.

Trace Elements

Trace element variation of Coronaca rocks is shown in Figure 14. Strontium, Rb and Y display curvilinear trends on the Harker plots. The two low Sr samples that plot off the main trend are the anomalous quartz syenite samples (CS-43 and CS-43m). When plotted versus the DI, the highly differentiated nature of these quartz syenite samples is illustrated. The low Y concentrations may be approaching the analytical detection limits. The three samples with high Y concentrations were found to contain substantial amounts of allanite.

The Harker plot for Zr shows relative enrichment in rocks of intermediate composition. Zirconium versus the DI displays a nearly linear trend for mafic and intermediate rocks, while more felsic lithologies plot as a group below the trend. Barium variations show scatter in intermediate rocks but mafic and felsic lithologies plot in clusters. Barium commonly substitutes for K in feldspars but in Coronaca rocks there is little correlation between Ba content and modal K-feldspar ($r=0.34$) or weight percent K₂O ($r=0.37$). Zinc shows a strong negative correlation with SiO₂ in felsic and intermediate lithologies, but plots as a cluster for the mafic compositions (Figure 15).

Chromium, Cu and Pb content is low for all phases in the Coronaca. Nickel content is much higher for the norites than in all other phases. Nickel is removed during crystallization of

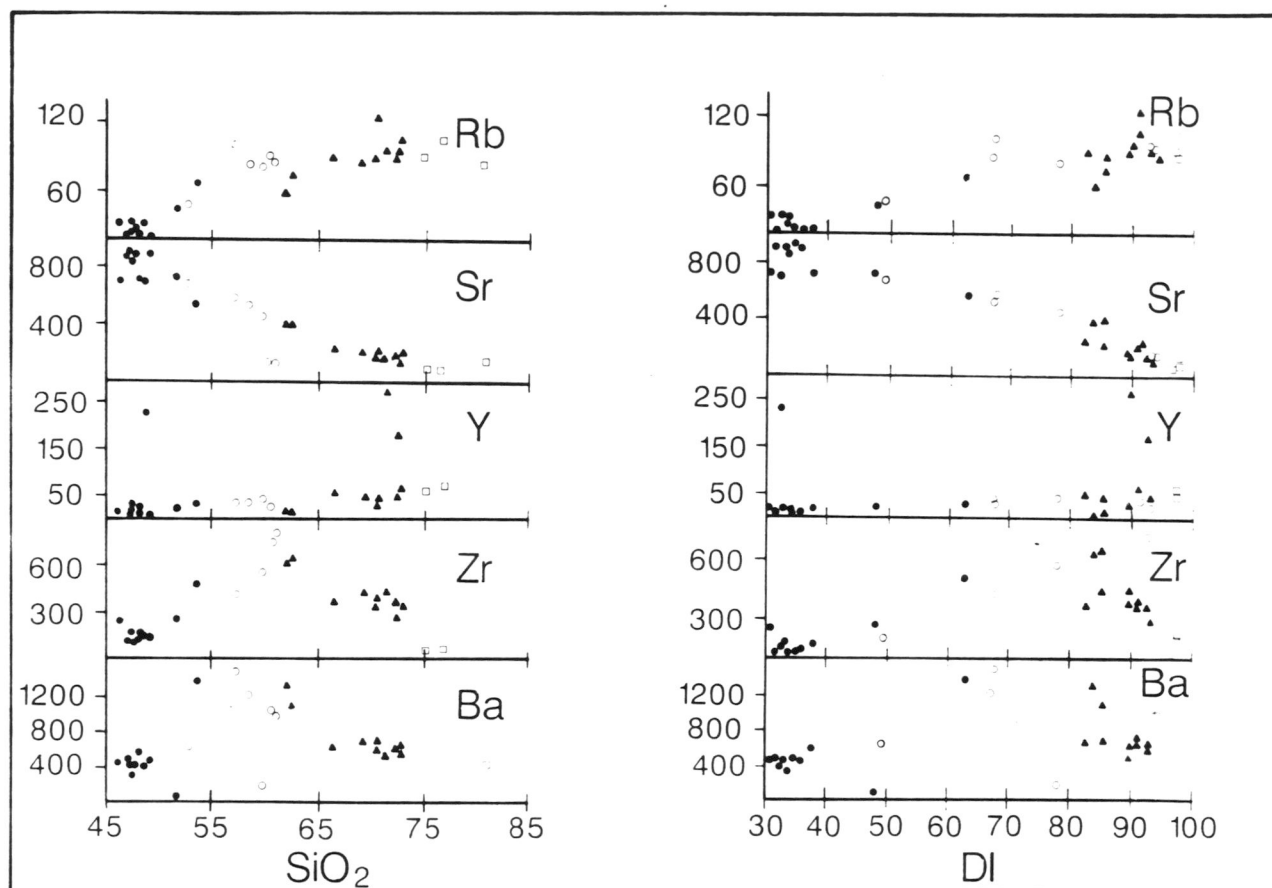


Figure 14. Trace element variation diagrams for Coronaca rocks.
 (•)= mafic rocks, (◦)= intermediate rocks,
 (▲)= felsic rocks, (◻)= alaskites

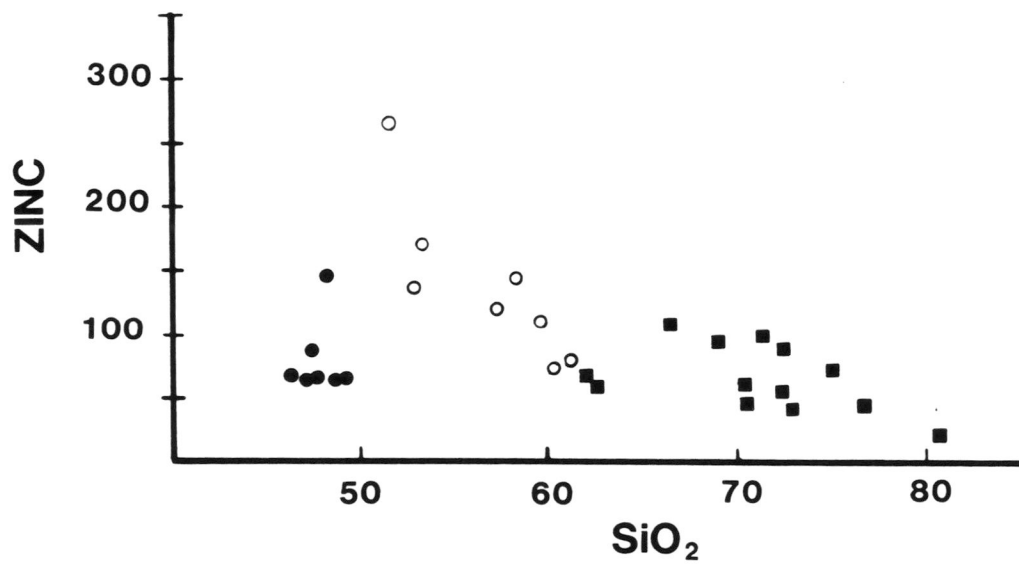


Figure 15. Zinc Harker plot showing negative correlation for intermediate (o) and felsic (■) rocks. Mafic (●) rocks fall below this trend.

olivine in the early stages of solidification, and any remaining Ni will preferentially enter octahedral sites in pyroxenes, leading to the depletion of Ni in the derivative magma (Taylor and others, 1969).

Discussion

The petrology and bulk-rock geochemistry of each lithology reveals a relationship indicative of a common petrogenetic history for the rocks in the Coronaca pluton. A comagmatic origin is suggested by: 1) coherent variations in major and trace element content, illustrated by curvilinear trends on variation diagrams; 2) an apparent lithologic gradation from a mafic norite through intermediate compositions (syenite, monzonite and monzodiorite) to the most evolved granite; 3) sharp internal contacts between lithologies are lacking and 4) lack of regional foliation which may indicate a common age.

The diverse but comagmatic lithologies of the Coronaca pluton may have arisen by: 1) magma mixing, 2) magma assimilation or partial melting of felsic wall rock, or 3) differentiation of a single magma by fractional crystallization.

Lithologic compositional differences in the Coronaca suite may have been produced by fractional crystallization. As crystallization proceeds in the undifferentiated magma, the compositions and proportions of minerals being removed are constantly changing. This is likely to produce a curvilinear trend on the Harker plots and a more linear trend on the DI variation plots (McBirney, 1984). From the Harker and DI plots, the intermediate composition quartz syenites and syenites are shown to have relatively low SiO₂ content,

but are highly differentiated. The unusual geochemical behavior of these rocks may be a function of their low modal quartz content and abundance of late-stage felsic minerals. The AFM diagram also demonstrates the chemical gradation between lithologies, and shows a moderate iron-enrichment trend like that observed in many strongly differentiated gabbroic suites (ie. Skaargard, Muskox, etc.).

To determine source material composition for felsic portions of the Coronaca, the properties outlined by Chappell and White (1974) and White and Chappell (1983) can be used to estimate whether the parent rock to a granite is sedimentary (S-type) or igneous (I-type). The rocks of the Coronaca have definite I-type affinities based on geochemical and mineralogical properties (Table 1). Characteristics for I-type granitoids suggest that source rocks are fractionated by-products of relatively mafic lower crustal/upper mantle rocks. A low Sr^{87}/Sr^{86} ratio for the granite/quartz syenite implies little upper crustal contamination. The magma is most likely derived from a primitive source (lower crust/upper mantle).

The post-tectonic Coronaca pluton lacks the regional foliation that is characteristic of the meta-igneous rock of the Charlotte belt. The comparatively young age (278 ± 2) supports an origin associated with a late Alleghanian magmatic event.

Radioactivity, magnetic and gravity anomalies coincide closely with the exposed pluton. The gravity and magnetic

Table 1

PARAMETERS SUGGESTING I-TYPE PARENTAGE
FOR THE CORONACA COMPOSITE STOCK

MINERALOGY

Felsic minerals	overall low quartz content
Mafic minerals	Biotite common Muscovite absent
Opagues	magnetite-ilmenite-pyrite -pyrrhotite
Accessories	sphene common
Inclusions	igneous appearance

CHEMISTRY

SiO ₂	wide range (52.88 - 72.6) overall avg. = 64.97
Na ₂ O	>2.2 in mafics >3.2 in felsics
$\frac{\text{Al}_2\text{O}_3}{\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO}}$	<1
CIPW Norm	corundum = 0
Cr	low (avg. = <40 ppm)
Ni	low (avg. = <50 ppm)
⁸⁷ Sr/ ⁸⁶ Sr	low (0.7045 $\pm$.0002)

anomalies indicate a denser, more magnetic body at depth and the radioactive highs show the areal extent of the surficial felsic rocks. These geophysical data suggest that the Coronaca pluton may have a felsic cap which overlies a larger, more mafic body at depth.

CONCLUSIONS

1. The study has revealed that the Coronaca pluton is a composite stock, subdivided on the basis of petrology and geochemistry. Three distinct, apparently gradational phases make up the pluton. The felsic phase consists of granite and quartz syenite, the intermediate phase consists of quartz monzonite, quartz monzodiorite, syenite, monzonite and monzodiorite and the mafic phase consists of norite.
2. Geophysical data suggests that the norite is actually more widespread and may underlie the pluton at depth. At the surface the norite appears to be a minor component.
3. Major and trace element variations suggest that the entire suite is comagmatic. An origin involving fractional crystallization is preferred. Evidence from Sr isotopes points to a primitive upper mantle or lower crustal source. From petrologic and chemical data, the granite/quartz syenite are I-type further supporting a comagmatic origin.

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Appendix A

Modal Compositions

Mineral	CS-1	CS-3°	CS-5°	CS-6X	CS-6°	CS-7°	CS-8°
Quartz	26	24	13	4	32	17	4
Alkali Feldspar	55	52	36	49	36	65	pr
Plagioclase	14	18	17	8	14	10	50
Biotite	2	2	18	25	8	5	10
Hornblende	nd	2	9	8	3	nd	9
Opx	nd	nd	nd	nd	nd	nd	17
Cpx	nd	nd	nd	1	nd	nd	5
Opakes	1	pr	2	3	1	1	1
Other	2	2	5	2	6	2	4
AN content	24	24	25	nd	nd	nd	45

Mineral	CS-9	CS-10	CS-11	CS-12	CS-13	CS-14c	CS-15
Quartz	1	2	nd	1	42	3	nd
Alkali Feldspar	24	3	5	1	52	15	pr
Plagioclase	35	56	57	54	6	49	48
Biotite	15	7	3	8	nd	7	14
Hornblende	3	6	3	11	nd	2	4
Opx	11	17	21	15	nd	12	31
Cpx	1	8	3	1	nd	4	1
Opakes	8	1	2	3	nd	8	1
Other	2	nd	6	6	nd	pr	1
AN content	26	36	47	48	nd	32	45

pr denotes a modal % of <1.

° indicates a chemically analyzed sample

Sample	Rock type
CS-1	Granite
CS-3	Granite
CS-5	Syenite
CS-6x	Inclusion
CS-6	Granite
CS-7	Quartz Syenite
CS-8	Norite
CS-9	Monzonite
CS-11	Leuconorite
CS-12	Norite
CS-13	Pegmatite
CS-14c	Monzodiorite
CS-15	Norite

Modal Compositions
(continued)

Mineral	CS-16°	CS-17a°	CS-17	CS-18	CS-20	CS-21°	CS-22°
Quartz	5	nd	23	5	33	11	10
Alkali Fdsp	23	1	50	31	52	65	76
Plagioclase	41	62	12	29	9	11	7
Biotite	11	17	6	18	2	9	4
Hornblende	4	5	3	2	nd	pr	pr
Opx	8	7	nd	nd	nd	nd	nd
Cpx	4	2	nd	12	nd	nd	nd
Opagues	4	4	pr	pr	pr	pr	1
Other	pr	2	5	3	4	4	2
AN content	32	44	nd	24	nd	nd	24

Mineral	CS-23	CS-27°	CS-28	CS-32°	CS-34	CS-35	CS-36°
Quartz	21	27	10	10	16	16	20
Alkali Fdsp	62	49	56	65	30	66	64
Plagioclase	11	17	11	5	27	6	11
Biotite	4	6	16	5	20	8	2
Hornblende	nd	nd	2	10	3	pr	pr
Opx	nd	nd	pr	pr	2	nd	nd
Cpx	nd	nd	pr	pr	pr	nd	nd
Opagues	1	pr	1	4	1	pr	1
Other	1	1	4	1	1	3	1
AN content	nd	nd	nd	nd	28	nd	24

pr denotes a modal % of <1.

° indicates a chemically analyzed sample

Sample	Rock type
CS-16	Quartz Monzodiorite
CS-17a	Leuconorite
CS-17	Granite
CS-18	Syenite
CS-20	Aplite
CS-21	Inclusion
CS-22	Granite
CS-23	Granite
CS-27	Granite
CS-28	Quartz Syenite
CS-32	Alkali Feldspar Syenite
CS-34	Quartz Monzonite
CS-35	Alkali Feldspar Quartz Syenite
CS-36	Granite

Modal Compositions
(continued)

Mineral	CS-37	CS-38	CS-39°	CS-40	CS-42°	CS-42a	CS-43°
Quartz	29	24	30	31	3	5	11
Alkali Fdsp	55	55	60	27	58	76	74
Plagioclase	12	17	6	3	29	7	10
Biotite	1	2	2	3	9	5	3
Hornblende	pr	nd	pr	nd	nd	2	nd
Opx	nd	nd	nd	nd	nd	nd	nd
Cpx	nd	nd	nd	1	nd	nd	nd
Opakes	1	1	1	5	nd	2	1
Other	2	1	1	30	1	3	1
AN content	nd	nd	nd	25	30	nd	nd

Mineral	CS-43x°	CS-45	CS-46°	CS-46a°	CS-47	CS-48	CS-49
Quartz	11	1	nd	2	26	nd	1
Alkali Fdsp	52	1	5	1	62	64	1
Plagioclase	28	52	45	66	7	3	71
Biotite	5	13	16	9	2	4	2
Hornblende	nd	13	6	3	nd	2	1
Opx	nd	18	23	17	nd	20	15
Cpx	nd	nd	nd	nd	nd	nd	1
Opakes	2	nd	5	2	nd	7	8
Other	2	2	nd	nd	3	nd	nd
AN content	nd	52	39	52	nd	41	50

pr denotes a modal % of <1.

° indicates a chemically analyzed sample.

Sample	Rock type
CS-37	Granite
CS-38	Granite
CS-39	Alkali Feldspar Granite
CS-40	Granite
CS-42	Quartz Syenite
CS-42a	Alkali Feldspar Quartz Syenite
CS-43	Quartz Syenite
CS-43x	Quartz Syenite
CS-45	Norite
CS-46	Norite
CS-46a	Leuconorite
CS-47	Alkali Feldspar Granite
CS-48	Leuconorite
CS-49	Leuconorite

Modal Compositions
(continued)

Mineral	CS-50°	CS-51°	CS-54	CS-56°	CS-57°	CS-62°	CS-63
Quartz	2	nd	11	nd	37	30	16
Alkali Fdsp	2	1	65	7	54	55	60
Plagioclase	58	50	15	47	7	12	11
Biotite	3	6	6	11	1	2	6
Hornblende	1	4	nd	7	nd	nd	nd
Opx	20	30	nd	15	nd	nd	nd
Cpx	5	4	nd	2	nd	nd	nd
Opakes	8	3	2	10	nd	1	1
Other	pr	2	1	1	1	pr	6
AN content	54	44	nd	52	nd	nd	nd

Mineral	CS-65	CS-70	CS-71	CS-74°	CO-1	NS-337
Quartz	16	34	30	8	nd	24
Alkali Fdsp	67	50	52	36	7	65
Plagioclase	10	10	14	22	50	9
Biotite	3	3	1	22	7	1
Hornblende	pr	nd	nd	6	9	nd
Opx	nd	nd	nd	nd	14	nd
Cpx	nd	nd	nd	2	9	nd
Opakes	2	1	1	3	2	pr
Other	5	2	2	1	2	pr
AN content	nd	nd	nd	27	44	nd

pr denotes a modal % of <1.

° indicates a chemically analyzed sample.

Sample	Rock type
CS-50	Leuconorite
CS-51	Norite
CS-54	Quartz Syenite
CS-56	Norite
CS-57	Alaskite
CS-62	Alaskite
CS-63	Quartz Syenite
CS-65	Quartz Syenite
CS-70	Alaskite
CS-71	Alaskite
CS-74	Quartz Monzonite
CO-1	Norite
NS-337	Alkali Feldspar Granite

Appendix B

X-Ray Fluorescence Spectrometer Operating Conditions General Electric Model XRD-6VS

Element	Target	Crystal	Peak 2θ	Line	Detector	Path	KV	MA
CaO	Cr	LiF200	113.03	Ka	Gas Prop	Vacuum	45	10
MnO	W	LiF200	63.74	Ka	Gas Prop	Vacuum	45	15
TiO ₂	Cr	LiF200	86.26	Ka	Gas Prop	Vacuum	45	10
P ₂ O ₅	Cr	Ge	141.32	Ka	Gas Prop	Vacuum	45	34
SiO ₂	Cr	PET	110.18	Ka	Gas Prop	Vacuum	45	36
Rb	Mo	LiF220	38.52	Ka	Scint	Air	50	46
Sr	Mo	LiF220	36.35	Ka	Scint	Air	50	46
Y	Mo	LiF220	34.42	Ka	Scint	Air	50	46
Zr	Mo	LiF220	32.60	Ka	Scint	Air	50	46
Ba	Cr	LiF220	116.08	Lb ₂	Gas Prop	Vacuum	50	48

U. V. - Visible Absorption Spectrophotometer Operating Conditions Hitachi Model 100-60

Element	Wavelength nm	Lamp	Mode	Response	Absorbance range
SiO ₂	640	W	Abs	Fast	0-2

Energy Dispersive X-Ray Fluorescence Spectrometer Operating Conditions KEVEX Model 0600 Ultra-Trace

Element	KV	MA	Vacuum	Target	Filter
Cr, Ni, Pb, Zn, Cu	41	38.7	On	W	Ag

Atomic Absorption Spectrophotometer Operating Conditions Instrumentation Laboratories Model 457

Element	Wavelength nm	Burner type	Burner* position	Spectral Bandwidth	Lamp Current	Photo- Multiplier
MgO	285.1	air/acetylene	// + $\perp$	1.0	3	620
K ₂ O	765.6	air/acetylene	//	1.0	7	800
Fe ₂ O ₃	248.2	air/acetylene	//	0.3	8	800
Al ₂ O ₃	309.4	N ₂ O/acetylene	//	1.0	8	460
Na ₂ O	584.8	air/acetylene	$\perp$	0.5	8	460

* Burner head position relative to beam.

Appendix C

Norite

Element Wt. %	CS-8	CS-10	CS-17a	CS-19	CS-46	CS-46m	CS-46a	CS-50	CS-51	CS-56
SiO ₂	46.28	47.18	51.64	53.58	47.86	47.45	49.16	47.58	48.72	48.23
Al ₂ O ₃	14.34	16.84	14.83	14.62	17.05	16.98	17.12	17.12	14.14	14.21
Fe ₂ O ₃ T	11.25	8.98	10.73	9.23	9.62	9.37	9.59	11.82	9.83	12.39
TiO ₂	1.03	1.15	3.04	2.35	0.98	1.05	1.04	1.91	1.37	2.44
MgO	12.60	8.87	4.72	2.88	8.49	9.03	8.64	5.5	8.70	6.44
MnO	0.18	0.15	0.14	0.14	0.14	0.15	0.14	0.11	0.14	0.18
CaO	8.34	9.27	8.26	5.43	9.22	9.57	8.88	10.94	10.39	8.92
K ₂ O	0.91	0.94	1.59	2.29	0.95	0.94	0.97	0.81	0.89	1.12
Na ₂ O	2.20	2.58	3.11	2.29	2.74	2.77	2.83	2.58	2.39	2.74
P ₂ O ₅	0.35	0.36	0.76	0.99	0.29	0.34	0.24	0.46	0.51	0.42
H ₂ O-	0.48	0.82	0.84	2.09	0.89	0.69	0.52	0.29	0.91	0.51
L.O.I.	0.16	0.10	0.14	0.16	0.21	0.24	0.15	0.20	0.17	0.13
Ba (ppm)	478.0	508.0	109.0	1413.0	450.0	470.0	499.0	342.0	424.0	588.0
Cr (ppm)	<40.0	<40.0	<40.0	<40.0	<40.0	<40.0	<40.0	<40.0	70.0	<40.0
Cu (ppm)	<10.0	<10.0	<37.0	<10.0	<10.0	<10.0	<10.0	152.0	67.0	<10.0
Ni (ppm)	470.0	310.0	<50.0	<50.0	190.0	230.0	200.0	<50.0	60.0	50.0
Pb (ppm)	<15.0	<15.0	16.0	35.0	<15.0	<15.0	<15.0	241.0	<15.0	34.0
Rb (ppm)	37.0	26.0	47.0	69.0	21.0	35.0	21.0	28.0	35.0	25.0
Sr (ppm)	729.0	940.0	742.0	560.0	908.0	915.0	919.0	865.0	714.0	729.0
Y (ppm)	21.0	20.0	26.0	42.0	20.0	18.0	21.0	15.0	21.0	26.0
Zn (ppm)	67.0	64.0	258.0	168.0	67.0	64.0	68.0	85.0	64.0	144.0
Zr (ppm)	264.0	141.0	278.0	501.0	158.0	193.0	142.0	141.0	166.0	178.0
TOTAL	98.12	97.24	99.80	97.44	98.44	98.58	99.28	99.32	98.16	97.73

NORMS

Q♦	--	--	--	4.36	7.92	--	--	--	--	--
C	--	--	--	--	--	--	--	--	--	--
OR♦	5.47	5.74	9.73	14.51	5.75	7.02	5.79	4.94	5.45	6.97
AB♦	20.12	23.95	28.94	35.44	25.21	26.11	25.69	23.93	22.23	25.90
AN	27.06	32.67	22.60	17.82	32.20	32.62	31.50	33.82	26.14	24.40
NE♦	1.40	1.40	1.40	1.40	1.40	--	--	1.40	1.40	1.40
KP	3.48	3.48	3.48	3.48	3.48	--	--	3.47	3.47	3.47
AC	0.17	0.17	0.17	0.17	0.17	--	--	0.17	0.17	0.17
EN	35.43	25.32	13.50	8.53	24.02	18.88	24.12	80.29	80.29	80.29
NS	80.29	80.29	80.29	80.29	80.29	--	--	24.88	18.72	15.68
FS	9.83	7.50	6.53	6.25	8.32	8.31	8.08	8.03	9.25	9.17
MT	2.48	2.01	2.40	2.14	2.13	2.15	2.09	2.19	2.82	2.65
HM	--	--	--	--	--	--	--	--	--	--
IL	1.46	1.66	4.39	3.51	1.40	1.55	1.46	1.98	3.58	2.75
AP	0.75	0.78	1.65	2.22	0.62	0.93	0.51	1.10	0.92	0.99
DI	10.20	9.96	11.77	3.31	10.19	9.16	9.17	19.05	15.45	15.31
HY	9.34	9.43	14.15	13.12	8.26	13.98	12.24	17.26	19.08	10.86
OL	23.11	13.81	0.88	13.81	14.24	6.47	11.53	4.60	0.88	4.75
D.I.	30.47	34.57	47.91	62.76	35.84	33.14	31.49	33.75	32.56	37.75

♦ indicates normative mineral used in calculating D.I.

Granite/Quartz Syenite

Elements Wt. %	CS-3	CS-6	CS-7	CS-22	CS-27	CS-36	CS-39	CS-43	CS-43m
SiO ₂	72.49	70.64	70.61	72.85	69.24	71.42	72.60	62.64	62.09
Al ₂ O ₃	13.25	14.07	13.87	13.12	14.41	12.44	13.46	16.98	18.74
Fe ₂ O ₃ T	2.23	2.35	2.88	2.26	3.31	3.24	2.55	2.74	2.84
TiO ₂	0.40	0.45	0.42	0.39	0.49	0.52	0.46	0.44	0.46
MgO	0.56	0.59	0.71	0.57	0.83	0.76	0.58	0.60	0.63
MnO	0.07	0.06	0.04	0.07	0.09	0.08	0.08	0.08	0.06
CaO	1.07	1.22	1.33	1.20	1.56	1.26	1.09	2.30	2.34
K ₂ O	6.00	6.31	5.64	5.78	4.79	5.09	5.94	5.01	4.98
Na ₂ O	3.53	3.50	3.59	3.17	3.86	3.38	3.58	5.02	5.41
P ₂ O ₅	0.12	0.13	0.14	0.13	0.18	0.14	0.11	0.08	0.08
H ₂ O-	0.09	0.07	0.16	0.24	0.09	0.30	0.02	0.12	0.08
L.O.I.	0.35	0.51	0.71	0.81	0.59	0.66	0.70	0.33	0.47
Ba (ppm)	598.0	719.0	638.0	657.0	714.0	543.0	635.0	1131.0	1347.0
Cr (ppm)	<40.0	<40.0	<40.0	<40.0	<40.0	60.0	<40.0	<40.0	<40.0
Cu (ppm)	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Ni (ppm)	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0
Pb (ppm)	<15.0	19.0	19.0	<15.0	30.0	17.0	20.0	<15.0	<15.0
Rb (ppm)	93.0	126.0	92.0	106.0	88.0	97.0	97.0	76.0	62.0
Sr (ppm)	171.0	216.0	185.0	310.0	222.0	172.0	159.0	422.0	407.0
Y (ppm)	76.0	42.0	41.0	31.0	55.0	305.0	183.0	<15.0	<15.0
Zn (ppm)	56.0	54.0	61.0	44.0	92.0	98.0	89.0	58.0	67.0
Zr (ppm)	298.0	389.0	382.0	354.0	438.0	450.0	369.0	654.0	631.0
TOTAL	100.59	99.90	100.10	100.59	99.44	99.29	101.17	96.32	98.18

NORMS

Q♦	25.04	21.70	23.06	27.49	22.60	27.62	24.77	8.47	5.23
C	--	--	--	--	--	--	--	--	0.43
OR♦	35.98	37.78	33.86	34.73	28.31	31.03	35.42	30.53	29.67
AB♦	32.17	31.85	32.76	28.95	34.67	31.31	32.44	46.50	48.98
AN	2.63	4.10	5.16	4.58	6.57	3.86	3.14	9.29	11.18
NE♦	--	--	--	--	--	--	--	--	--
KP	--	--	--	--	--	--	--	--	--
AC	--	--	--	--	--	--	--	--	--
NS	--	--	--	--	--	--	--	--	--
EN	1.57	1.66	1.99	1.60	2.29	2.17	1.62	1.71	1.75
FS	--	0.28	0.50	0.36	--	0.56	--	0.42	0.45
MT	0.66	1.25	1.53	1.20	--	1.75	0.56	1.48	1.50
IL	--	--	--	--	--	--	--	--	--
HM	0.35	--	--	--	1.16	--	0.53	--	--
RU	--	--	--	--	1.08	--	--	0.66	0.65
AP	0.25	0.28	0.30	0.28	0.38	0.30	0.23	0.17	0.17
DI	1.57	0.94	0.50	0.49	--	1.32	1.27	1.56	--
HY	0.78	1.47	2.25	1.72	2.29	2.06	0.98	1.35	2.20
OL	--	--	--	--	--	--	--	--	--
D.I.	93.18	91.33	89.68	91.18	85.57	89.96	92.64	85.49	83.88

♦ indicates normative minerals used in calculating D.I.

Intermediate Rocks

Element Wt. %	CS-5	CS-32	CS-21	CS-16	CS-74	CS-42	CS-42m
SiO ₂	58.51	59.78	66.52	52.88	57.24	61.05	60.52
Al ₂ O ₃	14.83	15.17	14.69	15.58	14.62	16.35	16.98
Fe ₂ O ₃	9.25	6.68	4.12	11.12	8.91	3.46	3.75
TiO ₂	2.08	1.31	0.44	2.15	1.99	0.56	0.67
MgO	2.77	1.55	1.14	4.20	2.75	0.91	0.95
MnO	0.13	0.11	0.09	0.13	0.12	0.08	0.08
CaO	5.43	4.13	2.61	7.87	5.38	1.66	1.66
K ₂ O	2.97	4.24	3.49	1.60	3.03	7.60	7.71
Na ₂ O	3.35	3.89	4.71	3.43	3.44	4.48	4.82
P ₂ O ₅	0.95	0.45	0.28	0.88	0.79	0.16	0.18
H ₂ O-	0.11	0.17	0.09	0.18	0.14	0.17	0.24
L.O.I.	0.83	0.99	0.65	0.75	0.95	0.81	0.85
Ba (ppm)	1237.0	200.0	661.0	647.0	1523.0	1003.0	1071.0
Cr (ppm)	<40.0	<40.0	<40.0	<40.0	<40.0	<40.0	<40.0
Cu (ppm)	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Ni (ppm)	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0	<50.0
Pb (ppm)	29.0	<15.0	<15.0	<15.0	<15.0	<15.0	<15.0
Rb (ppm)	85.0	83.0	92.0	51.0	102.0	87.0	94.0
Sr (ppm)	540.0	474.0	250.0	701.0	581.0	143.0	150.0
Y (ppm)	47.0	37.0	38.0	39.0	31.0	29.0	29.0
Zn (ppm)	139.0	106.0	107.0	133.0	119.0	78.0	72.0
Zr (ppm)	B.D.L.	565.0	377.0	216.0	427.0	817.0	764.0
TOTAL	101.21	98.39	99.03	100.77	99.36	97.29	98.41

NORMS

Q♦	14.32	11.46	18.37	4.30	12.72	--	2.14
C	--	--	--	--	--	--	--
OR♦	17.93	26.07	21.04	9.68	18.61	46.19	46.14
AB♦	30.74	36.35	43.15	31.52	32.11	43.04	41.34
AN	17.02	11.88	8.81	22.92	16.12	1.95	2.11
NE♦	0.51	0.51	--	0.51	0.51	0.51	1.40
KP	3.48	3.48	--	3.48	3.48	3.48	3.48
AC	0.17	0.17	--	0.17	0.17	0.17	0.17
NS	80.29	80.29	--	80.29	80.29	80.29	80.29
EN	7.82	4.45	3.21	11.87	7.89	2.66	2.58
FS	0.63	0.76	0.70	7.57	0.63	0.54	0.60
MT	4.89	3.60	2.20	2.73	4.79	1.97	1.84
HM	--	--	--	--	--	--	--
IL	2.96	1.90	0.91	3.07	2.88	0.95	0.80
AP	2.03	0.98	0.60	1.88	1.72	0.38	0.34
DI	3.33	5.11	2.03	8.93	5.01	4.17	4.23
HY	6.78	2.66	2.89	14.98	6.04	--	1.07
OL	0.84	0.84	--	0.84	0.84	0.84	14.24
D. I.	66.97	77.86	82.56	49.48	67.43	93.23	94.50

♦ indicates normative mineral used in calculating D.I.

Alaskites and Pegmatite

Element Wt. %	CS-13	CS-57	CS-62
SiO ₂	80.63	74.96	76.67
Al ₂ O ₃	9.97	11.23	11.03
Fe ₂ O ₃	0.21	1.78	0.99
TiO ₂	0.11	0.34	0.26
MgO	0.05	0.12	0.10
MnO	0.04	0.04	0.05
CaO	0.46	0.21	0.34
K ₂ O	3.15	5.97	5.93
Na ₂ O	3.53	2.60	2.49
P ₂ O ₅	0.13	0.05	0.06
H ₂ O-	0.13	0.14	0.09
L.O.I.	0.77	0.78	0.47
Ba (ppm)	446.0	B.D.L.	B.D.L.
Cr (ppm)	<40.0	<40.0	<40.0
Cu (ppm)	<10.0	<10.0	<10.0
Ni (ppm)	<50.0	<50.0	<50.0
Pb (ppm)	<15.0	<15.0	<15.0
Rb (ppm)	86.0	93.0	105.0
Sr (ppm)	163.0	96.0	90.0
Y (ppm)	<15.0	72.0	56.0
Zn (ppm)	<20.0	71.0	45.0
Zr (ppm)	443.0	323.0	207.0
TOTAL	99.18	98.22	98.48

NORMS

Q♦	45.45	35.58	37.41
C	0.26	0.26	0.05
OR♦	19.28	37.11	36.50
AB♦	32.84	24.57	23.30
AN	1.48	0.75	1.35
NE♦	--	--	--
KP	--	--	--
AC	--	--	--
EN	0.14	0.35	0.29
NS	--	--	--
FS	--	--	0.06
MT	0.07	0.34	0.54
HM	0.04	0.43	--
IL	0.16	0.50	0.38
AP	0.28	0.11	0.13
DI	--	--	--
HY	0.14	0.35	0.35
OL	--	--	--
D. I.	97.57	97.26	97.20

♦ indicates normative mineral used in calculating D.I.

Appendix D

Analytical Methods, Precision and Accuracy

Element	Device	Analytical ^o Precision %	Accuracy*
SiO ₂	U-V vis/XRF	0.6	0.63
Al ₂ O ₃	AA	3.3	0.18
Fe ₂ O ₃ LO♦	AA	3.1	0.02
Fe ₂ O ₃ HI♦	AA	1.9	0.14
TiO ₂	XRF	8.2	0.08
MgO LO♦	AA	3.3	0.01
MgO HI♦	AA	4.3	0.07
MnO	XRF	3.2	0.02
CaO	XRF	0.9	0.19
K ₂ O	AA	0.7	0.08
Na ₂ O	AA	3.7	0.06
P ₂ O ₅	XRF	7.0	0.03
H ₂ O	GRAV	20.5	n.d.
L.O.I.	GRAV	15.3	n.d.
Ba	XRF	4.7	38 ppm
Cr	EDXRF	n.d.	n.d.
Cu	EDXRF	n.d.	5 ppm
Ni	EDXRF	13.4	57 ppm
Pb	EDXRF	12.9	19 ppm
Rb	XRF	10.1	25 ppm
Sr	XRF	2.2	9 ppm
Y	XRF	3.7	6 ppm
Zn	EDXRF	6.4	17 ppm
Zr	XRF	7.0	8 ppm

* Accuracy is calculated as the average deviation of all standards from the standards curve in weight percent (except where noted).

^o Precision is defined as the coefficient of variation ($s/x * 100$) which expresses the standard deviation as a percentage of the mean for replicate sample data (Freund, 1979).

♦ Unknowns were analyzed for Fe₂O₃ and MgO in separate Hi and Lo concentration runs.

XRF is wavelength dispersive X-ray Fluorescence spectrometry.

EDXRF is energy dispersive X-Ray Fluorescence spectrometry.