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Electron Microprobe Analyses of Minerals in Precambrian Rocks at the Los Alamos Scientific Laboratory Geothermal Test Site

Jemez Mountains, New Mexico

by

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ELECTRON MICROPROBE ANALYSES OF MINERALS IN PRECAMBRIAN ROCKS AT THE LOS ALAMOS SCIENTIFIC LABORATORY GEOTHERMAL TEST SITE, JEMEZ MOUNTAINS, NEW MEXICO

by

Stephen N. Ehrenberg

and

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ABSTRACT

Electron microprobe analyses are presented for plagioclase, biotite, hornblende, magnetite, microcline, and chlorite in core samples from Granite Test Hole One at the Los Alamos Geothermal Test Site. The analyses and accompanying petrographic descriptions characterize material that is being exposed to artificial hydrothermal systems in laboratory experiments. Plagioclase in granitoid rocks exhibits significant compositional variation (albite rims on calcic oligoclase) and alteration to sericite and epidote.

I. INTRODUCTION

In a previous study, Perkins (1973) described the petrography of Precambrian rocks near the Los Alamos Scientific Laboratory Geothermal Test Site. The object of that study was to predict and characterize the likely host rocks for geothermal experiments to be carried out at depth below the level of the first drill hole, Granite Test Hole One. It was demonstrated that rock types in the first test hole exhibit a variation in mineralogy that makes the test hole material representative of Precambrian rocks likely to be encountered at depth. Rocks in the recovered core are similar to those in the Sandia and Nacimiento Mountains, and in Precambrian outcrops exposed nearest the test site. The Precambrian basement at the test site is overlain by a cover of Paleozoic and Mesozoic sediments and Cenozoic volcanics of the Jemez Plateau.

Having shown that granitic rocks are likely to be dominant at depth and associated with lesser amounts of amphibolite, the problem remained to determine the probable range of chemical composition of mineral phases which may be expected to interact with circulating hot fluids in fractured basement rocks during the experiment.

II. ANALYZED SAMPLES

Twelve samples of core from Granite Test Hole One were selected for mineral analysis. Locations and partial modal analyses of all samples are tabulated in the previous report (Perkins, 1973, Tables I, IV and V.) Detailed petrographic descriptions on the PD-2 series of samples are presented in Table I. Tables II through IX contain electron microprobe analyses of plagioclase, biotite, hornblende, magnetite, microcline, and chlorite.

III. ANALYTICAL PROCEDURE

All analyses were made using an Applied Research Laboratories (EMX) Electron Microprobe in the Department of Geology at the University of California, Los Angeles. Polished thin sections were prepared for each specimen and coated with carbon simultaneously with polished standards. Operating conditions were 15-KV accelerating potential and 0.02-microamperes sample current. Three detectors were used for simultaneous analysis of three elements at one spot. K, Ca, and Na were run first, followed by Si, Al, and Fe. Integration time varied from 20 to 100 seconds in order to record a minimum of 10 000 counts for major elements.

"Rims" and "cores" in the tables of analyses refer to outer and inner portions of crystals, rather than to actual edges or centers of grains. Each analysis reported is an average of six analyzed spots on a crystal.

IV. CALCULATION OF ANALYSES

Raw data were corrected by an oxide correction computer program at UCLA using techniques of Bence and Albee (1968). All iron is calculated as FeO since the microprobe does not discriminate between Fe^{+2} and Fe^{+3}. Some ferric iron content is to be expected in biotite and hornblende. Magnetite analyses are reported as weight percent elements, although it would be possible to calculate oxides assuming the ideal ratio of FeO/Fe_2O_3. Water content in biotite and hornblende is not analyzed on the microprobe but is calculated to match the stoichiometric balance expected in these hydrous minerals.

V. EVALUATION OF ANALYSES

Most analyses total to between 99% and 100%. However, analyses PD-3-8 (plagioclase), PD-3-3 (plagioclase) and PD-2-2 (microcline) total 101.7, 98.2, and 98.5 percent, respectively. The discrepancies are probably due to inexact duplication of analytical spots on inhomogeneous grains during analysis of the second or third set of elements. Only three elements can be analyzed at one time on the UCLA microprobe. Most plagioclase crystals have calcium-rich cores and sodium-rich rims. Cores are crowded with secondary sericite and epidote which may contaminate analysis by additional K or Ca, respectively.

Totals for biotite and hornblende fall consistently short of 100% assuming normal water contents of 2% and 3% respectively. Possible sources of error include deviation of standards from recorded compositions (for example, inhomogeneity), inexact duplication of analytical spots during analyses of second and third element sets, and possible presence of other oxides. The first source of error is not considered to be an important factor, because standards used were cross-checked with other standards during analysis, and hornblende was analyzed using two sets of standards.

Inexact duplication of analytical spots would be expected to produce a more random pattern of variation than is observed. This would not be a major source of error, because hornblende and biotite do not appear to be optically zoned, and most analyzed samples were homogeneous with respect to major elements. The low totals are likely to be due to the presence of ferric iron which is not calculated in the analysis. All iron is calculated as FeO in the tables.

VI. DISCUSSION

The purpose of analyzing minerals in rocks of Granite Test Hole One was to characterize further the starting material to be used in geochemical investigations of the reactions to be expected between rocks similar to the core and hot fluids which will be circulated in the Precambrian basement during geothermal experiments.

In general, the microprobe analyses confirm optical determinations of minerals previously reported for the core material. Plagioclase compositions determined by the universal stage (Perkins, 1973, Table VII, p.8) are in general agreement with microprobe determinations, but the latter show a greater variety in compositions, and somewhat more calcic compositions, than did the former.

Petrographic observations and microprobe analyses show that there is considerable alteration and inhomogeneity in the feldspars of the core rocks. The identity of the fine-grained material in the cores of plagioclase crystals was confirmed as epidote and sericite by partial analyses showing high Ca and K contents respectively. The percentage of epidote-sericite alteration in plagioclase of the granitoid rocks ranges from 2 to 35 percent (Perkins, 1973, Table VIII). In addition, feldspars of these of these rocks exhibit perthite and antiperthite lamellae, myrmekite zones between adjacent microline and plagioclase, and thin albite overgrowths on calcic plagioclase. Such chemical variations in K, Ca and Na present in the starting material are important factors to be considered in monitoring the alteration of feldspars during hydrothermal experiments on these samples. Quartz in the core rocks is homogeneous and unaltered, so that it will be easier to trace changes which affect quartz during the experiments.

Compositions of minerals in the tables may be used in conjunction with volume percentages of minerals in core rocks (Perkins, 1973) to calculate "model" rock compositions which may be expected to be exposed to fluids during the geothermal experiment. These compositions may be used as the basis for theoretical predictions of the chemistry of reactions and the amount and nature of solution and deposition to be expected in artifical hydrothermal systems.

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This work was performed while Perkins was a Visiting Staff Member of the Los Alamos Scientific Laboratory in the CNC Division under the supervision of John P. Balagna.

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TABLE I

PETROGRAPHIC DESCRIPTIONS OF ANALYZED SAMPLES

Petrographer: P. C. Perkins

Sample PD-2-2

Name: granite (variety: adamellite) veined by syenogranite aplite-pegmatite

Color: brownish gray with pale red to pale reddish brown microcline

Grain Size: medium-grained quartz monzonite; medium- to coarse-grained aplite-pegmatite

Texture: matrix granitic (hypidomorphic granular) cut by 1-cm-wide vein varying from medium-grained aplite to coarse-grained pegmatite; vein dips 60^{0}; microcline subhedral in vein, anhedral to aubhedral in matrix

Modal Analysis:

whole rock average including matrix and vein

Essential Minerals: microcline 35%; oligoclase 21%; altered oligoclase 13%; quartz 20%

Accessory Minerals: biotite 2%; chlorite 1%; opaques 1%

Trace Minerals: apatite, epidote, muscovite, myrmekite, sphene

matrix:

Essential Minerals: oligoclase 32%; altered oligoclase 18%; microcline 21%; quartz 13%, biotite 10%

Accessory Minerals: sphene 2%

Trace Minerals: apatite, calcite, chlorite, epidote, muscovite, myrmekite, opaques, zircon

syenogranite aplite-pegmatite

Essential minerals: microcline 52%, quartz 39%; oligoclase 6%; altered oligoclase 3%

Plagioclase Composition Determined by Universal Stage

Anorthite Content matrix	Twin Law in Measured Crystal
An 24-26	albite with second cleavage
An 24-25	albite

Thin Section Description:

Texture: crack transverse to trend of aplite vein along calcite vein entirely within aplite; several subparallel thin calcite veins in aplite; they cut microcline and quartz

Quartz: undulatory and mosaic extinction; inclusion trains subparallel to mosaic extinction boundaries; mosaic simple boundaries with plagioclase and microcline; implicate boundaries between quartz crystals

Microcline: Carlsbad twins to 5 mm; well-developed grid twinning; poikilitic, enclosing quartz blebs and round grains of sericitized plagioclase; perthite, film type; thin parallel calcite films along direction of perthite lamellae, at intervals 1 mm apart in larger crystals

Plagioclase: oligoclase slightly to moderately sericitized; as granular subhedral altered crystals 0.05 mm diameter along microcline selvages; as inclusions in microcline surrounded by thin clear albite rims; most crystals 2 to 4 mm; antiperthite with microcline blebs

Biotite: pleochroic pale olive to dark yellowish brown

Apatite: subhedral grains to 0.1 mm diameter, associated with sphene

Calcite: branching veins 0.05 mm thick in aplite

Chlorite: pale green, replacing biotite

Epidote: anhedral, to 0.3 mm; pale greenish yellow to grayish yellow green

Muscovite: flakes with chloritized biotite to 0.1 mm

Opaques: equant isometric granules of magnetic to 0.2 mm; minor pyrite and chalcopyrite

Sphene: euhedral to 2 mm.; pleochroic pale yellowish orange to grayish yellow; colorless rims on larger crystals; rims 0.05 mm thick

TABLE I
continued

Sample PD-2-3

Name: granite (variety: adamellite)

Color: brownish gray; pale reddish brown to pale red microcline

Grain Size: medium-grained, with coarse-grained microcline

Texture: granitic (hypidiomorphic granular)

Modal Analysis:

Essential Minerals: microcline 37%; quartz 28%; plagioclase 20%; altered plagioclase 8%

Accessory Minerals: biotite 4%; opaques 1%

Trace Minerals: allanite; apatite; calcite; chlorite; epidote; muscovite; myrmekite; sphene; zircon

Thin Section Description:

Texture: granitic texture (hypidomorphic granular) slightly modified by implicate grain boundaries; a few coarse-grained microcline crystals (subhedral)

Quartz: mosaic and undulatory extinction; in some mosaics of grains with implicate grain boundaries, there are two mutually perpendicular sets of inclusion trains

Microcline: medium-grained to coarse-grained subhedra; poikilitic, enclosing quartz blebs and rounded blebs of sericitized plagioclase; grid twinning and Carlsbad twins well developed; grid twinning lamellae offset by minute cracks in some grains; perthitic, with films and beads of plagioclase

Myrmekite: well-developed wormy rims on plagioclase invading microcline

Plagioclase: subhedral to 3 mm; granular borders with microcline; slightly to moderately sericitized; slightly zoned extinction; in some grains twinning becomes faint or disappears near grain boundary; antiperthite blebs in cores; some grains have clear well-twinned rims of albite growing into microcline

Biotite: pleochroic pale greenish yellow to olive green; slightly altered to chlorite

Allanite: subhedral rectangular crystal 0.5 x 0.3 mm; pleochroic dark yellowish orange to moderate brown; nearly metamict core; pleochroic halo in adjacent biotite; radiating expansion cracks into surrounding quartz

Apatite: to 0.2 mm, associated with biotite

Calcite: discrete grains in altered plagioclase

Chlorite: replacement of biotite; pleochroic pale yellowish green to moderate yellowish green

Epidote: anhedral; associated with chlorite; to 0.2 mm

Muscovite: flakes in altered plagioclase

Opaques: magnetite to 2 mm anhedral with inclusions of apatite and sphene; equant granules 0.2 mm, minor pyrite

Sphene: dusky yellow when up to 0.5 mm

Zircon: rounded subhedral inclusions in biotite surrounded by pleochroic halos

TABLE I

continued

Sample PD-2-4

Name: granite (variety: adamellite)

Color: brownish gray; pale reddish brown to pale red microcline

Grain Size: medium-grained, with a few coarse-grained plagioclase crystals

Texture: granitic (hypidiomorphic granular); in hand specimen, largest crystals are microcline

Modal Analysis:

Essential Minerals: quartz 31%; oligoclase 27%; altered oligoclase 3%; microcline 30%; biotite 6%

Accessory Minerals: opaques, sphene

Trace Minerals: apatite, calcite, chlorite, epidote, muscovite, myrmekite, zircon

Plagioclase Composition Determined by Universal Stage

Anorthite Content	Twin Law in Measured Crystal
An 26	albite
An 24	albite
clear rim on altered plagioclase:	
An 3-5	albite

Thin Section Description

Texture: slightly modified hypidiomorphic granular; implicate boundaries on subhedral feldspars

Quartz: mosaic and undulatory extinction; implicate grain boundaries; fine grained, up to 5 mm

Microcline: grid and Carlsbad twins; film perthite; poikilitic, enclosing round quartz blebs and square to rounded sericitized plagioclase

Myrmekite: at ends of plagioclase crystals protruding into microcline; as bleb in microcline; rims between microcline and plagioclase to 0.2 mm thick

Plagioclase: oligoclase to 7 mm; slightly sericitized; large crystals have fresh clear albite rims with twin composition planes continuous with inner part of crystal, but with different extinction angle; also as fine-grained subhedral granules bordering microcline; antiperthite with twinned microcline beads

Biotite: pleochroic grayish yellow green to olive gray; some altered to chlorite and calcite

Apatite: euhedral to subhedral inclusions in biotite to 0.3 mm; inclusions in microcline

Calcite: discrete grains in microcline and oligoclase

Chlorite: replacement of biotite in parallel intergrowth; pleochroic pale yellowish green to moderate yellowish green

Muscovite: discrete flakes in slightly sericitized oligoclase; as fringes on biotite; to 0.2 mm

Opaques: equant granules and larger anhedral grains of magnetite to 1 mm; minor pyrite

Sphene: fine-grained colorless; larger euhedral grains to 1 mm pleochroic yellowish gray to dusky yellow; some have inclusions of apatite

Zircon: rounded subhdral grains in biotite surrounded by pleochroic halos; grain size to 0.05 mm

TABLE I

continued

Sample PD-2-6

Name: gneissic tonalite matrix; with clots of microcline, gneissic granite (adamellite)

Color: medium dark gray

Grain Size: medium-grained with coarse-grained megacrysts of microcline

Texture: foliated; foliation defined by discontinuous thin layers of biotite; thin (0.05- to 0.2-mm) vein of calcite parallel to foliation (specimen not cracked along it); hand specimen has clot of pale reddish brown microcline 2 cm in diameter; microcline crystals very localized; foliation dip 50^0 - 60^0

Modal Analysis:

for thin section with two 6 mm megacrysts of microcline,gneissic adamellite average composition

Essential Minerals: plagioclase 32%; altered plagioclase 11%; microcline 24%; quartz 22%; biotite 8%

Accessory Minerals: muscovite 1%; opaques 1%

Trace Minerals: calcite, chlorite, epidote, myrmekite, sphene

for matrix of thin section excluding two microcline megacrysts, gneissic tonalite

Essential Minerals: plagioclase 51%; altered plagioclase 4%; quartz 26%; biotite 15%

Accessory Minerals: microcline 2%

Trace Minerals: apatite, calcite, chlorite, muscovite, opaques, sphene

Thin Section Description:

Texture: thin section contains two megacrysts of microcline and is not representative of hand specimen, which is generally devoid of microcline except for a 2-cm clot and one isolated megacryst 0.5 cm; lenticles of plagioclase and quartz parallel to foliation defined by biotite

Quartz: undulatory and mosaic extinction; generally clear, with inclusion trains (?Boehm lamellae), planes of round inclusions continuous through quartz grains of differing optical orientation

Microcline: two megacrysts 5 to 7 mm in length on edge of slide; part of clot of microcline crystals in hand specimen; poikilitic, containing altered plagioclase crystals with thin clear albite rims or rims of myrmekite; perthitic, with very thin films and small beads of plagioclase twinned on albite law; poikilitic crystals also enclose biotite partly altered to chlorite; contain parallel films of calcite associated with hematite, 0.05 mm wide; some crystal areas are internally cracked, offsetting grid twinning

Myrmekite: films with radiating structure penetrating microcline from adjacent plagioclase

Plagioclase: slightly to moderately sericitized; continuous zoned extinction; some partly replaced by calcite; antiperthite, with blebs of twinned microcline concentrated in crystal cores; some crystals show slightly bent twin lamellae; also as small round strongly sericitized inclusions in poikilitic microcline; in matrix anhedral to subhedral, to 2 or 3 mm

Biotite: pleochroic moderate greenish yellow to dark yellowish brown; extremely fine-grained alteration product (?sphene)

Apatite: subhedral, with biotite; to 0.2 mm diameter

Calcite: vein 0.05 mm wide to 0.2 mm wide; very fine-grained dusty crystals; extends out from vein along twin planes in plagioclase

Chlorite: pleochroic grayish yellow green to pale green, parallel intergrowths replacing chlorite

Muscovite: fringes on some biotite flakes; flakes between plagioclase grains to 0.2 mm

Opaques: euhedral magnetite to 0.3 mm

Sphene: with biotite and chlorite; anhedral to subhedral

TABLE I

continued

Sample PD-2-9

Name: biotite amphibolite with tonalite aplite

Color: amphibolite dark gray

Grain Size: amphibolite fine grained; with clusters of hornblende crystals in mosaic arrangement up to 4 mm across; clusters are elongate and define a foliation which is parallel to boundary of medium grained massive aplite; calcite veins .5 mm thick dip 10^{0} and 80^{0}, aplite border dips 60^{0}

Modal Analysis:

Essential Minerals: hornblende 46%; plagioclase 19%; altered plagioclase 11%; biotite 15%; quartz 8%

Trace Minerals: apatite, chlorite, opaques, sphene

Thin Section Description:

Texture: zone of alteration of plagioclase along 0.03-mm-wide filled crack with 90^{0} dip along middle of slide

Quartz: mosaic and undulatory extinction; fills part of alteration crack

Plagioclase: slightly to strongly sericitized along edges and twin planes; in aplite, crystals to 2 mm are poikilitic containing quartz blebs and biotite

Biotite: pleochroic pale greenish yellow to grayish olive; crystals are somewhat oriented, defining a vague foliation

Hornblende: pleochroic grayish green to grayish yellow green; elongate clusters of mosaic crystals associated with opaques and sphene are aligned parallel to the slight foliation of the biotite; some crystals with thin pale rims of ?actinolite, pleochroic pale green to grayish yellow green

Apatite: euhedral to subhedral needles and grains in plagioclase; as inclusions in biotite surrounded by pleochroic halos

Chlorite: pale yellowish green, in parallel intergrowths replacing biotite

Opaques: equant grains of magnetite to 0.1 mm; tiny equant grains as inclusions in hornblende

Sphene: with chlorite and biotite

TABLE I

continued

Sample PD-2-13

Name: band (1) : quartz-biotite amphibolite
band (2) : tonalite aplite
band (3) : hornblende-biotite-quartz-oligoclase gneiss

Color: (1) dark gray; (2) medium light gray; (3) medium dark gray

Grain Size: fine-grained; medium-grained aplite

Texture: foliated; foliation defined by alternating thin bands of biotite-hornblende and quartz-oligoclase; aplite vein parallel to matrix foliation; biotite and hornblende have strong preferred orientation; foliation dip 40^0; calcite vein in hand specimen has dip of 80^0

Modal Analysis:

quartz-biotite amphibolite:

Essential Minerals: hornblende 42%; oligoclase 26%; altered oligoclase 3%; biotite 16%; quartz 12%

Trace Minerals: epidote; microcline; sphene

tonalite aplite:

Essential Minerals: oligoclase 42%; altered oligoclase 6%; quartz 41%; biotite 5%

Accessory Minerals: microcline 4%; hornblende 1%

Trace Minerals: chlorite; epidote; sphene

hornblende-biotite-quartz-oligoclase gneiss

Essential Minerals: oligoclase 36%; altered oligoclase 2%; quartz 36%; biotite 15%; hornblende 8%

Accessory Minerals: microcline 2%

Trace minerals: epidote; opaques; sphene; zircon

Plagioclase Composition Determined by Universal Stage

Anorthite Content	Twin Law in Measured Crystals
Band (2)	
An 27-30	albite with pericline
Band (3)	
An 26	albite, Carlsbad, Carlsbad-albite

Thin Section Description

Texture: strong preferred orientation of biotite and hornblende in mosaic of plagioclase; edge of aplite vein defined only by decrease in hornblende and increase of grain size and alteration of feldspar; long axes of foliated minerals are parallel to orientation of the aplite vein; there is no smooth boundary along which a crack would be likely

Quartz: undulatory and mosaic extinction

Microcline: anhedral, interstitial poikilitic grains enclosing biotite, quartz, and oligoclase; largest crystals are most poikilitic; up to 0.7 mm

Myrmekite: One grain surrounded by quartz in aplite

Plagioclase: granoblastic mosaic of anhedral grains; some larger crystals are poikilitic and enclose quartz grains; alteration product almost opaque, low birefringence (kaolinite?); most alteration along edges of crystals; well-twinned antiperthite in some crystals in aplite

Biotite: strong preferred orientation in band (3); up to 0.3 mm in length; pleochroic yellowish gray to olive gray

Hornblende: pleochroic pale olive to dusky green; some clumps of crystals with mosaic texture; clumps 1 mm in diameter; preferred orientation of c axes in amphibolite

TABLE I

continued

Sample PD-2-13

Apatite: euhedral to subhedral inclusions in hornblende and very fine-grained needles in plagioclase; also inclusions in biotite

Epidote: pleochroic greyish yellow to moderate greenish yellow; up to 0.5 mm

Opaques: magnetite grains up to 0.5 mm in band (3); elsewhere smaller equant grains

Sphene: interstitial small grains beside hornblende and biotite crystals

Zircon: tiny inclusions in biotite surrounded by pleochroic halos

TABLE II

PLAGIOCLASE IN GRANITOID ROCKS

Analyst: S. Ehrenberg

	PD-3-5 rim	PD-3-5 core	PD-2-2 rim	PD-2-2 rim
Weight Percent Oxides				
SiO_2	64.5	63.2	61.5	62.7
Al_2O_3	21.6	22.8	23.7	22.8
FeO	0.03	0.03	0.10	0.13
CaO	2.4	4.3	6.6	4.9
K_2O	0.10	0.11	0.12	0.35
Na_2O	10.4	9.2	7.6	8.5
TOTAL	99.0	99.6	99.6	99.4
Number of Ions on the Basis of 8 Oxygens				
Si	2.868	2.804	2.741	2.793
Al	1.133	1.193	1.244	1.199
Fe	0.001	0.001	0.004	0.005
Ca	0.112	0.204	0.314	0.283
K	0.005	0.006	0.007	0.020
Na	0.897	0.789	0.661	0.736
TOTAL	5.016	4.997	4.970	5.036
Ab	88.5	79.0	67.3	70.8
An	11.0	20.6	32.0	27.2
Or	0.5	0.6	0.7	1.9

PLAGIOCLASE IN GRANITOID ROCKS

	PD-2-3	PD-2-4	PD-3-7	PD-2-6
Weight Percent Oxides				
SiO_2	60.8	60.8	61.4	60.8
Al_2O_3	23.8	24.2	24.0	24.2
FeO	0.14	0.12	0.16	0.12
CaO	5.7	6.2	5.8	5.9
K_2O	0.14	0.20	0.32	0.11
Na_2O	8.6	8.3	8.1	8.2
TOTAL	99.2	99.8	99.8	99.3
Number of Ions on the Basis of 8 Oxygens				
Si	2.728	2.713	2.735	2.717
Al	1.259	1.272	1.258	1.279
Fe	0.005	0.005	0.006	0.005
Ca	0.274	0.295	0.276	0.282
K	0.008	0.011	0.018	0.006
Na	0.744	0.721	0.702	0.715
TOTAL	5.018	5.017	4.995	5.004

TABLE II
continued

PLAGIOCLASE IN GRANITOID ROCKS

Ab	72.5	70.2	70.5	71.3
An	26.7	28.7	27.7	28.1
Or	0.8	1.1	1.8	0.6

TABLE III

PLAGIOCLASE IN AMPHIBOLITES AND APLITES

Analyst: S. Ehrenberg

	PD-2-13	PD-2-8 amphibolite	PD-3-8 aplite	PD-2-9
Weight Percent Oxides				
SiO_2	60.5	61.2	62.1	58.4
Al_2O_3	24.9	24.7	23.1	26.0
FeO	0.16	0.22	0.10	0.13
CaO	6.7	7.3	5.9	7.5
K_2O	0.20	0.17	0.21	0.11
Na_2O	7.8	8.1	8.3	7.4
TOTAL	100.3	101.7	99.7	99.5
Number of Ions on the Basis of 8 Oxygens				
Si	2.688	2.688	2.764	2.623
Al	1.307	1.279	1.213	1.376
Fe	0.006	0.008	0.004	0.005
Ca	0.317	0.345	0.283	0.361
K	0.011	0.009	0.012	0.006
Na	0.672	0.690	0.720	0.642
TOTAL	5.000	5.018	4.995	5.013
Ab	67.2	66.1	70.9	63.6
An	31.7	33.0	27.9	35.8
Or	0.1	0.9	1.2	0.6

	PD-2-9 rim	PD-2-9 core	PD-3-1 core	PD-3-1 rim
Weight Percent Oxides				
SiO_2	58.4	58.3	56.2	54.3
Al_2O_3	26.0	25.9	27.1	28.8
FeO	0.13	0.13	0.21	0.13
CaO	7.8	8.9	8.6	12.2
K_2O	0.16	0.18	0.08	0.11
Na_2O	7.2	6.5	6.8	4.7
TOTAL	99.7	99.9	99.1	100.2

TABLE III, continued

PLAGIOCLASE IN AMPHIBOLITES AND APLITES

Number of Ions on the Basis of 8 Oxygens

Si	2.620	2.612	2.548	2.450
Al	1.374	1.370	1.449	1.532
Fe	0.005	0.005	0.008	0.005
Ca	0.375	0.427	0.419	0.589
K	0.009	0.010	0.005	0.006
Na	0.628	0.568	0.599	0.412
TOTAL	5.011	4.991	5.028	4.993
Ab	62.1	56.5	58.6	58.5
An	37.0	42.4	41.0	40.9
Or	0.9	0.1	0.4	0.6

	PD-3-3 rim	PD-3-2	PD-3-2 rim	PD-3-2 core
Weight Percent Oxides				
SiO_2	60.1	60.0	60.6	59.4
Al_2O_3	24.5	24.0	23.9	24.4
FeO	0.10	0.09	0.18	0.19
CaO	5.3	6.7	6.0	7.1
K_2O	0.93	0.14	0.46	0.54
Na_2O	7.4	8.1	8.1	7.6
TOTAL	98.2	99.0	99.2	99.2
Number of Ions on the Basis of 8 Oxygens				
Si	2.716	2.700	2.721	2.679
Al	1.305	1.274	1.265	1.297
Fe	0.004	0.003	0.007	0.007
Ca	0.256	0.323	0.288	0.341
K	0.054	0.008	0.027	0.031
Na	0.647	0.709	0.707	0.666
TOTAL	4.981	5.018	5.013	5.021
Ab	67.6	68.2	69.2	64.2
An	26.8	31.1	28.2	32.9
Or	5.6	0.7	2.6	2.9

TABLE IV

BIOTITE IN GRANITOID ROCKS

Analyst: S. Ehrenberg

	PD-3-5	PD-2-2	PD-2-3	PD-3-7	PD-2-6
Weight Percent Oxides					
SiO_2	36.0	35.6	36.2	36.3	36.1
TiO_2	3.4	2.0	2.9	3.1	1.6
Al_2O_3	14.7	14.9	14.8	14.9	15.4
FeO	18.9	18.7	19.1	18.9	19.7
MnO	0.56	0.07	0.63	0.59	0.41
MgO	10.0	10.7	10.7	11.0	11.1
CaO	0.04	0.08	0.07	0.06	0.09
K_2O	9.4	9.1	9.3	9.4	9.1
Na_2O	0.09	0.08	0.12	0.14	0.11
H_2O (calc)	7.0	8.7	6.0	5.5	6.2
TOTAL	100.1	99.9	99.8	99.9	99.8
Number of Ions on the Basis of 24 Oxygens					
Si	5.186	5.006	5.297	5.336	5.262
Ti	0.364	0.213	0.321	0.345	0.178
Al	2.495	2.462	2.559	2.589	2.645
Fe	2.278	2.198	2.333	2.325	2.397
Mn	0.069	0.008	0.078	0.073	0.050
Mg	2.157	2.232	2.340	2.403	2.411
Ca	0.007	0.012	0.011	0.010	0.015
K	1.732	1.639	1.743	1.765	1.693
Na	0.025	0.020	0.033	0.038	0.031

TABLE V

BIOTITE IN AMPHIBOLITES AND APLITES

Analyst: S. Ehrenberg

	PD-2-13	PD-3-8	PD-2-9	PD-3-3	PD-3-2 aplite	PD-3-2 amphibolite
			Weight Percent Oxides			
SiO_2	36.7	36.5	36.5	35.9	36.0	36.4
TiO_2	2.3	2.4	2.8	2.7	3.2	2.5
Al_2O_3	15.4	15.1	15.5	14.8	14.6	14.9
FeO	17.3	17.7	17.5	17.4	18.2	17.8
MnO	0.20	0.43	0.17	0.41	0.39	0.42
MgO	12.5	12.3	12.6	12.1	11.4	12.1
CaO	0.05	0.05	0.29	0.06	0.06	0.08
K_2O	9.4	9.4	9.5	9.3	9.2	9.3
Na_2O	0.08	0.10	0.09	0.12	0.10	0.11
H_2O (calc)	6.1	5.9	5.0	7.2	6.8	6.3
TOTAL	100.0	99.9	100.0	100.0	100.0	99.9
			Number of Ions on the Basis of 24 Oxygens			
Si	5.295	5.306	5.361	5.120	5.185	5.256
Ti	0.250	0.265	0.307	0.286	0.347	0.276
Al	2.627	2.578	2.676	2.489	2.476	2.536
Fe	2.084	2.155	2.152	2.081	2.190	2.151
Mn	0.024	0.053	0.022	0.050	0.047	0.051
Mg	2.680	2.661	2.759	2.576	2.441	2.612
Ca	0.008	0.008	0.046	0.008	0.008	0.012
K	1.724	1.742	1.787	1.686	1.690	1.705
Na	0.023	0.028	0.024	0.034	0.028	0.030

TABLE VI

HORNBLENDE

Analyst: S. Ehrenberg

	PD-2-13	PD-3-8 amphibolite	PD-3-8 aplite	PD-2-9
Weight Percent Oxides				
SiO_2	43.7	42.6	45.8	44.4
TiO_2	0.86	1.1	0.32	1.7
Al_2O_3	9.4	9.5	7.6	9.0
FeO	17.0	17.3	16.2	14.9
MnO	0.45	0.70	0.67	0.3
MgO	11.1	10.5	10.9	12.1
CaO	11.6	11.7	11.8	11.8
K_2O	1.2	1.2	0.6	0.96
Na_2O	1.5	1.4	1.1	1.4
H_2O(calc)	3.2	4.0	5.0	3.5
TOTAL	100.0	100.0	100.0	100.1
Number of Ions on the Basis of 23 Oxygens				
Si	6.161	5.978	6.240	6.165
Ti	0.091	0.117	0.033	0.176
Al	1.571	1.563	1.221	1.475
Fe	2.009	2.025	1.851	1.725
Mn	0.054	0.083	0.077	0.038
Mg	2.338	2.195	2.215	2.489
Ca	1.748	1.753	1.725	1.758
K	0.216	0.217	0.100	0.169
Na	0.405	0.375	0.283	0.368

	PD-2-9	PD-3-1	PD-3-3	PD-3-2
Weight Percent Oxides				
SiO_2	44.3	45.6	44.0	43.8
TiO_2	1.8	1.1	0.9	1.0
Al_2O_3	9.5	8.5	8.6	8.9
FeO	15.1	14.4	16.3	16.7
MnO	0.3	0.3	0.76	0.81
MgO	12.1	12.8	11.6	11.1
CaO	12.3	11.7	11.7	11.4
K_2O	0.95	0.57	1.0	1.1
Na_2O	1.5	1.0	1.4	1.3
H_2O (calc)	2.0	3.9	3.6	3.8
TOTAL	99.9	99.9	99.9	99.9

TABLE VI
continued

HORNBLENDE

Number of Ions on the Basis of 23 Oxygens

Si	6.292	6.247	6.157	6.115
Ti	0.193	0.116	0.099	0.107
Al	1.592	1.373	1.422	1.471
Fe	1.795	1.649	1.905	1.946
Mn	0.037	0.033	0.091	0.096
Mg	2.565	2.614	2.412	2.317
Ca	1.871	1.725	1.758	1.707
K	0.172	0.100	0.180	0.196
Na	0.412	0.274	0.375	0.356

TABLE VII

MAGNETITE

Analyst: S. Ehrenberg

	PD-3-5	PD-2-2	PD-2-3	PD-3-7	PD-2-6	PD-2-13
Weight Percent Elements						
Si	0.08	0.03	0.17	0.07	0.06	0.05
Ti	0.02	0.02	0.02	0.05	0.01	0.02
Al	0.12	0.12	0.14	0.11	0.12	0.11
Fe	70.4	70.3	69.7	71.3	71.1	71.1
Mn	0.06	0.08	0.06	0.05	0.06	0.03
Mg	0.03	0.05	0.03	0.04	0.05	0.04
Ca	1.2	0.06	0.05	0.05	0.05	0.04
K	0.02	0.02	0.04	0.03	0.03	0.03
Na	0.02	0.02	0.02	0.01	0.03	0.01

TABLE VIII

MICROCLINE

Analyst: S. Ehrenberg

	PD-2-2 rim	PD-2-2 core	PD-2-2 rim	PD-2-2 core
Weight Percent Oxides				
SiO_2	64.9	64.7	64.6	64.0
Al_2O_3	18.3	17.9	18.0	18.1
FeO	0.05	0.02	0.03	0.04
CaO	0.02	0.01	0.02	BD[a]
Na_2O	0.46	0.52	0.39	0.51
K_2O	16.0	15.8	16.0	15.8
TOTAL	99.8	99.0	99.0	98.5
Number of Ions on Basis of 8 Oxygens				
Si	3.004	3.015	3.011	3.001
Al	0.998	0.984	0.987	1.001
Fe	0.002	0.001	0.001	0.001
Ca	0.001	----	0.001	----
Na	0.041	0.047	0.036	0.047
K	0.945	0.938	0.954	0.943

[a]BD = below detection limit

TABLE IX

CHLORITE

Analyst: S. Ehrenberg

	PD-3-5 granite	PD-3-8	PD-3-1 amphibolites	PD-3-2
Weight Percent Oxides				
SiO_2	25.5	26.5	25.8	24.9
TiO_2	0.06	0.13	0.14	0.03
Al_2O_3	17.8	19.1	19.3	20.1
FeO	23.5	23.0	21.4	22.1
MnO	0.8	0.6	0.13	0.7
MgO	16.3	17.2	18.8	16.9
CaO	0.10	0.12	0.11	0.10
K_2O	0.06	0.08	0.02	0.10
Na_2O	0.04	0.04	0.02	0.06
H_2O (calc)	15.5	13.0	14.0	14.7
TOTAL	99.7	99.7	99.7	99.7

TABLE IX

continued

CHLORITE

Number of Ions on Basis of 36 Oxygens

Si	4.943	5.261	5.038	4.837
Ti	0.009	0.019	0.022	0.005
Al	4.071	4.467	4.435	4.615
Fe	3.812	3.823	3.488	3.597
Mn	0.132	0.105	0.022	0.114
Mg	4.706	5.078	5.457	4.910
Ca	0.021	0.025	0.023	0.020
K	0.015	0.019	0.005	0.024
Na	0.014	0.014	0.008	0.023

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