A TESTING OF THE PREDICTION OF FLOATING OR SETTLING OF PHENOCRYSTS IN A MAGMA BY MATHEMATICAL MODELS

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ABSTRACT

Previous work on densities of liquid silicate systems suggest that it is mathematically possible to determine whether phenocrysts in a magma should settle or float based on the density difference between the magma and phenocrysts. The density of most magmatic liquids can be calculated from the equation: $d_{melt} = \sum_i X_i M_i / \bar{V}_i M_i$, where X_i is the mole fraction of component i, $\bar{V}_i$ its partial molar volume, and M_i its gram formula weight. Mathematically derived results of density difference compare favorably with 4 out of the 5 field observations made on lavas and sills of the North Shore Volcanic Group. The good correlation between the results of the author's mathematically derived results and the field observation support the use of the mathematical model as a meaningful indicator of floating or settling of phenocrysts in a crystallizing melt. The single inconsistency (1 out of 5) suggest that factors other than density difference such as viscosity, affects density, crystal shapes, and convection in magmatic melts may have an effect on the settling or floating of phenocrysts.

INTRODUCTION

A reliable mathematical method which could be used to determine the settling or floating of phenocrysts in a crystallizing melt would be of significant help in the study of igneous petrogenesis and differentiation. The purpose of this paper was to determine how well densities of magmas, calculated by published methods, agree with field observations suggesting that phenocrysts in magma had settled or floated. The method was applied to five porphyritic lavas and sills of the North Shore Volcanic Group.

PREVIOUS WORK

Many problems are connected with the evolution and differentiation of igneous rocks. Such a problem is the settling of phenocrysts in an evolving magmatic liquid. Many variables must be considered to predict whether a phenocryst should float or settle. Because buoyancy of a crystal is primarily a function of density contrast with the liquid, one of the most important physical variables entering into such a problem is the density of the magmatic liquid.

Shaw (1965) discussed the many variables that must be considered in crystal settling. Crystal settling is a function of both density difference and viscosity. He described the changes in viscosity as a function of temperature, melt composition, water content, and proportion of crystals to melt. Effective viscosity of magma containing suspended crystals is predicted to increase by less than an order of magnitude over that of the melt fractions for amounts up to 50 per cent crystal by volume. Crystal settling is also greatly complicated by natural or forced convections in magmatic melts. Shaw (1965) paper pointed out that the number of variables that must be considered indetermining crystal settling make the problem extremely complicated.

The importance of viscosity must not be overlooked when considering crystal settling. High viscosities slow down the rate of crystallization and settling. Turner and Verhoogen (1960), for instance, state that viscosity of a melt decreases with increasing temperature; probably increases, at constant temperature, with increasing pressure; is directly related to silica content; decreases with the addition of H_2O. Turner and Verhoogen believed that it would be almost impossible to predict the viscosity of a natural magma because of the number of factors that viscosity is dependent on.

Shaw (1972) and Bottinga and Weill (1972) have subsequently developed mathematical methods to determine viscosities of magmatic melts. Although both models have shortcomings they do allow a more quantitative approach to many geologic problems involving viscosity. An understanding of both viscosity and density of magmatic melts will do much towards explaining the evolution of igneous rocks.

DENSITY CALCULATIONS

If a phenocryst is to settle or float a density difference must exist between the melt and the phenocryst. Bottinga and Weill (1970) have done considerable work in attempting to calculate the densities of most magmatic liquids. They have determined that partial molar volumes of SiO_2, Al_2O_3, MgO, SrO, CaO, FeO, Li_2O, Na_2O, K_2O, Fe_2O_3, MnO, and TiO_2 show little compositional dependence in liquids ranging from 40 to 80 moles per cent SiO_2 (see Table 7). This permits the calculation of the density of most magmatic liquids by the use of the formula: $d=\sum_i X_i M_i / X_i \bar{V}_i$ where X_i is the mol fraction of component i, $\bar{V}_i$ its partial molar volume, M_i its gram formula weight, and d is the density of the liquid.

The mol fraction, X_i, of the component can be calculated from the chemical analysis of the rock samples, assuming that the rock composition represents the magma composition. Bottinga and Weill (1970) have determined that the partial molar volumes, $\overline{V}$, of SiO_2, Al_2O_3, MgO, SrO, CaO, FeO, Li_2O, Na_2O, and K_2O show little composition dependence in liquids ranging from 40 to 80 mole per cent SiO_2. They calculated partial molar volumes, $\overline{V}$, for these components, which were used in determing the densities of the melts of the different Keweenawan rocks in this study.

Complete calculations were carried out for five rock units. Chemical analyses were obtained from John Green's work in the North Shore Volcanics (T-36, T-35G, and KC-9) and from James Kilburg's (1972) work on the Ely's Peak basalt (ES-10 and N-1).

Table 1. Two chemical analyses of Leveaux Porphyry Sill, Tofte-Lutsen, Cook County (Green, 1972, p.310)

	T-36 (nonporphyritic lower part of sill) in weight %	T-35G (groundmass of porphyritic upper part of sill) wt. %
SiO_2	52.82	..............45.37
TiO_2	2.15	.... 4.69
Al_2O_3	13.67	..............11.68
Fe_2O_3	7.66	..............15.51
FeO	6.61	.... 5.46
MnO	0.15	.... 0.21
MgO	3.66	.... 3.58

Table 1. (continued)

CaO	6.94 wt. %	7.42 wt. %
Na_2O	2.94	2.95
K_2O	1.19	1.39
P_2O	0.42	0.37
CO_2	0.01	___
H_2O	1.67	1.47
Total	99.89 wt. %	99.99 wt. %

Table 2. Chemical analysis of a basalt lava, North Shore Volcanic Group, near Durfee Creek (Green, 1972, p. 309).

KC-9	SiO_2	46.98 weight per cent
	Fe_2O_3	5.28
	TiO_2	1.81
	Al_2O_3	16.06
	FeO	6.63
	MnO	0.17
	MgO	6.32
	CaO	9.59
	Na_2O	2.64
	K_2O	0.50
	*H_2O	1.00
	P_2O_5	0.25
	CO_2	0.16
	Total	99.01 wt. %

*The analysis showed 2.79 weight per cent water, but this is highly improbable because most of this is probably the result of secondary enrichment of water, during hydrothermal alteration. Therefore, it was reduced and a 1.00

weight per cent was assumed as the maximum amount of original water.

Table 3. Calculated chemical analyses of groundmasses of two flows from the Ely's Peak Basalt (Kilburg, 1972).

	N-1	ES-10
SiO_2	41.30 weight %	43.93 wt. %
Al_2O_3	12.35	11.44
Fe_2O_3	3.32	2.34
FeO	21.03	15.68
MgO	4.71	7.43
CaO	8.10	8.14
Na_2O	2.74	2.95
K_2O	1.09	1.38
H_2O	1.67	3.02
CO_2	1.02	0.69
TiO_2	2.16	2.56
P_2O_5	.49	0.36
MnO	.02	0.06
Total	100.00 wt.%	99.99 wt. %

Note: The following weight per cent analyses were calculated from Tables 1, 3, 4, and 7 on pages 18-19, 25, 27, and 32-33 respectively (James Kilburg's thesis, 1972). General procedure: The chemical analyses of the pyroxenes for N-1 and ES-10 were averaged from Table 1. (Kilburg, 1972). It was determined from Table 7 that 53.6 volume per cent of the N-1 sample was augite phenocrysts. The phenocryst volume percentage was changed to a weight percentage of 59 per cent. Therefore, the groundmass was determined to be 41 per cent of the total mass by weight. Tables 4 gave the chemical analysis (in weight per cent) of the groundmass plus the pyroxene phenocrysts. The weight per cents of the augite phenocryst components were determined by multiplying the averaged chemical analyses of the pyroxene by 59 per cent. The augite phenocryst components were subtracted from the total chemical analyses and this yielded the chemical analysis in weight per cent minus the augite phenocrysts. This chemical analysis was then recalculated to 100 per cent and the results are given in Table 3 of this report as the composition of the groundmass. See Appendix A for the above computations.

The same procedure was followed to get the calculated chemical analysis of the groundmass of ES-10. Table 7 (Kilburg, 1972) revealed that 32.5 per cent by volume was augite phenocrysts and this was converted to a weight per cent of 37 per cent. The same tables to determine N-1 were used and the results are given in Table 3 of this report. See Appendix A for computations.

The weight per cent chemical analyses were then converted to mol fractions, X. See Appendixes B, C, D, E, and F for the complete calculations.

Table 4. Calculated mol fractions, X, of the Leveaux Porphyry Sill.

	T-36	T-35G
SiO_2	.5654	.5125
TiO_2	.0173	.0397
Al_2O_3	.0861	.0773
Fe_2O_3	.0308	.0657
FeO	.0590	.0514
MnO	.0013	.0020
MgO	.0588	.0607
CaO	.0796	.0898
Na_2O	.0304	.0323
K_2O	.0082	.0100
P_2O	.0035	.0032
CO_2	.0001	.
H_2O	.0596	.0554
Total	.9999	1.000

Table 5. Calculated mol fractions, X, of Ely's Peak Basalt flows.

	N-1	ES-10
SiO_2	.4329	.4329
Al_2O_3	.0762	.0663
Fe_2O_3	.0131	.0086
FeO	.1837	.1288
MgO	.0741	.1099
CaO	.0909	.0860
Na_2O	.0278	.0281
K_2O	.0073	.0087
H_2O	.0584	.0992
CO_2	.0146	.0093
TiO_2	.0170	.0189
P_2O_5	.0040	.0027
MnO	.0002	.0005
Total	1.0002	0.9999

Table 6. Calculated mol fractions, X, of basalt lava near Durfee Creek.

	KC-9
SiO_2	.5117
TiO_2	.0148
Al_2O_3	.1030
Fe_2O_3	.0216
FeO	.0619
MnO	.0016
MgO	.1033
CaO	.1119
Na_2O	.0278
K_2O	.0035
H_2O	.0363
P_2O_5	.0021
CO_2	.0024
Total	1.0019

The partial molar volumes, $\overline{V}$, were calculated from published density measurements in binary and ternary silicate melts. See Table 7.

Table 7. Partial molar volumes, $\overline{V}$, at 1200°C. (Bottinga and Weill, 1972):

TiO_2	21.00 cm^3/mole
SiO_2	26.80
Al_2O_3	37.96
MgO	11.60
CaO	16.50
FeO	12.80
Na_2O	28.90
K_2O	46.00
Fe_2O_3	52.00
MnO	14.00
H_2O	26.00

The density of the magmatic melts of T-36, T-35G, N-1, ES-10, and KC-9 were computed by using the data of tables 1-6 in the equation: $d=\sum_i X_i M_i / X_i \overline{V}_i$. The density of the contained phenocrysts were computed from the graph in Figure 1 (Bottinga and Weill, 1970). Density of melts were computed both with analyzed water content and anhydrous. It is believed that most of the water is secondary, and therefore, the latter calculations are the more accurate figures.

T-36 A porphyritic trachybasalt flow with plagioclase phenocrysts (An_{62}).

The density of the magma is calculated to be:

$$\sum_i X_i M_i / X_i \bar{V}_i = 64.0778 \text{ grams}/26.0363 \text{ cubic centimeter}$$

$$= 2.4610 \text{ g/cm}^3 \text{ with water}$$

$$= 62.8237\text{g}/24.4106\text{cm}^3$$

$$= 2.5736\text{g/cm}^3 \text{ without water}$$

(See Appendix B for complete computations)

Note: Because of the minute quantities of P_2O and CO_2 contained in the melt and the probability that CO_2 is secondary and never was in the original melt, they were eliminated in the calculations.

The density of the plagioclase phenocrysts was determined from the graph in Figure 1. (Bottinga and Weill, 1970). The plagioclase phenocrysts of T-36 computed to about 2.64 grams per cubic centimeter.

The above density data indicate that the phenocrysts, with or without the indicated water content should have settled in this melt.

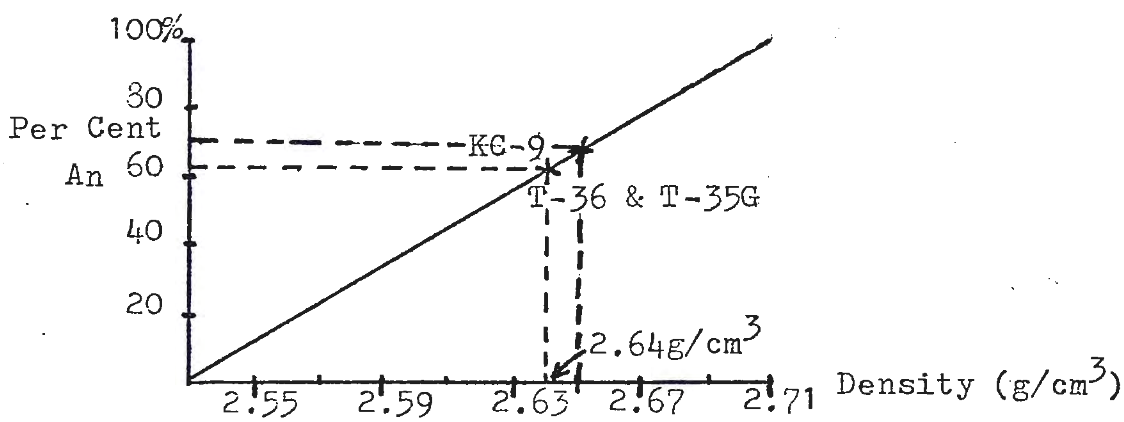

Figure 1. Density of plagioclase at 1,200°C as a function of composition (Bottinga and Weill, 1970).

T-35G Upper part of the T-36 porphyritic trachybasalt sill with plagioclase phenocrysts (An_{62}).

The density of the magma is:

$$\sum_i X_iM_i/X_i\overline{V}_i = 67.8116\text{grams}/26.6270\text{cubic centimeter}$$

$$= 2.5460\text{g/cm}^3 \text{ with water}$$

(See Appendix C for complete computations)

$$= 66.8144\text{g}/25.1866\text{cm}^3$$

$$= 2.6610\text{g/cm}^3 \text{ without water}$$

Note: Because of the minute quantity of P_2O_5 in the melt, the quantity was neglected.

The density of the plagioclase phenocrysts was again determined to be 2.64grams/centimeter^3. The density data (phenocrysts=2.64g/cm^3; melt=2.66g/cm^3) indicates that the phenocrysts of T-36 should have floated in the anhydrous melt. Because most of the water content is probably secondary, density calculations were made with and without analyzed water content. Density calculations of the phenocrysts were compared with the hydrous and anhydrous melts, but the anhydrous melt is the most probable of the two because the water is probably secondary.

N-1 Augite basalt porphyry, flow C of the Ely's Peak basalts Kilburg, 1972)

The density of the magma is calculated to be:

$$\sum_i X_iM_i/X_i\overline{V}_i = 62.0502\text{grams}/22.9397\text{cubic centimeters}$$

$=2.70 g/cm^3$ with water

(See Appendix D for complete computations)

$=60.9972 g/21.4187 cm^3$

$=2.85 g/cm^3$ without water

Note: Because of the minute quantity of CO_2 and P_2O_5 contained in the magma melt and the high probability that the CO_2 content is the result of secondary enrichment, these quantities were neglected.

The density of augite at standard temperature was found to be $3.3 g/cm^3$. Augite will expand 3.68 per cent of its origninal volume at 1,200°C. (Clark, 1966, p.47 and p.86). Therefore, augite has a density of $3.17 g/cm^3$ at 1,200°C. The above density data indicate that the phenocrysts of N-1 should have settled in this magma.

ES-10 Augite porphyritic basalt, flow A of Ely's Peak basalts (Kilburg, 1972).

The density of the magma is calculated to be:

$$\sum_i X_i M_i / X_i \bar{V}_i = 58.7717 \text{grams}/23.1995 \text{cubic centimeters}$$

$=2.53 g/cm^3$ with H_2O

(See Appendix E for complete computations)

$=56.9951 g/20.6333 cm^3$

$=2.76 g/cm^3$ without water

Note: CO_2 and P_2O_5 quantities were omitted.

The density of augite at 1,200°C is $3.17 g/cm^3$ (Clark, 1966, p. 47) as stated above. The above density data indicate that the augite phenocrysts should have settled.

KC-9 Ophitic olivine tholeiite of the North Shore lavas near Durfee Creek, Cook County.

The density of the magma is calculated to be:

$$\sum_i X_iM_i/X_i\bar{V}_i = 63.5236\text{grams}/24.8251\text{cubic centimeter}$$

$$= 2.56\text{g/cm}^3 \text{ with water}$$

$$= 62.8702\text{g}/23.3813\text{cm}^3$$

$$= 2.63\text{g/cm}^3 \text{ without water}$$

(See Appendix F for complete computations)

Note: P_2O_5 and CO_2 were omitted in the calculations because of their small amount and the high probability of CO_2 being secondary.

The density of the phenocrysts (An_{70}) is 2.65g/cm^3 (see Figure 1.). The above density data indicate that the phenocrysts should have settled in this melt, with or without the water content.

FIELD OBSERVATIONS

T-35 and T-36 are from the "Leveaux Porphyry sill, a brown, granular, iron-rich trachybasalt containing pigeonite and augite, large magnetite crystals and, in the upper half of the sill abundant, blocky, 1-2cm labradorite phenocrysts that are assumed to have floated." The lower part of the sill is nonporphyritic but appears to be the same rock as the ground mass of the upper porphyritic portion of the sill (Green, 1972, p.329).

T-35 This chemical analysis came from the south corner of a hill northeast of Onion River near Tofte, NE1/4, Sec. 2, T.60 N, R.3 W, Minnesota (from upper portion of the Leveaux Porphyry sill). The sample was taken just above the contact between the upper porphyritic and the lower non-porphyritic parts of the sill.

T-36 This sample came from just below the boundary between the porphyritic and nonporphyritic part, directly below sample T-35G and in the nonporphyritic part of the sill.

N-1 This sample came from flow C, an augite basalt porphyry, of the Ely's Peak basalts, SE1/4, SW1/4, Sec. 17, T.49N, R.15W in St. Louis County, Minnesota. The augite phenocrysts are larger near the base and are in abundance, whereas near the top of the flow they decrease in size and abundance (Kilburg, 1972, p.41). This field observation suggests a settling of the augite phenocrysts.

ES-10 This sample came from flow A, an augite-porphyritic basalt, of the Ely's Peak basalts, NE1/4, NW1/4, Sec.20, T.49N, R.15W in St. Louis County, Minnesota. Field observations reveal that the augite crystals had settled (Kilburg, 1972, p.37-39).

KC-9 This sample came from an ophitic basalt flow near Durfee Creek, SE1/4, NW1/4, Sec.34, T.61N, R.1W in Cook County, Minnesota, Field observations on the above ophitic basalt flows (a series of about five flows) show that a few phenocrysts have floated in one flow and sunk in another (Green, 1972, p.318). Therefore, it is difficult to state whether there was a definite trend in floating or sinking of phenocrysts in this group of flows.

COMPARISON OF CALCULATED DENSITIES TO FIELD OBSERVATIONS

Field observations of T-35G and T-36 by Green (1972) indicate that the labradorite phenocrysts floated. Calculations on T-35G imply that the phenocrysts should have floated (groundmass=2.66g/cm^3; phenocrysts=2.64g/cm^3), but calculations on T-36 imply that the phenocrysts should have settled (groundmass=2.53g/cm^3; Phenocrysts=2.64g/cm^3). It is possible that factors other than density difference such as crystal size, viscosity, and convection had a determining influence on the settling or floating of phenocrysts in T-36 (see Conclusion).

Field observations of N-1 and ES-10 suggest a settling of augite phenocrysts. Density calculations carried out for this report are in agreement with these field observations. The mathematically derived densities for the melt and the phenocrysts were distinctly different for both N-1 and ES-10 (groundmass=2.85g/cm^3, phenocrysts=3.17g/cm^3; groundmass=2.76g/cm^3, phenocrysts=3.17g/cm^3, respectively).

Field observations of the phenocrysts of KC-9 suggest that there was no definite tendency for settling or floating. Density calculations for the groundmass and phenocrysts of KC-9 were very close (ground=2.63g/cm^3; phenocrysts, An_{70}=2.65g/cm^3), but do suggest a trend toward the phenocrysts' settling in the flow sampled.

CONCLUSION

Calculations of the density of a magmatic melt based on its composition can be used to predict floating or sinking of known or specified phenocrysts, assuming no factors other than density are involved. However, it was found that this method is not 100 per cent reliable, as one out of the five density calculations did not agree with field observations.

Thus, it is possible that other factors besides density difference must be considered when determining whether phenocrysts should have floated or settled. Such factors as field interpretations, viscosity, water content, crystal shape, and convection in magmatic melts probably play varying roles in the settling or floating of phenocrysts. The importance of the above factors probably increase as the densities of the phenocrysts and magmatic melt become more similar.

Viscosity has a definite influence over the rate of crystal settling, especially when the density of the melt and the phenocrysts are very close. A high viscosity could retard the rate of settling or possibly stop the settling of phenocrysts in a melt (Daly, 1933, p.278). This may have been just the case in the Leveaux Porphyry Sill T-36. It must also be remembered that viscosity is dependent on temperature, melt composition, and proportion of crystal to melt.

Most of the analyzed water content in the samples was probably the result of secondary enrichment and not primary. The exact amount of water that was present at crystallization is usually unknown. Therefore, an estimate of the origional water content must be made. This estimated water content may have an erroneous effect on the predicted sink/

float relationship. Bottinga and Weill (1970, p.180) have stated, "It is not until later stages of solidification that water concentration in the liquid is sufficient to reverse the trend of increasing density of the melt".

The shape of crystals plays a role in the settling rate of phenocrysts in a melt (Shaw, 1965). Deviation of a crystal from a sphere shape will make the settling rate of a crystal a function of time plus density, and decrease the settling rate.

The conclusions reached in this paper concerning the settling of crystals assumed static conditions. Forced or natural convections would have an effect on the motions of crystals in a liquid. Forced convection means the transfer of a fluid as a result of an externally applied force and natural convection results from the transfer of a fluid under the action of a gravitational field. Shaw (1965) discussed many of the flow patterns of crystals that could be produced by convection. Normal layering would not occur in most types of convection. In order to determine the flow pattern of crystals under the influence of convection, detailed data on the geometry of the igneous body and its extension in depth are needed. Data on the size, curvature, and the roughness of the conduits that may connect the igneous flows with an underlying reseroir would be very helpful in determining the flow pattern of crystals. At the present, data is known about the general shape of the flows (Green, 1972), but data is lacking on the igneous bodies at depth and the conduit pipes that may link the flows with an underlying reservoir.

The number of factors that one must consider in determining if a phenocryst will settle or float in a magma, especially when the phenocrysts and melt are of near equal density are many. Although, it seems apparent from this report that density difference (between phenocryst and melt) is the dominant factor in the prediction of whether a phenocryst will float or settle in a melt. The mathematical method to predict whether phenocrysts will settle or float based on density difference proved to be a relatively successful method, as indicated by the field observations. However, the complexity of the crystallization of an igneous melt must not be overlooked.

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Appendix A

The weight per cent analyses for N-1 and ES-10 were calculated from Tables 1, 3, 6, and 7 on pages 18-19, 25, 31, and 32-33 respectively of Kilburg (1972) by the following:

Step 1. The microprobe anelyses (7samples) of the pyroxenes for N-1 and ES-10 were averaged from Table 1. and yielded:

	N-1	ES-10
SiO_2	51.73 weight %	53.25 wt. %
Al_2O_3	2.79	2.78
CaO	18.43	18.00
MgO	18.86	16.91
FeO	4.53	4.93
TiO_2	.83	.80
MnO	.19	.02
Na_2O	.30	.27

Step 2. Convert the volume per cents of augite phenocrysts to weight per cents:

N-1 Sample

Data (from Table 7 of Kilburg, 1972)

augite phenocrysts=53.6 volume per cent of N-1 sample

groundmass=46.4 volume per cent of N-1 sample

pyroxene density=3.3g/cc.
groundmass density=2.7g/cc. (Deer, Howie, and Zussman, 1963, p. 109)

a. Determine the weight per cents of the rock sample:

53.6% x 3.3g/cc=176.88g weight of pyroxene phenocrysts in 100cc rock

46.4% x 2.7g/cc=125.28g weight of groundmass in 100cc rock

302.16g Total weight of 100cc rock

b. Finally, determine the weight per cent of phenocrysts

$$\frac{176.88\text{g (wt. of phenocrysts)}}{302.16\text{g (total weight)}} \doteq .5853 = .59 \text{ weight per cent phenocrysts}$$

Therefore, groundmass=41 wt. %

ES-10 Sample

Data (from Table 7 of Kilburg):

augite phenocrysts=32.5 volume per cent of ES-10

groundmass=67.5 volume per cent of ES-10

a. Determine the weight per cents of the rock samples:

32.5% x 3.3g/cc=107.25g weight of pyroxene phenocrysts in 100cc rock

67.5% x 2.7g/cc=182.25g weight of groundmass in 100cc rock

289.50g Total weight of 100cc rock

b. Finally, determine the weight per cent of phenocrysts

$$\frac{107.25\text{g (wt. of phenocrysts)}}{289.50\text{g (total weight)}} = .3705 = 37 \text{ weight per cent phenocrysts}$$

Therefore, groundmass=63wt. %

<u>Step. 3</u> Determine the chemical analysis in weight per cent minus the augite phenocrysts:

N-1 Sample

Table 6 yielded the chemical analysis of N-1 (weight per cent): (in weight per cent)

	with augite p.	augite phenocryts	without augite p. (groundmass)
SiO_2	47.55wt.%	.59 x 51.73=30.52wt.%	17.03 wt. %
Al_2O_3	6.74	" x 2.79= 1.65	5.09
Fe_2O_3	1.37	———	1.37
FeO	11.34	" x 4.53= 2.67	8.67
MgO	13.07	" x 18.36=11.13	1.94
CaO	14.21	" x 18.43=10.87	3.34
Na_2O	1.13	" x 0.30= .18	.95
K_2O	.45	———	.45
H_2O	1.89	———	1.89
CO_2	.42	———	.42
TiO_2	1.38	" x .83= .49	.89
P_2O_5	.20	———	.20
MnO	.20	" x .19= .11	.01
		Total	42.25 wt. %

ES-10 Sample

	with augite p.	augite phenocrysts	without augite p. (groundmass)
SiO_2	47.65wt.%	53.25 x .37=19.70wt.%	27.95wt.%
Al_2O_3	8.31	2.78 x " = 1.03	7.28
Fe_2O_3	1.49	———	1.49
FeO	11.80	4.93 x " = 1.82	9.98
MgO	10.99	16.91 x " = 6.26	4.73
CaO	11.84	18.00 x " = 6.66	5.18
NaO_2	1.98	.27 x " = .10	1.88

(continued)

K_2O	.88wt.%	________		.88
H_2O	1.92	________		1.92
CO_2	.44	________		.44
TiO_2	1.93	.80 x .37=	.30	1.63
P_2O_5	.23	________		.23
MnO	.19	.02 x " =	.01	.04
			Total	63.77wt.%

Step 4. The chemical analyses (minus the augite phenocrysts) were then recalculated to 100 per cent:

N-1 Sample

Component weight percentages divided by total weight percentage (41.23):

SiO_2	17.03/42.25	= 40.31	weight per cent
Al_2O_3	5.09/ "	= 12.05	
Fe_2O_3	1.37/ "	= 3.24	
FeO	8.67/ "	= 20.52	
MgO	1.94/ "	= 4.59	
CaO	3.34/ "	= 7.91	
Na_2O	1.13/ "	= 2.67	
K_2O	.45/ "	= 1.07	
H_2O	.69/ "	= 1.63	
CO_2	.42/ "	= .99	
TiO_2	.89/ "	= 2.11	
P_2O_5	.20/ "	= .47	
MnO	.01/ "	= .02	

ES-10 Sample

Component weight percentages divided by total weight percentage (63.63):

SiO_2	27.95/63.77	=	43.83
Al_2O_3	7.28/ "	=	11.42
Fe_2O_3	1.49/ "	=	2.34
FeO	9.98/ "	=	15.65
MgO	4.73/ "	=	7.42
CaO	5.18/ "	=	8.12
Na_2O	1.88/ "	=	2.95
K_2O	.88/ "	=	1.38
H_2O	1.92/ "	=	3.01
CO_2	.44/ "	=	.69
TiO_2	1.63/ "	=	2.56
P_2O_5	.23/ "	=	.36
MnO	.04/ "	=	.06

Appendix B

The density of the magma of sample T-36 was calculated by the formula: $\sum_i X_i M_i / X_i \bar{V}_i$, where X_i is the mol fraction of component i, $\bar{V}_i$ its partial molar volume, and M_i its gram formula weight.

Step 1. Change the weight percentages of the components of sample T-36 to mole fractions:

Components	Gram Formula Wt. (M) grams	Wt. % (%)	Mol Prop. (Wt. %)	Mol Fraction (Mol P./T. Mols)
1. SiO_2	60	52.82	.8803	.5654
2. TiO_2	80	2.15	.0269	.0173
3. Al_2O_3	102	13.67	.1340	.0861
4. Fe_2O_3	160	7.66	.0479	.0308
5. FeO	72	6.61	.0918	.0590
6. MnO	71	.15	.0021	.0013
7. MgO	40	3.66	.0915	.0588
8. CaO	56	6.94	.1239	.0796
9. Na_2O	62	2.94	.0474	.0304
10. K_2O	94	1.19	.0127	.0082
11. P_2O_5	142	.42	.0054	.0035
12. CO_2	44	.01	.0002	.0001
13. H_2O	18	1.67	.0928	.0596
		Total Mol P.	1.5569	

Step 2. Continued

Step 2. Summation of the products (X_iM_i and $X_i\bar{V}_i$):

Note: Products are in same order as component listing.

	X_iM_i	$X_i\bar{V}_i$
1. SiO_2	33.9240grams	15.1527cc/mole
2. TiO_2	1.3840	.3633
3. Al_2O_3	8.7822	3.2684
4. Fe_2O_3	4.9280	1.6016
5. FeO	4.2480	.7552
6. MnO	.0923	.0182
7. MgO	2.3520	.6820
8. CaO	4.4576	1.3134
9. Na_2O	1.8848	.8786
10. K_2O	.7708	.3772
11. P_2O_5	———	———
12. CO_2	———	———
13. H_2O	1.0728	1.5496
total	63.8965g	total 25.9602cc/m

Step 3. Divide summations of product ($\sum_i X_iM_i / \sum_i X_i\bar{V}_i$):

d_{magma}= 63.8965g/25.9602cc=2.4610=2.46g/cc with H_2O

d_{magma}= 62.8237g/24.4106cc=2.5276=2.52g/cc without H_2O

(Number 13 product subtracted from each summation)

Appendix C

The density of the magma of sample T-35G was calculated by the formula: $\sum_i X_i M_i / X_i \bar{V}_i$, where X_i is the mol fractions of component i, $\bar{V}_i$ its partial molar volume, and M_i its gram formula weight.

Step 1. Change the weight percentages of the components of sample T-35G to mole fractions:

Components	Gram Formula Wt. (M) grams	Wt. % (%)	Mol Prop. (Wt. %/M)	Mol Fractions (Mol P/Total Mol)
1. SiO_2	60	45.37	.7562	.5125
2. Al_2O_3	102	11.68	.1141	.0773
3. Fe_2O_3	160	15.51	.0969	.0657
4. FeO	72	5.46	.0758	.0514
5. TiO_2	80	4.69	.0568	.0397
6. MnO	71	.21	.0030	.0020
7. CaO	56	7.42	.1325	.0898
8. MgO	40	3.58	.0895	.0607
9. Na_2O	62	2.95	.0476	.0323
10. K_2O	94	1.39	.0148	.0100
11. H_2O	18	1.47	.0817	.0554
12. P_2O_5	142	.37	.0047	.0032
		Total Mol P.	1.4754	

Step 2. Continued

<u>Step 2.</u> Summation of the products (X_iM_i and $X_i\bar{V}_i$):

Note: Products are in same order as component listing.

	X_iM_i	$X_i\bar{V}_i$
1. SiO_2	30.7500grams	13.7350cc/mole
2. Al_2O_3	7.8846	2.9343
3. Fe_2O_3	10.5120	3.4164
4. FeO	3.7008	.6599
5. TiO_2	3.1760	.8337
6. MnO	.1420	.0280
7. CaO	5.0288	1.4817
8. MgO	2.4280	.7041
9. Na_2O	2.0026	.9335
10. K_2O	.9400	.4600
11. H_2O	.9972	1.4404
12. P_2O_5	<u>omitted</u>	<u>omitted</u>
	total 67.8116g	total 26.6270cc/m

<u>Step 3.</u> Divide summations of products ($\sum_i X_iM_i / \sum_i X_i\bar{V}_i$):

d_{magma}=67.8116g/26.6270cc=2.5460=2.56g/cc with H_2O

d_{magma}=66.8144g/25.1866cc=2.6610=2.66g/cc without H_2O

(Number 11 product subtracted from each summation)

Appendix D

The density of the magma of sample N-1 was calculated by the formula: $\sum_i X_i M_i / X_i \bar{V}_i$, where X_i is the mol fraction of component i, $\bar{V}_i$ its partial molar volume, and M_i its gram formula weight.

Step 1. Change the weight percentages of the components of sample N-1 to mole fractions:

Components	Gram Formula Wt. (M) grams	Wt. % (%)	Mol Prop (Wt.%/M)	Mole Fractions (X) (Mol P./T. Mols)
1. SiO_2	60	40.31	.6717	.4337
2. Al_2O_3	102	12.05	.1181	.0763
3. Fe_2O_3	160	3.24	.0202	.0130
4. FeO	72	20.52	.2850	.1840
5. MgO	40	4.59	.1148	.0741
6. CaO	56	7.91	.1412	.0912
7. Na_2O	62	2.67	.0431	.0278
8. K_2O	94	1.07	.0114	.0074
9. H_2O	18	1.63	.0906	.0585
10. CO_2	44	.99	.0225	.0145
11. TiO_2	80	2.11	.0264	.0170
12. P_2O_5	142	.47	.0033	.0021
13. MnO	71	.02	.0003	.0002
		Total Mol P.	1.5486	

Step 2. Continued

Step 2. Summation of the products (X_iM_i and $X_i\bar{V}_i$):

Note: Products are in same order as component listing.

	X_iM_i	$X_i\bar{V}_i$
1. SiO_2	26.0220 grams	11.6232 cc/mole
2. Al_2O_3	7.7826	2.8963
3. Fe_2O_3	2.0800	.6760
4. FeO	13.2480	2.3552
5. MgO	2.9640	.8596
6. CaO	5.1072	1.5048
7. Na_2O	1.7236	.8034
8. K_2O	.6956	.3404
9. H_2O	1.0530	1.5210
10. CO_2	______	______
11. TiO_2	1.3600	.3570
12. P_2O_5	______	______
13. MnO	.0142	.0028
total	62.0502g	total 22.9397cc/mole

Step 3. Divide summations of products ($\sum_i X_iM_i/\sum_i X_i\bar{V}_i$):

d_{magma}=62.0502g/22.9397cc=2.70g/cc with H_2O

d_{magma}=60.9972g/21.4187cc=2.85g/cc without H_2O

(Number 9 product subtracted from each summation)

Appendix E

The density of the magma of sample ES-10 was calculated by the formula: $\sum_i X_i M_i / X_i \bar{V}_i$, where X_i is the mol fractions of component i, $\bar{V}_i$ its partial molar volume, and M_i its gram formula weight.

Step 1. Change the weight percentages of the components of sample ES-10 to mole fractions:

Components	Gram Formula Wt. (M) gram	Wt. % (%)	Mol Prop. (Wt.%/M)	Mol Fractions (X) (Mo.%/Total Mo.)
1. SiO_2	60	43.83	.7305	.4314
2. Al_2O_3	102	11.42	.1196	.0706
3. Fe_2O_3	160	2.34	.0146	.0086
4. FeO	72	15.65	.2174	.1284
5. MgO	40	7.42	.1858	.1097
6. CaO	56	8.12	.1450	.0856
7. Na_2O	62	2.95	.0476	.0281
8. K_2O	94	1.38	.0147	.0087
9. H_2O	18	3.02	.1672	.0987
10. CO_2	44	.69	.0157	.0093
11. TiO_2	80	2.56	.0320	.0189
12. P_2O_5	142	.36	.0025	.0015
13. MnO	71	.06	.0008	.0005
		Total Mol P.	1.6934	

Step 2. Continued

Step 2. Summation of the product (X_iM_i and $X_i\overline{V}_i$):

Note: Products are in same order as component listing.

	X_iM_i	$X_i\overline{V}_i$
1. SiO_2	25.8840 grams	11.5615 cc/mole
2. Al_2O_3	7.2012	2.6800
3. Fe_2O_3	1.3760	.4472
4. FeO	9.2448	1.6435
5. MgO	4.3880	1.2725
6. CaO	4.7936	1.4124
7. Na_2O	1.7422	.8121
8. K_2O	.8178	.4002
9. H_2O	1.7766	2.5662
10. CO_2	———	———
11. TiO_2	1.5120	.3969
12. P_2O_5	———	———
13. MnO	.0355	.0070
total	58.7717g	total 23.1995cc/mole

Step 3. Divide summations of products ($X_iM_i/X_i\overline{V}_i$):

d_{magma}= 58.7717g/23.1995cc/mole= 2.53g/cc with H_2O

d_{magma}= 56.9951g/20.6333cc=2.76g/cc without H_2O

(Number 9 product subtracted from each summation)

Appendix F

The density of the magma of sample KC-9 was calculated by the formula: $\sum_i X_iM_i/X_i\bar{V}_i$, where X_i is the mol fraction of component i, $\bar{V}_i$ its partial molar volume, and M_i gram formula weight.

Step 1. Change the weight percentages of the components of sample KC-9 to mole fractions:

Components	Gram Formula Wt.	Wt. %	Mol Prop*	Mole Fractions** (X)
1. SiO_2	60grams (M)	46.98%	.7830	.5121
2. TiO_2	80	1.81	.0226	.0147
3. Al_2O_3	102	16.06	.1575	.1030
4. Fe_2O_3	160	5.28	.0330	.0216
5. FeO	72	6.63	.0921	.0602
6. MnO	71	.17	.0024	.0016
7. MgO	40	6.32	.1580	.1033
8. CaO	56	9.59	.1713	.1120
9. Na_2O	62	2.64	.0426	.0279
10. K_2O	94	.50	.0053	.0035
11. H_2O	18	1.00	.0556	.0364
12. P_2O_5	142	.25	.0018	.0012
13. CO_2	44	.16	.0036	.0024
		Total Mol P.	1.5288	

*Weight per cent/gram formula weight=Mole

**Moles/total number of moles

Step 2. Continued

Step 2. Summation of the product (X_iM_i and $X_i\bar{V}_i$):

Note: Products are in same order as component listing.

	X_iM_i	$X_i\bar{V}_i$
1. SiO_2	30.7260grams	13.7243cc/moles
2. TiO_2	1.1760	.3087
3. Al_2O_3	10.5060	3.9099
4. Fe_2O_3	3.4560	1.1232
5. FeO	4.3344	.7706
6. MnO	.1136	.0224
7. MgO	4.1320	1.1983
8. CaO	6.2720	1.8480
9. Na_2O	1.7298	.8063
10. K_2O	.3290	.1610
11. H_2O	.6552	.9464
12. P_2O_5	———	———
13. CO_2	———	———
total	63.4300grams	24.8191cubic centimeters

Step 3. Divide summations of products (X_iM_i/X_iV_i):

d_{magma}=63.4300g/24.8191cc=2.56g/cc with H_2O

d_{magma}=62.7748g/23.8727cc=2.63g/cc without H_2O

(Number 11 product subtracted from each summation)