A QUANTITATIVE CHEMICAL TEST FOR THE ORIGIN OF THE GRANITIC PORTION OF THE POUDRE CANYON MIGMATITE

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Philip Arno Mariotti

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ABSTRACT

A QUANTITATIVE CHEMICAL TEST FOR THE ORIGIN OF THE GRANITIC PORTION OF THE POUDRE CANYON MIGMATITE

By

Philip Arno Mariotti

Density corrected volume percent measurements show that the Poudre Canyon Migmatite contains an average of 24 weight percent granitic rock.

Mineralogies of the metamorphic rocks are compatible with upper amphibolite facies level of metamorphism.

Statistical analysis of granitic rocks and metamorphic rocks show no significant elemental interactions on the scale of samples collected 30 inches apart. If such interactions are present but were not seen because of too large a sampling interval, re-sampling would have to be done on the scale of inches.

Looking at the region as a whole, some of the metamorphic rocks can be seen to be granitized when compared with the main population. They show increases in biotite normative Or relative to the ungranitized population.

Twenty-six of the 41 granitic rocks (63%) fit a magmatic fractionation trend that could be expected at pressures of 1 to 2 kilobars. Since generally accepted estimates of amphibolite facies pressures are in the neighborhood of 5 to 8 kilobars, it is concluded that these 26 granitic rocks are the result of igneous intrusion that

post-dates the main episode of metamorphism.

By forming a biotite (annite-phlogopite) prior to the calculation of normative orthoclase, a biotite norm has been developed to adjust the normative mineralogy of aluminous and siliceous metasediments so that it more closely resembles the mode in amphibolite grade rocks.

To the degree to which the profound lithologic and chemical heterogeneity found in this study are representative of sedimentary and metasedimentary piles in general, melts forming from such rocks, if they are considered to be sources of plutonic masses of granitic rocks, must be thoroughly homogenized after separation from the pile.

Melting of sediments and metasediments should bring about granitic magmas that first precipitate quartz during fractionation. This is in opposition of the trends normally observed in plutonic masses of granitic rock.

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By

Philip Arno Mariotti

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INTRODUCTION

Migmatites are megascopically heterogeneous rocks composed of portions that are granitic in character and portions that are metamorphic in character. They may be highly folded and contorted or occur as alternating layers of granitic rock and metamorphic rock. They differ from what would be called gneissic rocks in that the granitic portion, if separated, is a granitic rock and the metamorphic portion, if separated, is a metamorphic rock. The segregations observed are lithologic while in gneisses the segregations are mineralogic.

"...one of the most firmly established facts of metamorphic geology is the close association in the field of highest grade metamorphic rocks and migmatites (Read, 1940)." This world-wide association suggests a causal relationship between granitic rocks and high levels of metamorphic activity, and two alternative hypotheses--- one being that the granitic material is the result of the metamorphism, the other, that the metamorphism is the result of the presence of the granitic material. The former suggests an origin of the granitic material in a closed system, the pre-migmatization metamorphic rock by selective fluidization and segregation,

while the latter suggests that the system was open to addition of granitic material. Both hypotheses should be testable employing standard petrologic and geochemical techniques.

The open system hypothesis leads to two generally accepted mechanisms for the origin of the granitic portion. One involves the direct injection of granitic magma, the other, that the metamorphic rocks have been permeated by what have been variously described as magmatic juices, ichor or hydrothermal fluids escaping from a subjacent magma. Such permeation should lead to feldspathization and blastesis of the metamorphic rocks. If the amount of granitic rock is locally variable, it would be expected that the surrounding metamorphic rocks should be more granitic in character when associated with larger amounts of granitic rock than with smaller amounts. This mode of origin should then show either porphyroblasts of feldspar in the field or strong positive correlations between the amount of granitic rock locally present and the SiO_2, Al_2O_3, Na_2O and K_2O, the granitophile elements, in the surrounding metamorphic rocks.

Forceful intrusion of a dry granitic magma might show little interaction with the intruded rocks, or, if wet, could produce granitization of the intruded rocks due to vapor transport of alkalis and silica (Tuttle and Bowen, 1958 and Burnaham, 1967). It would

be expected that, owing to restricted solubilities of granitic material in a vapor phase (Burnham, 1967), attendant feldspathization and granitization of the surrounding rocks might be of less magnitude than for the magmatic "juice hypothesis. However, since the effects of permeation of such juices are unknown, an estimation of magnitude is not possible. It still might be possible to distinguish which of these two mechanisms has operated if the compositions of the granitic rocks themselves are in agreement with experimentally established fractional crystallization paths of liquid descent in magmatic systems.

Field evidence for the intrustion of magma would include distortion of the foliation at the granitic rock-metamorphic rock contacts and possible crushing of the surrounding rocks. Neither of these tests could be interpreted as conclusive since either could conceivably be produced by post-migmatization deformation.

Major element correlation analyses of the granitic rock and the surrounding metamorphic rocks could show no correlation, if the magma contained little vapor, or strong positive correlations similar to those expected for the permeation by magmatic juices hypothesis if the magma were wet.

Possible mechanisms for in situ origin are metamorphic differentiation and partial melting. Metamorphic differentiation, whereby the granitic material in the

metamorphic rocks becomes segregated into veins, lenses and pods of granitic rock has been suggested by Loberg (1968) and White (1967) however, the process by which this differentiation occurs is unknown.

Field evidence for metamorphic differentiation would be the presence of mafic selvedges surrounding the granitic portions (White, 1967) with the selvedge having formed from the selective removal of the granitic component of the rocks. The thickness of the selvedge should be proportional to the amount of granitic rock it surrounds.

Chemically, one would expect that there should be inverse correlations between the amount of granitic rock and the granitophile elements in the metamorphic rocks, and therefore the metamorphic rocks should show evidence of de-granitization.

Partial melting should show essentially the same effects as for the case of metamorphic differentiation. The only real difference between the two hypotheses is that partial melting indicates that the granitic portion formed from a silicate melt of granitic composition that had been derived from the adjacent rocks.

The other difference between the two in situ models is that metamorphic differentiation has never been experimentally demonstrated on the scale of a few feet under geologically reasonable conditions, while partial melting has been heavily investigated experimentally (Tuttle and

Bowen, 1958; Winkler and Von Platen, 1957, 1960, 1961, 1962; Luth, et al., 1964; Von Platen, 1965; Von Platen and Holler, 1966; Piwinskii and Wyllie, 1968; James and Hamilton, 1969; Piwinskii, 1970; Brown, 1970; Brown and Fyfe, 1970; Robertson and Wyllie, 1971; Huang and Wyllie, 1973; and Steiner, et al., 1975). Therefore, one may test the granitic and metamorphic rocks to see if they are in agreement, i.e., if the phase relationships suggested by their compositions are consistent with those for the experimental "granite"-water systems.

Since the phase relationships in the experimental granitic systems are not as straightforward as it is generally held and because of this one frequently sees erroneous conclusions based on misunderstandings of these relationships (King, p. 231, 1965), a brief summary of the compositional constraints within this system follows.

The phase relationships in the "granite"-water (Q-Ab-Or-An-H_2O) system approximate those of a simple binary eutectic with the exception that, in a simple binary eutectic, a liquid with the composition of the eutectic is always present--either at the end of crystallization or at the beginning of melting. In the "granite"-water system a liquid with the composition of the minimum is only to be expected for fractional crystallization of melts already having the composition of the minimum. For melting, liquids will have the composition of the minimum

only if the rocks undergoing melting have nearly the same Or/Ab ratio as that of the minimum itself.

The composition of the minimum becomes increasingly Ab rich and SiO_2 poor as the pressure increases from 1 to 10 kilobars (Tuttle and Bowen, 1958 and Luth et al., 1964). An anorthite component in the plagioclase tends to shift the minimum toward the Q-Or side of the phase diagram relative to its position in an anorthite free system (Von Platen, 1965; Winkler, 1967 and James and Hamilton, 1969). A recent study by Steiner et al., (1975) at 4 kilobars indicates that the minimum also migrates toward the Q-Or side in water undersaturated "granite"-water systems.

The location of the minimum is only important in that it determines the path on the cotectic that a liquid produced from partial melting will take as melting progresses. For example, for a bulk composition lying to the left of a given minimum, the melt will begin to form on the cotectic and will proceed to rise up (thermally) on the cotectic away from the minimum with the liquid composition becoming richer in Ab and Q. Under a different set of physical conditions, however, the same bulk composition could lie to the right of the minimum. The liquid formed in this case would then migrate away from the minimum toward the Q-Or join. It is clear that the composition of the initial melt could largely be a function of the P, T conditions during the formation of the

melt, even at constant bulk composition.

The location of the cotectic between the quartz and feldspar fields is of greater importance than the location of the minimum because liquids forming from any bulk composition must have compositions that lie somewhere on the cotectic -- regardless of the location of the minimum. The minimum only serves to indicate which way the composition of the melt will change with continued temperature increase.

Figure 1 shows the expected phase relationships in granitic systems having an anorthite component in the plagioclase for conditions expected in upper amphibolite facies environments -- temperatures from 500° to 700°C and pressures from 5 to 8 kilobars. Since a plagioclase around An_{30} would be expected in high grade metamorphic rocks (Winkler, 1967), the minimum would be located in the region of the letters "ic" in the word cotectic in Figure 1.

In addition to the preceding compositional restrictions for liquids produced from partial melting, it should be added that these liquids cannot migrate across the cotectic zone into the field not containing the bulk composition of the source of the melt. Liquids produced from source rocks lying in the quartz field must migrate into the quartz field and similarly, liquids from source rocks in the feldspar field must migrate from the cotectic zone into the feldspar field.

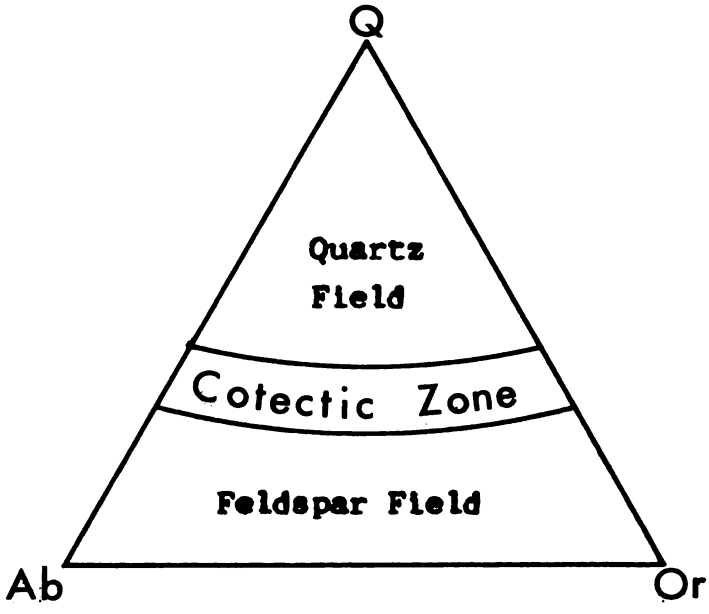


Figure 1. Expected phase relations in anorthite containing "granite"-water systems under amphibolite facies conditions (after Winkler, 1967). Minima would be located in the area of the letters "ic" in the word cotectic.

An additional chemical test for rocks suspected of having undergone partial melting is suggested. It stems from the fact that liquids must originate in the cotectic zone regardless of the composition of the source rocks. Namely, that the granitic rocks produced from partial melting should show less variability with respect to the granitophile elements than do the source rocks.

To test the various models for the origin of granitic rocks, the Poudre Canyon Migmatite, Larimer County, Colorado (Ward and Werner, 1962) was chosen because a good estimate of the volume percent granitic and metamorphic rock could be obtained from thousands of lithology thickness measurements (Ward and Werner, 1962) and because the metamorphic portion of the migmatite is not granite gneiss, but rather, clear cut metasediments. This avoids intuitive notions as to the prior state of the non-granitic portion of the migmatite.

LOCATION OF AREA

The area under study lies 8 miles northwest of Fort Collins, Colorado in the northern Front Range. Lithology thickness measurements and samples were collected along the course of the Cache La Poudre River from the mouth of the Poudre Canyon to Stove Prirle Landing--a straight line distance of 8 miles

The canyon affords excellent fresh exposures produced by blasting during the widening of Colorado Route 14, the

highway that goes up the canyon.

LITHOLOGIES AND FIELD OCCURRENCE

Structurally, the granitic rocks are dominantly concordant to the metamorphic host. Those granitic rocks that are not concordant were not included in the sampled population because it is believed that they have a greater chance of representing a post-metamorphic event.

A dominant characteristic of the granitic rocks is that they occur as ellipsoidal pods and lenses from one inch to 12 inches in thickness, the average thickness being 1.75 inches.

Mineralogically, they range quartz rich (80-90%) to 100% potash feldspar. While thin section analysis was not undertaken, potash feldspar and plagioclase feldspar stained slabs and megascopic examination showed most of them to be one feldspar granites with most of the feldspar being a potash feldspar perthite.

The metamorphic rock, and in fact, the migmatite as a whole is not highly contorted but rather appears as layered rocks. Evidences of folding, on the scale of an outcrop, are lacking. It appears as if one were looking at the limbs of tight isoclinal folds.

Petrologically, the metamorphic rocks range from biotite-sillimanite schists to quartzo-feldspathic biotite gneisses. Amphibolites, though present, are minor in amount. The general character of these rocks is that

of straightforward metasediments--there is no evidence of feldspathization, blastesis or mafic selvedge development.

Petrography of potash feldspar stained thin sections shows that the mineralogy of these pelites and psammites is quartz + biotite + plagioclase (ca. An_{30}) ± potash feldspar ± sillimanite ± garnet ± muscovite ± rutile or sphene ± opaque oxides. Blue-green to green-brown hornblende + plagioclase + opaque oxides and sulfides ± an epidote mineral are found in the amphibolites. All of the mineral assemblages are characteristic of rocks having undergone upper amphibolite facies level (Sillimanite-Almandine-Orthoclase subfacies) of metamorphism (Winkler, 1967 and Turner, 1968).

Detailed mapping of the region was not undertaken so that the lithologic and structural relationships of the migmatite and the rocks in the vicinity are not known. Therefore, it is not yet possible to put the migmatite into the geological context of the region as a whole.

SAMPLING AND FIELD MEASUREMENTS

Prior to the collection of samples and lithology thickness measurements, an outcrop was defined as one hundred feet of continuous exposure measured perpendicular to the foliation (Ward and Werner, 1962). Exposures were measured and those fitting the above definition

were numbered. From these numbered outcrops, a group was randomly selected for sampling and lithology thickness measurements.

At each of the selected outcrops (20 in all), four ten foot lines with random starts were measured -- also perpendicular to the foliation -- to determine the volume percent of granitic and metamorphic rock. Rocks classified as granitic were defined as unfoliated quartz and feldspar rich rocks greater than or equal to one-quarter inch in thickness. Metamorphic rocks were rocks greater than or equal to one-quarter inch in thickness not fitting the definition of granitic rock. Pure quartz veins, when encountered, were counted as metamorphic rocks.

Three rock samples were collected at each ten foot line. The granitic rock nearest the 2½ foot mark on the measuring tape and the metamorphic rocks nearest the 5 foot and 7½ foot marks on the tape were collected. This random scheme was adhered to for the collection of all samples.

SAMPLES USED

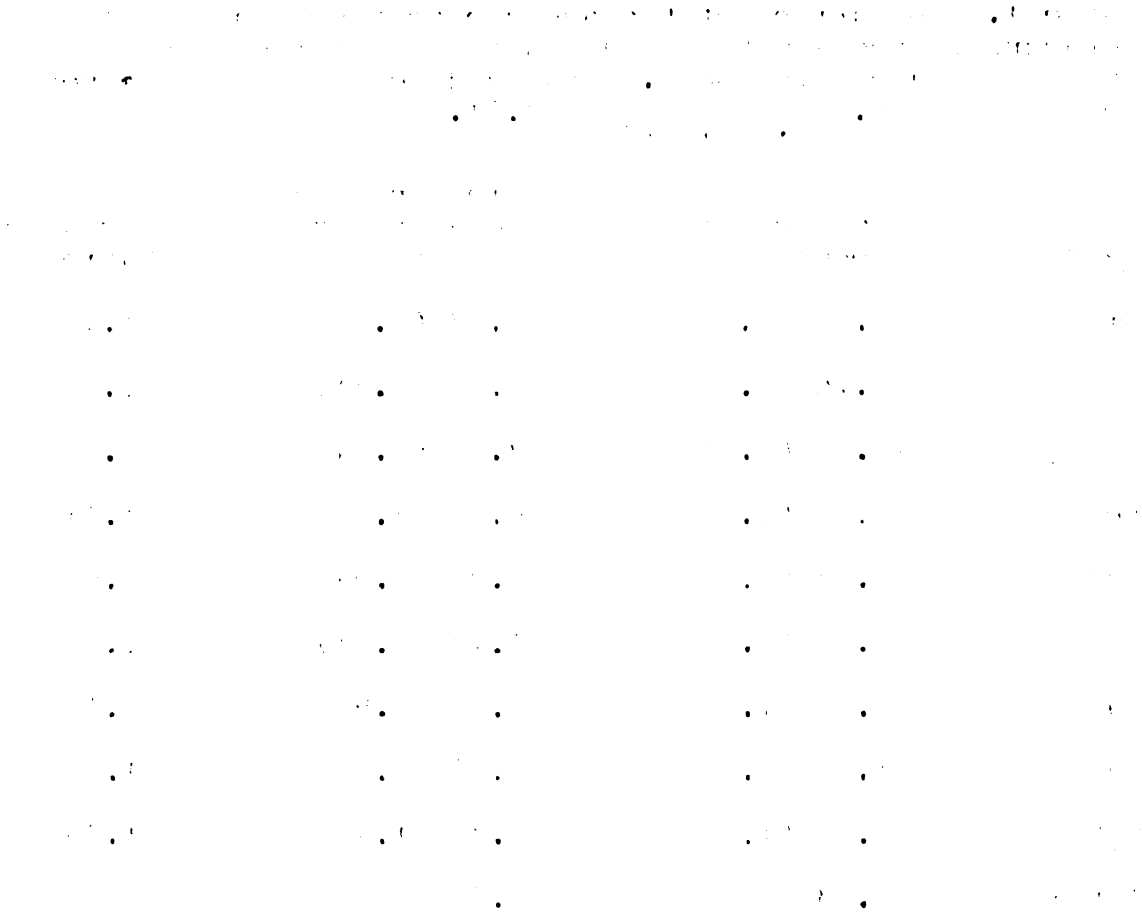
In all, the major element chemistry and densities of 46 granitic rocks and 85 coexisting, by line, metamorphic rocks were determined, (Techniques used with statistical reliability estimates are given in Appendix A. Raw chemical data is given in Appendix B). Five of the granitic rocks occurred within amphibolites and were

deleted from further analysis since the amphibolites are chemically much different from the main body of the metamorphic rocks. This could lead to spurious correlations due to tight clusters of deviate points. Forty-one granitic rocks and their coexisting 75 metamorphic rocks remain.

Since the amount of each of the two metamorphic rocks per line is not known, their chemical compositions were averaged. The means, standard deviations and the variance ratios for each of the oxides of the 75 metamorphic rocks and the 41 line average metamorphic rocks are shown in Table 1. It is clear from Table 1 that there is no significant difference between the average of all 75 metamorphic rocks and the 41 line average metamorphic rocks -- at the 99.9% level. This suggests that there is a very high level of chemical heterogeneity within lines as well as between lines. In this light, the use of the line average metamorphic compositions seems justified. The conclusion that there is small scale lithologic heterogeneity was also reached by Ward and Werner (1962) on the basis of nested analysis of variance of lithologic thickness distributions between lines, outcrops and groups of outcrops. Similar small scale lithologic and chemical heterogeneity in a metamorphic terrane has also been found in the Moine metasediments (Butler, 1965).

Table 1. Comparison of the average composition of all metamorphic rocks with the average composition of the line average metamorphic rocks. Standard deviations are given in parentheses. $F_{.001,74,40} = 2.51$.

Oxide	All Metamorphic Rocks(n=75)	Line Average Metamorphic Rocks(n=41)	Variance Ratio
SiO_2	69.18 (7.98)	69.33 (7.46)	1.14
TiO_2	.76 (0.36)	.75 (0.31)	1.34
Al_2O_3	13.64 (3.07)	13.61 (2.94)	1.09
FeO	6.69 (2.74)	6.60 (2.60)	1.11
MnO	.08 (0.04)	.08 (0.04)	1.00
MgO	1.50 (0.85)	1.52 (0.82)	1.07
CaO	1.39 (1.06)	1.42 (0.99)	1.15
Na_2O	1.74 (0.96)	1.72 (0.87)	1.22
K_2O	3.45 (1.62)	3.35 (1.48)	1.20
Total	98.43	98.37	



STATISTICAL ANALYSIS OF CHEMICAL DATA

The average granitic rock composition and the line average metamorphic rock composition are given in Table 2, along with the standard deviations. The granitic rocks show greater variability with respect to SiO_2, Al_2O_3, K_2O and Na_2O than the line average metamorphic rocks. This is clear evidence against the origin of the granitic rocks by partial melting of the adjacent rocks. Anatectic melts should show less variation for these elements than the source rocks which produced them. This is especially striking in that those elements showing less variation in the granitic rocks than in the line average metamorphic rocks are TiO_2, FeO, MgO and CaO which are generally held to be granitophobe elements.

A 10 by 10 correlation matrix was obtained giving the correlations for each oxide and the weight percent granitic rock between the granitic rocks and the line average metamorphic rocks. (The whole matrix is given in Appendix C).

Of the 100 correlation coefficients, 12 were significant at the 95% level (two-tailed). Of these, the highest was r= .4501. This means that at best, only 20% of the variability is explained by regression.

High positive correlations between granitophile elements in the line average metamorphic rocks and the amount of granitic rock or the composition of the granitic rock expected in both the magmatic "juices" and hydrous

Table 2. Comparison of the average composition of the granitic rocks and the line average metamorphic rocks. Standard deviations are given in parentheses.

Oxide	All Granitic Rocks(n=41)	Line Average Metamorphic Rocks(n=75)
SiO_2	75.38 (8.07)	69.33 (7.46)
TiO_2	.14 (0.12)	.75 (0.31)
Al_2O_3	13.63 (4.20)	13.61 (2.94)
FeO	1.39 (1.46)	6.60 (2.60)
MnO	.03 (0.05)	.08 (0.04)
MgO	.31 (0.44)	1.52 (0.82)
CaO	.94 (0.94)	1.42 (0.99)
Na_2O	1.96 (1.09)	1.72 (0.87)
K_2O	6.71 (3.94)	3.35 (1.48)
Total	100.49	98.37

silicate magma models are not present. Neither are high negative correlations expected for the partial melting or metamorphic differentiation models.

The results of stepwise multiple regression analysis obtained (see Appendix D) by regressing the weight percent granite per line with the oxide composition of the granitic rocks and the weight percent granitic rock per line with the compositions of the line average metamorphic rocks gives lines with coefficients of determination of $r^2 = .3045$ and $r^2 = .2131$ respectively. Neither the chemical composition of the of the granitic rocks nor the compositions of the line average metamorphic rocks are good predictors of the amount of granitic rock present in a given line.

The total lack of correlation between the line average metamorphic rocks and the granitic rocks indicates either that there was no interaction between the two, or, more likely, that, owing to the high degree of local variability, differences could not be detected between samples collected 2½ feet apart even if they were present. The area would have to be re-sampled on the scale of inches to detect interactions.

Because of this high local variability, the continued treatment of data at the level of a line will be abandoned. Further analysis will be concerned with averages of all rocks and the regional picture rather than the local.

ESTIMATION OF THE BULK COMPOSITION OF THE MIGMATITE

Since the volume percent of each rock type per line is known from thickness measurements and the density of each rock sample is also known, it is possible to mathematically "mix" the chemical compositions according to weight percent and thereby obtain an estimate of the homogenized line bulk compositions. The average of all 41 homogenized line bulk compositions then gives a good estimate of the bulk composition of the whole migmatite, i.e., what the original bulk composition of the migmatite was if the granitic material now present had been derived in place. This average bulk composition of the migmatite as it now exists is given in Table 3.

TEST FOR COMPOSTIONS EXPECTED FROM THE PARTIAL MELTING MODEL

Even though an in place by partial melting origin of the granitic portion seems unlikely in the light of the preceding statistical analyses, it is desirable to test the observed compositional relationships with those expected from experimental systems.

As was done earlier, much use of CIPW normative Q-Ab-Or projections has been made for the interpretation of lines of liquid descent during fractional crystallization of granitic magmas as well as estimating compositions of early formed liquids during episodes of melting.

Bowen and Tuttle (1958) were careful in demonstrating the similarity of their experimentally determined phase

Table 3. The average bulk composition of the migmatite. Standard deviations are given in parentheses.

Oxide	Migmatite Bulk Composition
SiO_2	70.65 (5.74)
TiO_2	.59 (0.22)
Al_2O_3	13.76 (2.44)
FeO	5.28 (2.05)
MnO	.07 (0.03)
MgO	1.21 (0.62)
CaO	1.31 (0.89)
Na_2O	1.81 (0.77)
K_2O	4.22 (2.08)
Total	98.90

relationships with natural rocks in that they only chose rocks that contained 80% or more CIPW normative Q+Ab+Or. This means that the rocks so cited were already granite to quartz diorite in composition.

It has become fashionable since 1958 and especially since the establishment of a viable plate tectonic model to derive granitic melts from sedimentary rocks. These rocks, however, are not already granitic in composition -- which should live some doubts about continued usage of CIPW normative composition estimates. The chief reason being that, while the CIPW norm is a good approximation of the mode in granitic rocks, it is not a good approximation of the mode in sedimentary rocks undergoing prograde metamorphism during burial or subduction.

For example, depending upon the K_2O, FeO and MgO content of the sediment, biotite is almost certain to appear during prograde metamorphism. Furthermore, the amount of biotite would be expected to be proportional to the FeO and MgO content of the rock -- assuming sufficient K_2O is present. A biotite so formed would be expected to be stable until the onset of granulite facies conditions. The K_2O in the biotite could not contribute to an Or component in a melt forming under amphibolite facies conditions -- conditions in which biotite is stable. A CIPW normative calculation of such a rock would show all of the K_2O in an orthoclase molecule and thereby lead to inflated estimates of the amount of orthoclase

actually available during amphibolite facies conditions.

A biotite norm (see Appendix E for the formula for calculation) has been developed wherein a biotite --annite-phlogopite--is calculated prior to the calculation of normative orthoclase.

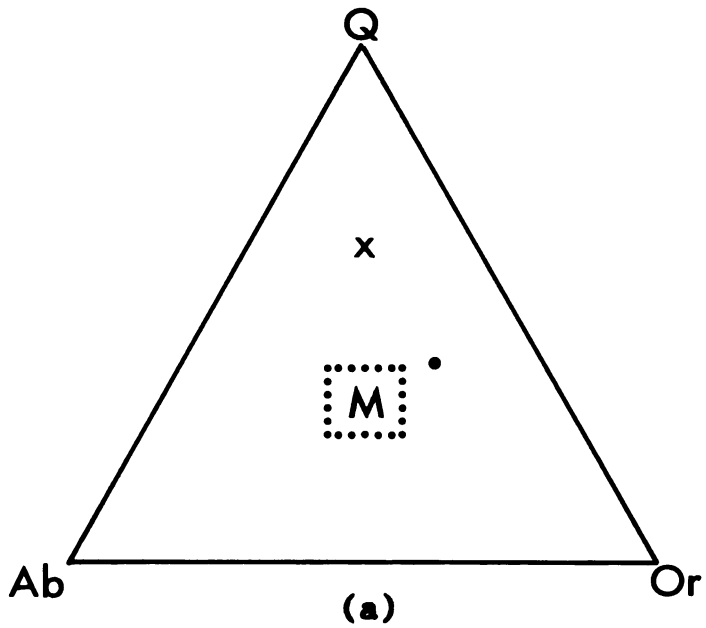
Table 4 gives the composition of a biotite-sillimanite schist along with the mircrometric mode and both the CIPW and biotite normative minerals. Noteworthy is that the amount of orthoclase in the CIPW norm is 18%, the biotite norm calculates 6% while the actual rock contains none. The biotite norm gives a more realistic picture of the actual amount of orthoclase present in amphibolite facies level rocks. Subsequent discussions of the Q-Ab-Or projection will be limited to those obtained from biotite normative calculations. CIPW normative projections are presented only for comparison since they are so well established in the literature.

Figure 2a shows the biotite normative Q-Ab-Or projection of the bulk composition of the migmatite and the average granitic rock composition, along with the portion of the cotectic zone in which liquid should form under amphibolite facies conditions for this bulk composition. Liquids produced from this bulk composition should lie either in the portion of the cotectic zone or between this area and the bulk composition of the migmatite. The average composition of the granitic rocks lies well outside this region being more othoclase rich than can be

Table 4. Comparison of CIPW norm and Biotite norm with actual micrometric mode of a biotite-sillimnaite schist.

Outcrop 33
line 04
Spec. No. 39

Oxide			CIPW Norm	Biotite Norm	Mode (Vol. %)
SiO_2	57.28	il	1.98	1.98	0.00
TiO_2	1.06	bi		31.45	46.66
Al_2O_3	20.37	or	17.73	5.56	0.00
FeO	10.84	ab	2.62	2.62	13.22(plag.)
MnO	.06	an	1.39	1.39	
MgO	2.36	cor	24.69		
CaO	.28	hyp	24.12		
Na_2O	.32	sill		23.33	10.94
K_2O	3.96	q	26.76	30.84	27.36
Tot.	96.13				



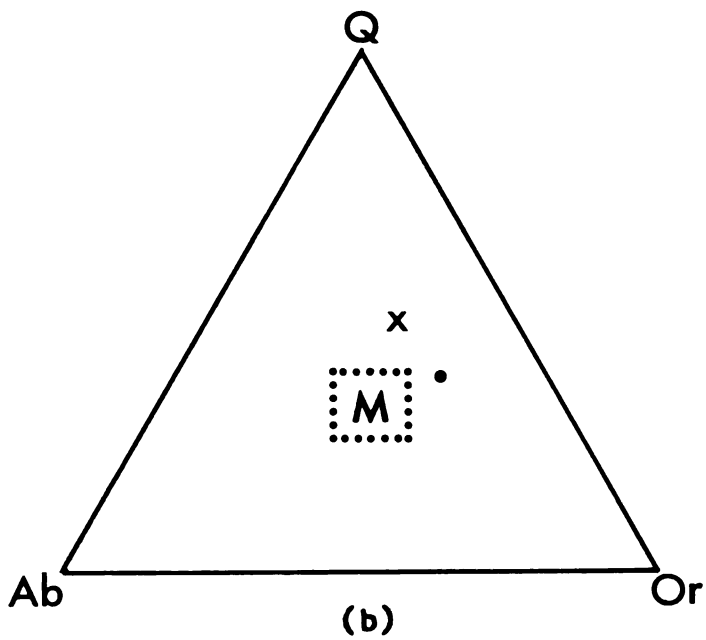
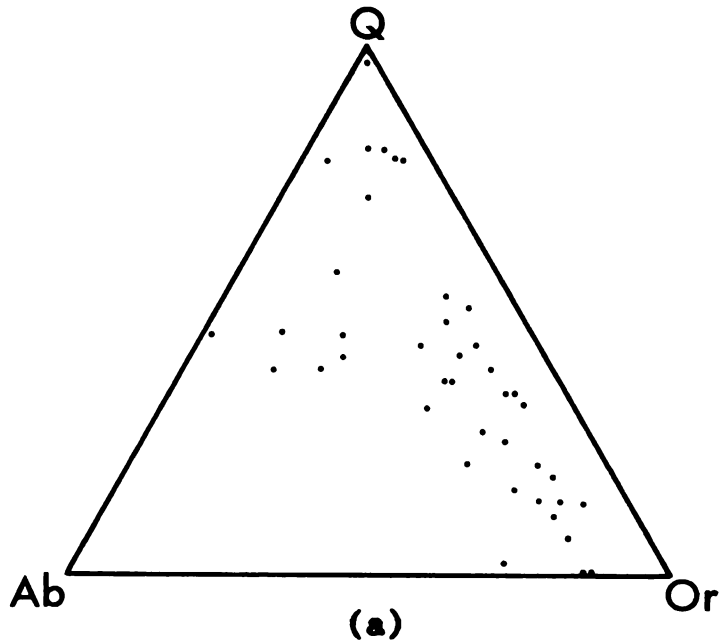


Figure 2, a & b. (a) biotite normative and (b) CIPW normative projections of the bulk composition of the migmatite (x) and the average granitic rock composition (dot). The dotted area corresponds to the part of the cotectic zone expected to be important in amphibolite facies conditions. The "M" is the location of the minima under these conditions.

explained by means of an anatectic model. This suggests that, on the average, the granitic rocks were not derived from in situ partial melting of the bulk composition of the migmatite as it now exists. Some other mechanism(s) must have been operating.

THE ORIGIN OF THE GRANITIC ROCKS

Figure 3a is the biotite normative Q-Ab-Or projection of the granitic rocks. There is a trend of granitic compositions beginning on the Ab-Or join near the Or corner and extending approximately half-way to the Q apex. Experimental studies in plagioclase containing "granite"-water systems at 1 to 2 kilobars total pressure indicate that location of the minimum is about $Q_{40}Ab_{20}Or_{40}$ and that there is a path of liquid descent beginning on the Ab-Or join near the Or corner terminating at the minimum (Von Platen, 1965; Winkler, 1967 and James and Hamilton, 1969). The trend seen above for the granitic rocks in this study coincides with this experimentally determined line of fractional crystallization. This means that 26 (63%) of the 41 granitic rocks could be explained as belonging to a series of liquids, fractionally derived, from a nearby pluton that was crystallizing both plagioclase and potash feldspar at pressures of 1 to 2 kilobars -- pressures well below those indicated by the mineral assemblages in the metamorphic rocks. These 26 granitic rocks must post-date the metamorphism -- they could not have been formed



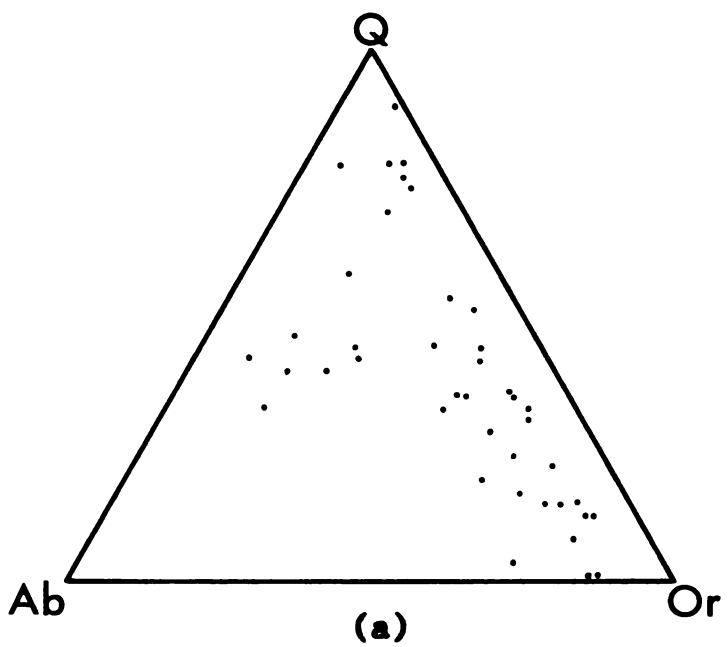


Figure 3, a & b. (a) biotite normative and (b) CIPW normative projections of the granitic rocks.

during the high levels of metamorphic intensity experienced by the metasediments.

Figure 4a, the biotite normative Q-Ab-Or projection of the line average metamorphic rocks, shows a trend of compositions away from the main body of compositions toward the Q-Or join. This trend would intersect the trend of the 26 granitic rocks in the area of the 1 to 2 kilobar minimum. This suggests that some of the metamorphic rocks have indeed been made more granitic in composition and furthermore, that the composition of the granitic material added was that of the minimum for the intruding granitic rocks. This is indicated schematically in Figure 5. The metamorphic rocks thereby confirm that 63% of the granitic rocks formed from injection of silicate magma.

The origin of the remaining 15 (37%) granitic rocks cannot be explained as the result of this study. Perhaps this is due to too few samples and to the high level of variability exhibited by these rocks.

DISCUSSION

The local chemical and lithologic variability found in the Poudre Canyon Migmatite, is so high that, even with sampling at 2½ foot intervals the interactions between the granitic rocks and the metamorphic rocks is obscured. Only when the rocks are examined in the context of the 8 mile long region does it become clear that there has

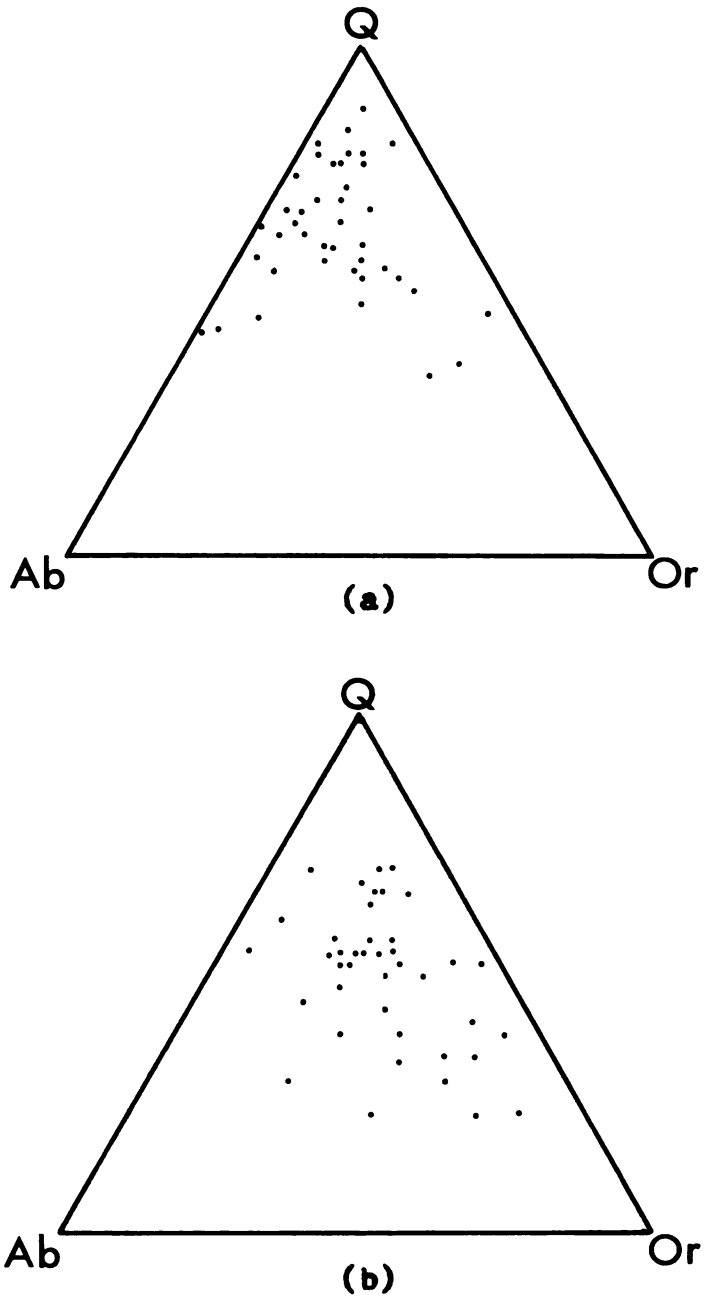


Figure 4, a & b. (a) biotite normative and (b) CIPW normative projections of the line average metamorphic rocks.

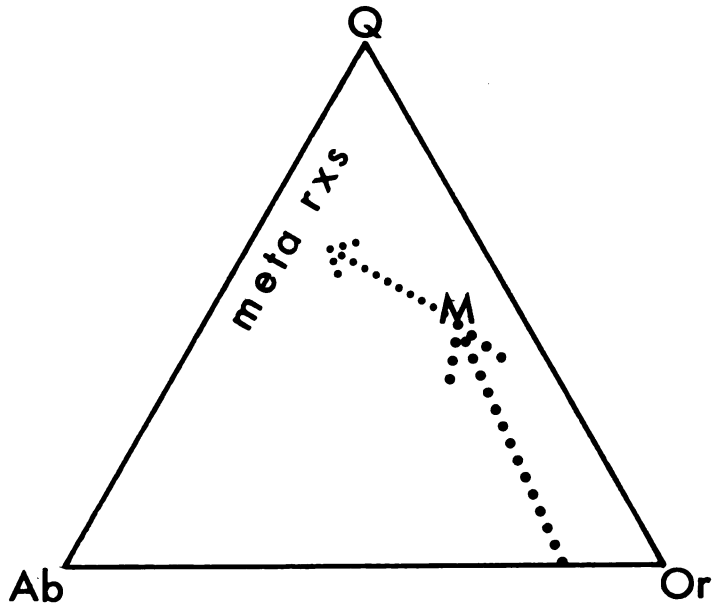


Figure 5. Schematic illustration of the fractionation trend of the granitic rocks(large dots) and the granitization trend(small dots) of the metamorphic rocks. The "M" is the location of the 1 to 2 kilobar minimum (after Winkler, 1967 and James and Hamilton, 1969).

been interaction. Had not 116 samples been analyzed, even this regional picture might have been obscured by the heterogeneity observed.

Those 26 granitic rocks that can be explained are members of a fractionating series of liquids derived from a nearby pluton. They were injected into the metasedimentary rocks after they had been metamorphosed to amphibolite facies level.

Geologic implications of this study must deal with the high level of chemical and lithologic variability that can be expected in metamorphic terranes. To the degree to which these rocks, and the rocks of the Moine series (Butler, 1965), are representative of metasediments in general, use of descriptive terms such as "pelitic" or "psammitic" grossly oversimplifies the true nature of the real variability -- both chemical and lithologic. In this context, use of chemical data to show that a given sample has been granitized or de-granitized relative to "normal" "pelitic" or "psammitic" rocks can have no meaning unless a good estimate of the total chemical variability naturally inherent in the given rock pile can be made.

If sedimentary rock piles are, in general, as heterogeneous as this study indicates, anatectic melts produced from such rocks should also show a high degree of local variability. To produce a homogeneous granitic pluton from melts so produced would require complete homogenization

of these melts after separation from the source rocks.

Another generally overlooked phenomena come to light while examining the consequences of the partial melting of sedimentary rocks. This is that sedimentary rocks are usually expected to concentrate silica -- especially as quartz. Extensive melting of such silica rich rocks should produce liquids which lie in the quartz field of the ternary "granite"-water system. If such a melt were intruded into higher levels of the crust, quartz should be the stable crystalline phase on the liquidus. Fractionation of such liquids should produce a series of granitic rocks that have quartz as the first precipitating mineral phase and show liquid descent paths from the quartz field toward the cotectic.

Tuttle and Bowen (Fig. 41, p. 78, 1958) show that the path of liquid descent of natural granitic rocks lies in the feldspar field and moves toward the cotectic from that side. Examination of natural granitic batholiths indicate that a feldspar is usually the first mineral phase to crystallize.

It would appear that batholithic masses of granite do not originate from partial melting of sedimentary rocks both because of their homogeneity and because quartz is seldom the first mineral to crystallize.

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REFERENCES CITED

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APPENDIX A

APPENDIX A

Sample Preparation

All rocks were cut into one-quarter inch thick slabs on a water-cooled diamond saw to avoid the possibility of including granitic stringers in metamorphic rocks and vice-versa. This is consistent with the field definitions used during the lithology measurements.

After the slabs were used for density determinations, they were ground for five minutes in a steel ring-and-puck disc mill.

In preparation for X-ray fluorescence analysis, one gram of rock powder was mixed with two grams of lithium metaborate($LiBO_2$) and then fused in graphite crucibles for ten minutes at 1000°C (after Welday, et al., 1964). The glass beads were ground for three minutes in the disc mill. The rock-borate powders were then pressed at seven tons/in.^{2} in aluminum Spex Caps using boric acid filler.

For neutron activation analysis, one gram of each rock powder was weighed into a polyvial that had been cleaned in reagent grade methyl alcohol. The polyvials were handled with rubber gloves to avoid fingerprint contamination.

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APPENDIX A

Analytical Techniques

Densities of the rock slabs were determined on a Jolly balance apparatus. Replicate determinations on some of the samples yielded densities that agreed to $\pm$ 0.01 gm/cm^3. In addition, a rose quartz standard was used throughout the weighings of the unknowns. The average density of the standard, form all eight determinations, was 2.649 gm/cm^3, the standard deviation, 0.0064 gm/cm^3, and the coefficient of variation was 0.0024% of the mean. The densities are believed to be accurate to $\pm$ 0.01 gm/cm^3.

SiO_2, TiO_2, Al_2O_3, total iron as FeO, MnO, MgO, CaO and K_2O were determined with a General Electric XRD-6 helium path spectrometer. A flow proportional counter with P-10 gas and pulse height discrimination was used for all runs. Only fixed clock time was used for counting. The particular time chosen was based on count rates for the USGS standard rocks G-2, GSP-1, AGV-1, BCR-1, DTS-1 and PCC-1, estimated sample concentrations for the element to be determined and the desirability of holding the counting error to one percent or less.

The correlation coefficients and the standard errors of estimate for the regression lines obtained for each of the elements are given in Table A-1.

APPENDIX A

Table A-1. Correlation coefficients and standard errors of estimates of regression lines obtained for the standard rocks.

Oxide	Correlation Coefficient	Standard Error of Estimate(in %)
SiO_2	.9994	.493
TiO_2	.99999	.005
Al_2O_3	.9988	.411
FeO	.9996	.151
MnO	.9999	.002
MgO	.9954	.135
CaO	.9997	.078
K_2O	.9993	.078

APPENDIX A

Na_2O was determined with Michigan State University's Triga reactor.

USGS standard rocks G-2, GSP-1, AGV-1, BCR-1 and W-1 were used in addition to one standard of reagent grade NaCl such that its concentration of Na_2O was equal to that contained in one gram of GSP-1.

The unknowns (up to 37) and three standards were placed in the reactor's lazy susan sample holder, which was rotated during irradiation, and irradiated for 15 minutes at 250 kilowatts. The samples were allowed to "cool" overnight--- 12 to 15 hours. The 2.75 Mev Na^{24}(n,gamma) peak was counted for 100 seconds live-time with a lithium drifted germanium (GeLi) detector maintained at the boiling point of liquid nitrogen. Absolute peak heights were determined and the average ratio of peak height to weight percent Na_2O of the standards was used to calculate the weight percent Na_2O of the unknowns.

The counting error, expressed as the relative standard deviation is given by $100/\sqrt{N}$, where N = the number of counts. Since the number of counts is proportional to the concentration of Na_2O, the counting error can be ralated to the concentration. The lowest concentration of Na_2O measured in this study was 0.54 weight percent and the highest, 4.68 weight percent. The associated counting error for these two samples is $\pm$ 2.45% and $\pm$ 0.83%, respectively. The

APPENDIX A

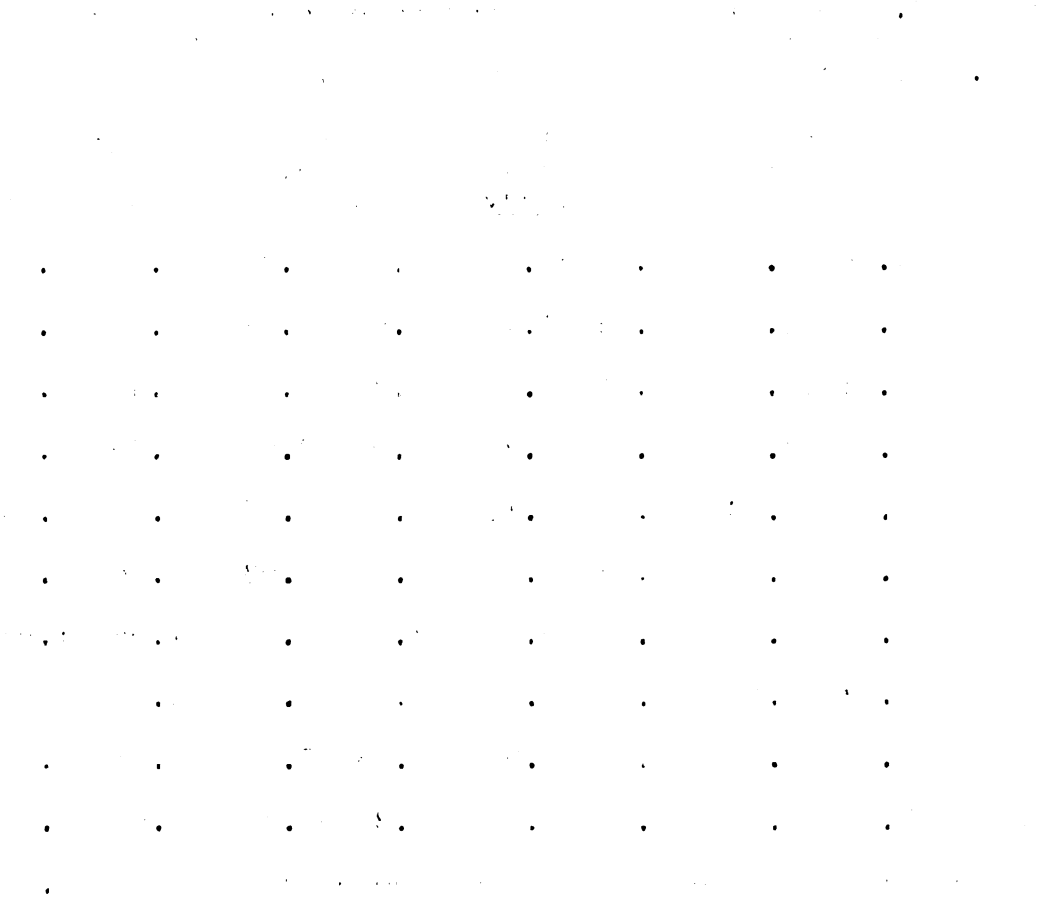
counting error for the other unknowns will lie within this interval.

A comparison of the values for the oxide concentrations of BCR-1, AGV-1, GSP-1, and G-2 obtained by this study with those recommended by Flanagan,(1973) is given in Table A-2.

Table A-2. Comparison of the results of chemical analysis of this study with the USGS recommended values (Flanagan, 1973). All values are in weight percent.

	BCR-1		AGV-1		GSP-1		G-2	
Oxide	USGS	This Study	USGS	This Study	USGS	This Study	USGS	This Study
SiO_2	54.50	54.77	59.00	58.99	67.38	67.27	69.11	69.19
TiO_2	2.20	2.23	1.04	1.19	.66	.77	.50	.58
Al_2O_3	13.61	12.97	17.25	16.98	15.25	15.40	15.40	15.69
FeO	12.06	12.08	6.08	6.30	3.90	3.88	2.39	2.39
MnO	.18	.23	.10	.12	.04	.05	.03	.04
MgO	3.46	3.03	1.53	1.50	.96	.93	.76	.78
CaO	6.92	6.89	4.90	5.08	2.02	2.00	1.94	1.92
Na_2O	3.27	3.40	4.26	4.35	2.80	2.85	4.07	ND
K_2O	1.70	1.66	2.89	2.95	5.53	5.52	4.51	4.43
Total	97.89	97.53	96.98	96.95	98.35	99.26	98.99	98.61*

*Na_2O equal to that of the USGS recommended value added.



APPENDIX B

APPENDIX B

Raw Chemical Data

The raw chemical data is listed on the following pages as it appeared on the IBM cards used for computer analysis. Each row gives the outcrop number, the line number, the specimen number, rock type, the results of the chemical analysis, the weight percent granitic rock in the line(abbreviated to "Gran) and the density of the specimen(abbreviated "Dens"). The columns containing the oxide concentrations, the weight percent granitic rock and the density of the sample are appropriately labeled. The key to the first 8 columns is as follows:

1. The first two columns (1-2) give the outcrop number.
2. The next two columns (3-4) give the line number.
3. The next three columns (5-7) give the specimen number.
4. The next column (8) gives the rock type-- "G" for granitic and "M" for metamorphic.
5. If columns 5 through 8 are all M's, the row represents the line average metamorphic rock.

For example, 0217394G would mean-- outcrop No. 2, line No. 17, specimen No. 394 and that the rock is granitic. If the first 8 columns contained the designation 0610MMMM, it would mean-- outcrop No. 6, line No. 10 and that the row represented the line average metamorphic rock composition.

APPENDIX B

Raw Chemical Data

Granitic Rocks associated with psammo-pelitic rocks

	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Gran	Dens
0217394G	91.54	.07	6.54	1.07	.01	.00	.64	1.78	.73	41	2.63
0505397G	85.83	.20	7.99	2.27	.02	.00	.75	1.54	2.57	12	2.61
0510400G	94.33	.06	5.01	.61	.01	.00	.24	.63	2.47	13	2.60
0518403G	89.90	.08	5.48	3.34	.04	.00	.89	1.03	1.86	19	2.62
0519406G	85.42	.28	6.98	4.50	.04	.36	.61	.81	2.60	18	2.64
3207025G	89.07	0.12	05.73	01.30	.01	0.00	0.15	0.72	02.56	13	2.63
3210028G	74.29	0.06	14.50	01.06	.01	0.00	0.56	2.62	06.83	19	2.58
3217034G	77.80	0.11	13.03	00.84	.01	0.00	0.96	3.48	03.97	11	2.61
3304037G	81.95	.08	10.62	.80	.01	0.00	.31	1.31	5.71	28	2.59
3319043G	78.27	.06	13.5	1.17	.01	0.00	1.14	2.59	2.42	19	2.63
3300046G	69.78	.08	16.29	.83	.01	.18	.48	2.10	10.20	20	2.59
3806064G	74.88	.11	15.03	1.13	.01	0.00	.81	4.68	2.42	39	2.65
3812067G	76.73	.10	13.14	1.69	.04	0.00	.95	4.07	2.08	19	2.65
2814019G	73.65	0.29	13.55	02.97	.04	0.54	0.46	1.20	07.90	20	2.61
2816022G	72.45	0.13	13.72	02.00	.07	0.27	0.48	2.11	06.74	14	2.61
3804061G	74.94	.08	13.75	2.44	.08	.27	.38	1.90	7.17	17	2.66
3813070G	71.15	.19	15.91	1.28	.02	.39	.42	1.91	8.19	12	2.62
4812103G	68.05	.12	16.02	1.08	.02	.45	1.10	1.09	12.05	2.8	2.57
1504445G	72.61	.25	12.48	5.37	.22	.78	.60	1.24	6.27	40	2.70
1213427G	70.46	.21	15.32	1.88	.02	1.26	1.12	1.03	8.32	28	2.64
1214430G	63.85	.37	16.74	3.34	.03	2.15	1.65	1.03	10.19	41	2.66
2310460G	64.56	.52	18.0	3.65	.03	1.49	3.71	3.96	1.86	23	2.71
2314463G	67.46	.11	18.1	.00	.01	.42	3.03	2.34	7.76	15	2.69
2700001G	70.81	0.33	15.30	03.25	.03	0.69	3.08	4.34	01.06	12	2.65
2708004G	90.22	0.50	03.93	05.03	.04	0.42	0.11	0.18	01.22	08.8	2.69
4304079G	73.33	.09	15.15	.33	.01	.21	.62	1.81	9.58	38.9	2.59
4504085G	65.61	.10	18.97	.17	.00	0.00	.92	3.16	11.19	26.0	2.58
4508091G	83.58	.05	10.46	.10	.00	0.00	.49	1.11	6.58	16.0	2.61
4514094G	79.22	.11	12.14	.66	.02	0.00	.78	2.14	5.78	22.2	2.60
4811100G	72.24	.08	15.33	.08	.01	.18	1.12	1.42	10.63	18.5	2.59
5000109G	64.95	.05	19.74	0.00	.00	.27	.50	1.72	13.79	72.9	2.55
5013115G	67.68	.09	17.75	.30	.00	.34	.50	1.41	11.57	24.8	2.59
5015118G	67.89	.06	18.72	.00	.00	.36	.67	1.73	12.52	13.8	2.59
5302121G	76.46	.05	14.0	.81	.25	0.00	.50	4.15	3.56	38.0	2.65
5700145G	69.19	.08	17.18	.00	.00	.24	.52	1.91	11.29	29.1	2.58
5703148G	65.39	.07	19.5	.00	.00	.39	.61	1.94	13.54	38.9	2.57
5709151G	76.53	.12	13.67	.61	.02	.12	.48	1.31	8.77	10.7	2.61
5802157G	76.62	.10	13.52	.32	.00	.00	.72	1.14	9.29	15.7	2.60
5804160G	79.62	.06	12.52	.00	.00	.12	.47	1.34	7.10	26.3	2.60
5805163G	69.62	.06	17.44	.00	.00	.28	.54	1.67	11.72	29.1	2.59
5906175G	72.67	.24	15.92	.74	.02	.54	4.47	2.67	3.04	34.4	2.57

APPENDIX B

Line average metamorphic rocks

	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Gran	Dens
0217MMMM	69.52	.90	12.96	7.32	.04	1.70	.88	1.42	3.18	41.3	2.76
0505MMMM	73.72	.75	11.35	7.92	.05	.90	.75	1.31	2.10	12.0	2.76
0510MMMM	58.11	1.00	18.36	10.27	.08	2.23	.82	1.28	4.62	13.3	2.82
0518MMMM	67.98	.88	16.22	7.73	.05	1.91	.53	.72	2.74	19.2	2.79
0519MMMM	58.66	.94	18.80	10.39	.08	2.32	.51	.60	3.74	18.9	2.79
3207MMMM	73.85	0.71	11.64	06.54	.10	1.21	0.58	1.26	02.54	13.7	2.70
3210MMMM	76.96	0.67	10.86	05.39	.05	1.02	0.59	1.49	02.67	19.9	2.69
3217MMMM	79.29	0.60	08.95	05.85	.14	0.84	.55	1.18	2.35	11.4	2.70
3304MMMM	57.01	1.05	20.1	10.77	.06	2.41	.29	.23	3.97	28.0	2.78
3319MMMM	68.64	.85	12.81	7.73	.06	1.38	.96	1.94	2.65	19.0	2.74
3300MMMM	54.67	1.08	20.45	11.21	.08	2.38	.48	.69	4.17	20.5	2.88
3806MMMM	79.00	.67	10.07	6.28	.04	1.11	.26	.47	2.32	39.4	2.72
3812MMMM	64.35	.98	15.29	7.93	.08	1.88	.83	1.90	3.66	19.6	2.74
2814MMMM	71.28	0.64	11.83	05.40	.07	1.04	0.47	0.65	07.56	20.2	2.68
2816MMMM	70.93	0.69	12.04	07.12	.15	1.12	1.89	2.28	02.52	14.4	2.74
3804MMMM	77.82	.63	10.21	5.79	.06	1.01	.39	.87	2.70	17.5	2.69
3813MMMM	65.14	.90	15.57	8.29	.09	1.88	.43	1.05	2.58	12.2	2.76
4812MMMM	69.64	.44	14.28	3.95	.05	.74	1.18	2.06	6.87	2.8	2.68
1504MMMM	67.58	.72	13.30	07.02	.12	1.37	1.52	2.08	4.68	40.0	2.72
1213MMMM	65.25	.44	16.11	4.30	.03	3.50	3.68	2.42	2.88	28.4	2.74
1214MMMM	70.34	.42	12.91	5.16	.03	2.75	2.61	2.06	2.45	41.5	2.73
2310MMMM	72.43	.66	12.17	5.01	.04	1.51	2.34	2.23	2.50	23.0	2.72
2314MMMM	75.40	.56	11.66	3.73	.06	.95	2.47	1.82	3.44	15.6	2.70
2700MMMM	69.24	0.81	13.09	06.38	.08	1.30	2.26	2.97	02.13	12.0	2.74
2708MMMM	62.33	1.03	15.37	07.53	.08	1.66	3.31	3.38	02.50	08.8	2.76
4304MMMM	56.53	1.91	12.7	12.68	.16	3.38	2.76	1.20	4.74	38.9	2.89
4504MMMM	79.03	.37	11.93	2.66	.07	.26	1.45	2.62	2.43	26.0	2.68
4508MMMM	75.58	.38	11.86	3.48	.12	.60	1.96	1.70	4.20	16.0	2.70
4514MMMM	78.27	.35	10.9	2.64	.06	.32	.85	1.63	5.31	22.2	2.64
4811MMMM	79.12	.35	10.9	2.76	.05	.28	1.49	2.31	3.51	18.5	2.65
5000MMMM	56.24	1.06	17.97	9.32	.09	2.36	.54	.92	6.66	72.9	2.82
5013MMMM	68.42	.98	13.9	7.27	.06	1.52	1.03	1.48	3.34	24.8	2.74
5015MMMM	71.87	.86	13.16	6.99	.06	1.36	1.00	1.22	2.46	13.8	2.68
5302MMMM	81.51	.44	8.59	3.53	.06	.75	1.27	2.21	1.07	38.0	2.70
5700MMMM	74.23	.37	11.30	3.97	.08	1.38	1.10	1.96	3.87	29.1	2.70
5703MMMM	59.55	1.06	16.06	10.38	.16	2.69	2.56	2.52	3.96	38.9	2.80
5709MMMM	70.01	.33	15.62	2.48	.06	.69	3.42	4.61	.79	10.7	2.69
5802MMMM	67.14	.78	14.15	6.24	.10	2.17	3.11	2.22	2.50	15.7	2.75
5804MMMM	71.24	.76	11.88	7.09	.10	1.59	1.84	1.70	2.73	26.3	2.77
5805MMMM	58.55	1.14	18.12	9.77	.14	2.44	.73	.99	5.16	29.1	2.83
5906MMMM	75.95	.40	12.20	4.21	.12	.31	2.68	2.92	.94	34.4	2.71

APPENDIX B

Psammo-pelitic metamorphic rocks

	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Gran	Dens
4304081M	48.88	2.88	13.61	13.64	.134	.314	.76	1.23	5.07	38.9	2.95
0510401M	57.88	1.07	17.58	10.81	.082	.60	.98	1.42	4.46	13.3	2.82
0510402M	58.34	.93	19.15	9.72	.081	.85	.65	1.13	4.78	13.3	2.81
0519407M	58.68	.93	19.63	10.42	.092	.39	.44	.44	3.56	18.9	2.79
0519408M	58.65	.94	17.96	10.35	.082	.24	.58	.77	3.91	18.9	2.79
3304038M	56.74	1.03	20.37	10.70	.062	.45	.30	.13	3.98	28.0	2.74
3304039M	57.28	1.06	19.9	10.84	.062	.36	.28	.32	3.96	28.0	2.81
3300047M	54.05	1.21	20.90	11.79	.082	.54	.57	.83	4.33	20.5	2.88
3300048M	55.28	.95	20.05	10.62	.082	.21	.39	.54	4.01	20.5	2.89
5000110M	56.24	1.06	17.97	9.32	.092	.36	.54	.92	6.66	72.9	2.82
5703149M	57.22	1.10	16.45	12.13	.203	.23	3.60	2.70	3.71	38.9	2.81
5805165M	54.11	1.30	19.11	11.23	.172	.75	.94	1.28	5.61	29.1	2.87
0217396M	68.35	.88	13.4	7.18	.051	.581	1.17	1.86	3.04	41.3	2.77
0518405M	64.27	.97	17.64	8.15	.052	.15	.60	.78	3.03	19.2	2.79
3207026M	67.35	0.82	13.7	08.52	.161	.700	.621	.230	2.83	13.7	2.73
3319044M	68.60	.80	14.55	6.94	.061	.201	1.15	2.12	2.45	19.0	2.74
3319045M	68.67	.90	11.07	8.52	.061	.55	.76	1.76	2.85	19.0	2.74
3812068M	61.46	.95	16.38	7.94	.081	.911	1.11	2.74	3.40	19.6	2.75
3812069M	67.24	1.01	14.19	7.92	.081	.85	.55	1.06	3.92	19.6	2.73
2814020M	69.49	0.64	12.45	05.94	.081	.230	.520	.630	7.77	20.2	2.69
2816024M	64.73	0.78	13.61	08.94	.171	.762	2.26	2.43	03.09	14.4	2.78
3813071M	63.27	.93	16.40	8.44	.091	.88	.42	.84	4.94	12.2	2.76
3813072M	67.01	.86	14.73	8.13	.091	.88	.44	1.25	3.22	12.2	2.72
4812105M	62.31	.52	17.14	4.80	.051	.141	1.17	1.92	9.06	2.8	2.67
1504446M	69.33	.71	13.05	6.21	.091	.042	2.39	2.96	1.89	40.0	2.72
1504447M	65.83	.72	13.55	7.83	.151	.70	.64	1.21	7.46	40.0	2.73
1213429M	65.25	.44	16.11	4.30	.033	.503	3.68	2.42	2.88	28.4	2.74
2700003M	65.70	0.80	14.98	05.85	.081	.282	2.94	3.72	02.02	12.0	2.73
2708005M	62.07	1.00	15.24	07.52	.101	.644	4.02	3.16	02.16	08.8	2.76
2708006M	62.60	1.05	15.49	07.55	.061	.672	2.60	3.60	02.84	08.8	2.75
4304080M	64.25	.94	11.89	11.71	.182	.45	.76	1.17	4.40	38.9	2.83
5013116M	67.47	1.00	13.42	7.92	.061	.731	1.48	2.14	2.91	24.8	2.72
5013117M	69.36	.95	14.56	6.62	.051	.31	.58	.81	3.76	24.8	2.75
5015119M	68.46	.99	14.44	7.50	.061	.64	.38	.59	3.67	13.8	2.70
5703150M	61.88	1.03	15.68	8.63	.122	.151	1.52	2.35	4.22	38.9	2.80
5802158M	66.66	.81	14.85	5.65	.091	.883	3.49	2.50	2.27	15.7	2.74

APPENDIX B

Psammo-pelitic metamorphic rocks (cont'd)

	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Gran	Dens
5802159M	67.61	.76	13.45	6.83	.11	2.45	2.73	1.94	2.74	15.7	2.76
5804161M	63.15	1.11	14.06	9.92	.13	2.09	1.55	1.92	3.93	26.3	2.82
5805164M	62.99	.97	17.12	8.31	.12	2.12	.52	.70	4.71	29.1	2.79
0217395M	70.70	.92	12.47	7.45	.03	1.82	.60	.98	3.31	41.3	2.76
0505399M	73.72	.75	11.35	7.92	.05	.90	.75	1.31	2.10	12.0	2.76
0518404M	71.70	.80	14.80	7.31	.05	1.67	.46	.67	2.46	19.2	2.79
3210029M	78.49	0.66	10.1	05.15	.04	0.75	0.64	1.58	02.31	19.9	2.68
3210030M	75.43	0.68	11.55	05.63	.06	1.28	0.54	4.39	03.02	19.9	2.70
3217035M	79.47	0.69	09.18	05.44	.10	0.93	0.62	1.32	02.32	11.4	2.70
3217036M	79.11	0.51	08.71	06.26	.18	0.75	0.48	1.04	02.38	11.4	2.70
3806065M	79.00	.67	10.07	6.28	.04	1.11	.26	.47	2.32	39.4	2.72
2814021M	73.06	0.64	11.21	04.86	.05	0.84	0.41	0.66	07.35	20.2	2.67
2816023M	77.12	0.59	10.47	05.29	.13	0.48	1.51	2.13	01.94	14.4	2.71
3804062M	78.74	.60	9.67	5.45	.04	.96	.38	.88	2.54	17.5	2.69
3804063M	76.89	.66	10.75	6.13	.07	1.05	.40	.86	2.86	17.5	2.69
4812104M	76.96	.36	11.42	3.10	.05	.34	1.20	2.19	4.68	2.8	2.68
1214432M	70.34	.42	12.9	5.16	.03	2.75	2.61	2.06	2.45	41.5	2.73
2310461M	74.44	.59	11.73	4.37	.04	1.23	1.96	1.99	2.90	23.0	2.71
2310462M	70.42	.72	12.61	5.65	.03	1.79	2.71	2.47	2.09	23.0	2.73
2314464M	75.26	.53	11.48	4.19	.07	.87	2.18	1.54	4.02	15.6	2.69
2314465M	75.55	.59	11.84	3.27	.04	1.02	2.76	2.11	2.87	15.6	2.71
2700002M	72.77	0.81	11.20	06.91	.08	1.31	1.58	2.22	02.23	12.0	2.74
4504086M	79.11	.39	12.99	2.66	.04	.27	1.30	3.39	1.26	26.0	2.67
4504087M	78.94	.34	10.86	2.65	.10	.24	1.59	1.85	3.59	26.0	2.68
4508092M	77.21	.34	11.43	2.93	.14	.63	1.85	1.06	5.11	16.0	2.69
4508093M	73.94	.41	12.29	4.03	.09	.57	2.06	2.34	3.29	16.0	2.71
4514095M	77.91	.33	11.54	2.25	.05	.15	1.06	2.16	4.68	22.2	2.65
4514096M	78.63	.36	10.30	3.02	.07	.48	.64	1.10	5.93	22.2	2.64
4811101M	79.70	.33	10.73	2.61	.05	.28	1.49	2.19	3.45	18.5	2.67
4811102M	78.53	.37	11.18	2.90	.06	.27	1.48	2.43	3.56	18.5	2.63
5015120M	75.28	.74	11.89	6.48	.06	1.07	1.63	1.84	1.26	13.8	2.67
5700146M	74.98	.34	12.00	2.85	.06	.45	1.68	2.95	2.41	29.1	2.67
5700147M	73.49	.40	10.59	5.08	.11	2.30	.51	.97	5.33	29.1	2.73
5709152M	70.01	.33	15.62	2.48	.06	.69	3.42	4.61	.79	10.7	2.69
5804162M	79.34	.41	9.71	4.26	.06	1.08	2.13	1.49	1.53	26.3	2.72
5906176M	77.56	.61	11.47	3.72	.04	.48	2.32	2.68	1.15	34.4	2.70
5906177M	74.31	.19	12.93	4.70	.21	.15	3.03	3.15	.72	34.4	2.72
3207027M	80.34	0.60	09.52	04.56	.04	0.72	0.53	1.29	02.25	13.7	2.67
5302122M	81.51	.44	8.59	3.53	.06	.75	1.27	2.21	1.07	38.0	2.70

APPENDIX B

Granitic rocks and associated amphibolites

	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Gran	Dens
0610412G	71.70	.22	14.64	1.62	.02	.96	.95	.92	8.35	72.	2.63
0614415G	59.26	.86	17.43	6.88	.06	2.30	3.56	4.56	2.07	04.	2.73
0617418G	79.31	.14	9.01	3.06	.04	.51	7.64	.71	.00	28.	2.69
2715007G	73.59	0.13	15.16	01.34	.02	0.00	3.12	4.46	00.60	19.	2.64
5600133G	62.85	.17	20.14	2.86	.03	.27	5.31	5.88	.40	53.	2.70
0610MMMM	57.66	1.42	13.63	10.12	.19	4.12	7.90	1.27	1.54	72.	2.94
0614MMMM	50.62	1.13	12.79	13.45	.28	6.19	8.62	2.92	.60	04.	2.99
0617MMMM	48.99	1.36	13.84	13.97	.30	5.91	9.29	2.66	.62	28.	3.02
2715MMMM	63.87	0.97	11.69	09.58	.18	3.13	4.99	1.69	01.44	19.	2.90
5600MMMM	52.62	1.18	13.1*	12.20	.36	5.09	8.78	1.64	1.52	53.	3.02
0610413M	59.20	1.25	13.20	10.06	.20	4.31	8.12	1.09	1.12	72.	2.95
0610414M	56.12	1.60	14.06	10.18	.18	3.92	7.69	1.45	1.96	72.	2.92
0614416M	52.33	.88	12.60	12.80	.27	6.01	8.77	2.98	.41	04.	2.99
0614417M	48.90	1.38	12.98	14.10	.30	6.37	8.46	2.87	.78	04.	3.00
0617419M	51.88	1.29	12.56	14.01	.29	5.68	9.19	2.92	.26	28.	3.01
0617420M	46.10	1.43	15.13	13.93	.30	6.13	9.39	2.40	.98	28.	3.04
2715008M	77.00	0.61	10.65	04.87	.07	0.78	1.47	2.41	01.51	19.	2.72
2715009M	50.73	1.32	12.73	14.29	.29	5.48	8.51	0.96	01.37	19.	3.09
5600134M	52.14	1.25	13.14	13.36	.36	4.90	7.35	2.10	1.90	53.	2.98
5600135M	53.09	1.10	13.11	11.03	.35	5.27	10.21	.19	1.15	53.	3.05

APPENDIX C

APPENDIX C

Correlation Matrix

Line Average Metamorphic Rocks

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	%Gran.
SiO_2	-.063	.142	.089	.203	-.046	-.041	-.209	-.172	-.121	-.294
TiO_2	-.038	-.081	-.001	-.090	-.169	.066	.388*	.308*	-.129	-.123
Al_2O_3	.090	-.116	-.111	-.193	.075	.003	.158	.136	.092	.326*
FeO	-.094	.021	.067	.084	-.174	.102	.070	.059	-.058	-.127
MnO	.192	-.149	-.235	-.131	.014	-.152	-.013	.117	-.124	.157
MgO	-.075	-.166	.041	-.137	-.214	.325*	.450*	.231	-.013	.187
CaO	.250	-.261	-.204	-.315*	-.112	-.205	.372*	.325*	-.276	.013
Na_2O	.393*	-.117	-.417*	-.191	-.049	-.291	-.130	.059	-.321*	.135
K_2O	-.171	.005	.168	-.027	.179	.172	.105	.013	.389*	.240
%Gran.	-.205	.205	.080	.205	.091	.350*	-.020	-.168	.201	1.000

Asterisk (*) indicates at least 95% confidence

%Gran. = weight percent granitic rock/line

APPENDIX D

APPENDIX D

Results of Stepwise Multiple Regression

Dependent variable = weight percent granitic rock/lime
Independent variables = oxide composition of granitic rock

Multiple correlation coefficient = .5518
Multiple coefficient of determination = .3045

Significance = 81%

Oxide	Beta
Al_2O_3	7.80
MnO	51.47
SiO_2	4.69
MgO	20.73
CaO	-.55
TiO_2	-31.12
FeO	4.09
K_2O	2.10
Na_2O	3.92
Constant	-466.32

APPENDIX E

APPENDIX E

Calculation of the biotite norm.

The biotite norm has not been generalized to work for all rocks. It was developed for siliceous and aluminous sediments and metasediments. Prior to calculation, the following relationships must hold:

(NOTE: All oxides in moles.)

1. $K_2O \geq \frac{1}{6}(FeO + MgO + MnO)$
2. $Al_2O_3 \geq (K_2O + CaO + Na_2O)$
3. $SiO_2 \geq (FeO + MgO + MnO + 6K_2O + 6Na_2O + 2CaO)$

The norm is then calculated as follows:

1. An amount of $FeO = TiO_2$ to produce ilmenite as in the CIPW norm.
2. The remaining FeO, MgO and MnO are added together. To this amount add:
   a. $K_2O = \frac{1}{6}(FeO + MgO + MnO)$
   b. $Al_2O_3 = \frac{1}{6}(FeO + MgO + MnO)$
   c. $SiO_2 = (FeO + MgO + MnO)$
   d. $H_2O = \frac{1}{3}(FeO + MgO + MnO)$ may be added if desired.
   e. The molecular weight of the biotite (annite-phlogopite) is given by:

      $MW = ((FeO/(FeO + MgO + MnO))(96)) + 416$
3. Remaining K_2O is used to form orthoclase as in the CIPW norm.
4. Na_2O is used to form albite as in the CIPW norm.
5. CaO is used to form anorthite as in the CIPW norm.
6. Any remaining Al_2O_3 is combined 1:1 with SiO_2 to

APPENDIX E

form sillimanite (mole. wt. = 162).

7. Fe_2O_3 is used to form hematite as in the CIPW norm.

8. Any remaining SiO_2 is used to form quartz as in the CIPW norm.