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Use of Magnetic Susceptibility, Density, and Modal Mineral Data as a Guide to the Composition of Granitic Plutons[1]

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Magnetic susceptibility, density, modal mineral, and whole rock geochemical data have been collected from two granitic plutons in Quebec. Each of the first three variables is correlated with SiO_2 to some degree. Multiple regression using all three variables simultaneously as independent variables and SiO_2 as a dependent variable yielded pluton dependent equations which were then used to calculate SiO_2 values for each analysis. Calculated values of SiO_2 typically differ from the analysed values by 1.5% for the first pluton and 1.0% for the second. The polynomials thus can be used to estimate the SiO_2 value of unanalyzed samples with some confidence. Plots of calculated SiO_2 reveal details of chemical variation with the pluton which were not observed when using chemical data alone due to the small number of analyzed rocks. The method also provides an independent evaluation of possible analytical errors.

KEY WORDS: magnetic susceptibility, density, granitic plutons.

INTRODUCTION

A common experience during studies of igneous plutons is that many more samples are collected than subsequently are analyzed chemically. A total of 274 and 114 samples of the Aylmer and St. Sébastien–Ste. Cécile (SSSC) plutons were collected during a field project in eastern Quebec, of which 38 and 32 were chemically analyzed, and thin section studies made, in order to effect a chemical and petrographic interpretation of the intrusions. Samples selected for this special attention were chosen largely on spatial grounds, that is, they were selected in order to assure that the sample density was approximately equal in all portions of the pluton.

The question arises as to how best to make use of data from the remaining outcrops which were not specifically chosen for follow-up work. The purpose

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of this communication is to demonstrate that significant correlation coefficients exist between the concentration of various oxides and three independently determined parameters: (1) magnetic susceptibility, as measured in the field, (2) modal analyses on stained slabs, and (3) density measurements on hand specimens. Specifically, it is possible to calculate a polynomial in which density, magnetic susceptibility, and modal mineral data are considered as independent variables and the various oxides as dependent variables for samples which have been chemically analyzed. Once this polynomial is established, which will vary from pluton to pluton, estimated values of oxides for the remaining samples may be calculated, thereby establishing a much better control on chemical variation exhibited by the pluton in question.

PETROGRAPHIC SUMMARY AND DATA DISTRIBUTION

The Aylmer and SSSC plutons are small Devonian intrusions east of Montreal. Both plutons are massive, post-tectonic, predominantly biotite-bearing, two feldspar granitoids which are reversely zoned, featuring a core of tonalite which grades outward to a granitic margin. Thin section studies show that the plutons are not particularly altered and that the grain size of all component minerals is approximately constant from one sample to another. Detailed petrographic descriptions as well as the chemical data used in this report are available in Bourne (1989) but are not germane to the discussion here.

MEASUREMENT OF PARAMETERS

Stained Slab Data

Determination of the percentage of plagioclase, K-feldspar, quartz, and mafic minerals were carried out on stained slabs by placing a transparent grid of 2-mm spacing on the surface of the stained specimen and counting frequencies of the mineral species at the intersections of the grid. Repeated measurements made on one particular specimen show that the volumes of the minerals may be determined to a precision of approximately 4% (95% confidence interval) which compares favorably to that obtained from thin section studies. Results of the modal mineral analyses for each pluton are shown graphically (Fig. 1). Both contain normalized quartz concentrations surpassing 20 modal %. Quartz values do not vary a great deal, as indicated by the crudely horizontal distribution of the modal data; however, the ppf ratio (modal plagioclase: plagioclase + potassium feldspar) varies from 0.39 to 0.93 in the Aylmer pluton and from 0.42

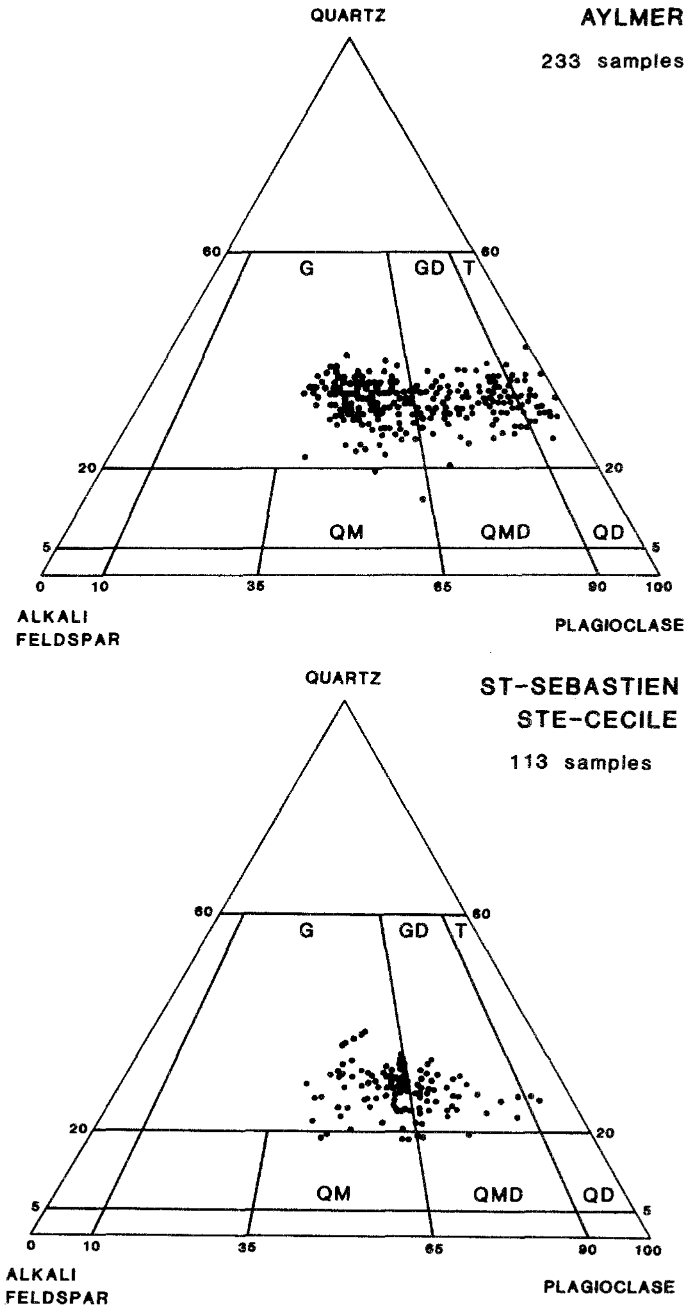

Fig. 1. Streckeisen modal mineral plot for the SSSC and Aylmer plutons.

to 0.92 in the SSSC pluton. Thus, most of the modal variation (of major rock-forming minerals) observed in the rocks is associated with variations in the value of this ratio.

Density

Density measurements on samples of the Aylmer pluton were made using the conventional technique of weighing the sample in both air and water and applying the formula.

$$\text{dens} = a/(a - w)$$

where: dens = density of the sample, a = weight in air, and w = weight in water. Some difficulty was experienced obtaining reliable results for some samples possibly due to the presence of small fractures. All samples were soaked in water for 1 hr prior to determining the water weight measurement. No density data are available for SSSC rocks.

Magnetic Susceptibility

Magnetic susceptibility (represented by the letter K) is a measure of the induced magnetization produced in a rock sample. All minerals contribute to the total magnetic susceptibility exhibited by a sample, but magnetite, when abundant, is by far the most important. Mafic minerals such as hornblende and biotite can also contribute to a significant extent and may predominate in those samples where magnetite content is small (Jover *et al.*, 1989). Feldspars and quartz contribute little to the overall magnetic susceptibility value of the rock specimen.

Cameron and Carrigan (1987) list three factors which largely influence the measured values of magnetic susceptibility of a sample: (a) the primary magnetite content of the sample, (b) (plus) any secondary magnetite which may have formed by replacement of pre-existing minerals, and (c) (minus) the loss of any magnetite which may accompany late-state oxidation along faults or fractures. To these may be added a fourth source of variation: (d) magnetic anisotropy of the sample.

Magnetite Content. Ishihara (1981) observed that magnetic susceptibility may be used as the basis for discrimination between magnetite series and ilmenite series granitoids and proposed that the boundary between these two groups be placed approximately 300×10^{-5} SI. Ishihara also showed that a good correlation exists between magnetite series and the presence of I type granites, and ilmenite series and S type granites. This and similar studies (e.g., Ellwood and Wenner, 1981; Kohei, 1983) have demonstrated the correspondence between rock type and magnetic susceptibility values on the large scale but do not contribute to knowledge of the variation of magnetic susceptibility on the scale of a pluton.

Magnetite of Second Origin. A study of the Liberty Hill Pluton, South Carolina, showed that magmatic reactions in which pyroxenes are replaced by amphiboles or amphiboles by biotite commonly produce magnetite as a by-product (Speer, 1987). Water derived from surrounding host rocks might move into the magmatic reservoir (Taylor and Forester, 1971) and promote the production of such magmatic textures.

Late Stage Alteration and Fracturing. Lapointe et al. (1984, 1986), Chomyn and Lapointe (1984), and Chomyn et al. (1985) have demonstrated conclusively that magnetic susceptibility values from a fractured or altered granite pluton are significantly smaller than values from unaltered or unfractured portions of the same pluton. They proposed that the decrease is related to circulation of late-stage oxidizing fluids in these fractures which caused replacement of magnetite and bioite by hematite and chlorite, respectively.

Magnetic Anisotropy. In foliated rocks, the orientation of minerals responsible for the bulk magnetic susceptibility value of a sample is not random. In such situations, a magnetic fabric is typically present. Three distinct magnetic susceptibility values, corresponding to the three axes of an ellipsoid, can be determined for each sample. This characteristic has been applied with considerable success to the structural analysis of granitic plutons (Birch, 1979; Ellwood and Whitney, 1980; Jover et al., 1989; Diot and Bouchez, 1989; Hrouda and Lanza, 1989). However, the anisotropy of the magnetic fabric cannot be determined during field studies such as the one described here. Thus, in order for reproducible results to be obtained it is imperative that the spatial distribution of minerals responsible for the magnetic susceptibility at each individual outcrop be random (i.e., that the rock be texturally massive).

Evaluation of Sources of Variation in Magnetic Susceptibility Data

Examination of approximately 50 thin sections from each pluton indicate that biotite is the only mafic mineral present. The biotite frequently occurs in aggregates with other accessory minerals such as titanite, apatite, ilmenite, magnetite, and zircon and may have formed by replacement of pre-existing hornblende, however this texture is present throughout both plutons and cannot itself be responsible for the observed variation in magnetic susceptibility values.

The magnetic susceptibility was measured in the field using a magnetic susceptibility meter manufactured by Geo-Instruments KY of Helsinki, Finland. The detection limit is 1×10^{-5} SI units. Field measurements of the magnetic susceptibility of the plutons at different points in a large outcrop do not vary by more than 5%, except near late-stage quartz veins. This suggests that alteration and/or microfracture development have not modified the magnetic susceptibility value of the rock at the outcrop scale. The fact that magnetic susceptibility varies in a regular and systematic manner as a function of rock composition, as will be demonstrated below, is evidence indicating that pluton-scale alteration or microfracture development are not important in either pluton.

Diot and Bouchez (1989) studied the magnetic anisotropy of a calc-alkaline post-tectonic granitic complex in Morocco and observed that the difference in magnitude of maximum and minimum magnetic susceptibility values does not surpass 10%. They used this anisotropy to study the intrusion mechanics of the pluton and noted that anisotropy is developed most near the margin of the mass where oriented laths of plagioclase also are observed. The two plutons studied here are texturally massive throughout and no preferred orientation of any mineral was observed anywhere. Furthermore, measurements made on the three surfaces of a cube of rock taken at random yielded the same magnetic susceptibility value on all three surfaces. Finally, it is noted that the magnetic susceptibility values at various sites within each pluton vary by more than 10% from the average value for the pluton as a whole which indicates that other factors in addition to any anisotropy which may be present are responsible for the majority of the observed variation. Therefore, it is reasonable to assume, as a first approximation, that a unique magnetic susceptibility value can be assigned to each outcrop in each pluton.

CALCULATIONS AND RESULTS

Because the purpose of this study is to develop polynomial equations for the purpose of estimating values of individual oxide concentrations, it is useful to describe the distribution of all variables used in the regression calculations. In this study, SiO_2 has been chosen arbitrarily as the chemical oxide to be investigated. Table I presents the database used to effect the calculations. Histograms for these variables as well as cumulative frequency plots (Fig. 2) indicate the frequency distributions for each variable. Plots of each of the last three variables against SiO_2 (Fig. 3) reveal that each of them is correlated linearily with SiO_2 to some extent and thus contributes to knowledge of the SiO_2 content of the sample. These plots indicate that none of the variables has a gaussian frequency distribution (Fig. 2), hence an assumption of a true statistical linear relationship of SiO_2 with each variable is questionable at best, and probably false (Fig. 3).

Pearson product-moment correlation coefficients, along with the equation of the best-fitting line, are shown in the upper portion of each plot (Fig. 3). However, the significance of these correlation coefficients is in doubt because they assume a bivariate normal distribution which is clearly not present (Fig. 2). Spearman rank correlation coefficients (SRCC) are useful in this case because no prior suppositions concerning data distribution are required (Mosteller and Rourke, 1973). They also are more robust in that SRCCs are less affected by extreme (outlying) values or by data transformations. The SRCC values calcu-

Table I. Values for the Chemical and Physical Parameters Used to Calculate Eqs. (1) and (2)[a]

	SSSC pluton				
Anal	SiO_2	*K*	ppf	SiO_2C	Diff
1	66.7	1700	0.803	68.69	1.99
2	67.1	1000	0.723	70.62	3.52
3	68.6	2500	0.643	69.50	0.90
4	68.8	1040	0.681	70.95	2.15
5	69.0	2400	0.703	68.98	0.02
6	69.2	1700	0.632	70.42	1.22
7	69.4	2000	0.706	69.33	0.07
8	69.5	1600	0.846	68.39	1.11
9	69.6	1100	0.645	71.20	1.60
10	69.6	1440	0.701	70.07	0.47
11	69.6	1800	0.641	70.20	0.60
12	69.7	1700	0.656	70.18	0.48
13	69.8	1440	0.564	71.45	1.65
14	70.0	800	0.746	70.85	0.85
15	70.3	1200	0.880	68.65	1.65
16	70.5	1600	0.678	70.08	0.42
17	70.6	1900	0.913	67.35	3.25
18	70.9	1500	0.638	70.62	0.28
19	71.2	1500	0.575	71.26	0.06
20	71.2	1600	0.638	70.48	0.72
21	71.3	1700	0.611	70.63	0.67
22	71.5	1400	0.599	71.17	0.33
23	71.6	2000	0.627	70.13	1.47
24	72.2	900	0.509	72.99	0.79
25	73.0	1700	0.517	71.57	1.43
26	73.8	740	0.469	73.80	0.00
27	74.4	840	0.435	73.87	0.53
28	74.4	700	0.494	73.66	0.74
29	74.5	600	0.500	73.93	0.57
30	74.6	740	0.521	73.27	1.33
31	75.0	540	0.518	73.96	1.04
32	75.0	640	0.443	74.36	0.64

	Aylmer pluton					
Anal	SiO_2	ppf	*K*	Dens	SiO_2C	Diff
1	65.8	0.903	24	2.687	70.12	4.32
2	67.3	0.562	6	2.618	72.93	5.63
3	68.4	0.713	10	2.634	71.75	3.35
4	68.5	0.880	18	2.668	70.46	1.96
5	68.5	0.867	20	2.662	70.40	1.90
6	69.3	0.786	12	2.657	71.28	1.98
7	69.4	0.909	14	2.668	70.56	1.16
8	69.5	0.815	12	2.671	71.18	1.68

Table I. Continued

	Aylmer pluton					
Anal	SiO_2	ppf	K	Dens	SiO_2C	Diff
9	69.7	0.507	2	2.602	74.22	4.52
10	69.8	0.831	16	2.646	70.75	0.95
11	70.8	0.777	8	2.648	71.69	0.89
12	71.2	0.634	16	2.649	71.72	0.52
13	71.9	0.678	20	2.618	71.19	0.71
14	71.9	1.000	12	2.654	70.22	1.68
15	72.0	0.737	12	2.646	71.49	0.51
16	72.1	0.746	14	2.640	71.27	0.83
17	72.6	0.524	32	2.630	71.54	1.06
18	72.6	0.876	14	2.667	70.72	1.88
19	72.8	0.659	6	2.639	72.52	0.28
20	72.9	0.595	12	2.637	72.16	0.74
21	73.1	0.594	8	2.638	72.56	0.54
22	73.4	0.556	16	2.622	72.02	1.38
23	73.5	0.571	2	2.571	73.81	0.31
24	74.1	0.596	4	2.611	73.14	0.96
25	74.3	0.756	6	2.635	72.03	2.27
26	74.4	0.526	8	2.635	72.89	1.51
27	74.6	0.875	24	2.682	70.25	4.35
28	74.7	0.532	4	2.615	73.46	1.24
29	74.8	0.409	1	2.619	75.43	0.63
30	75.1	0.608	1	2.611	74.42	0.68
31	75.2	0.494	2	2.617	74.33	0.87
32	75.2	0.550	1	2.597	74.66	0.54
33	75.3	0.534	2	2.603	74.09	1.21
34	75.4	0.484	1	2.614	75.04	0.36
35	75.4	0.856	16	2.667	70.69	4.71
36	75.4	0.391	1	2.611	75.49	0.09
37	75.8	0.516	1	2.606	74.86	0.94
38	75.9	0.426	1	2.602	75.29	0.61

[a] K = magnetic susceptibility (10^{-5} SI units); ppf = modal plagioclase: (plagioclase + potassium feldspar) ratio; dens = density (gms/cc).

lated for the two datasets (Table II) are compatible with the correlation coefficients shown in Fig. 3. Significance level tables for the SRCC (see MacDonald and Clarke, 1991) show that, for a dataset surpassing 32 paired observations, the correlation coefficient is significant if its absolute value surpasses 0.43. Thus, a significant linear relationship exists in a practical sense between SiO_2 and the other variables of both datasets.

Multiple regression calculations, in which the SiO_2 value of the sample

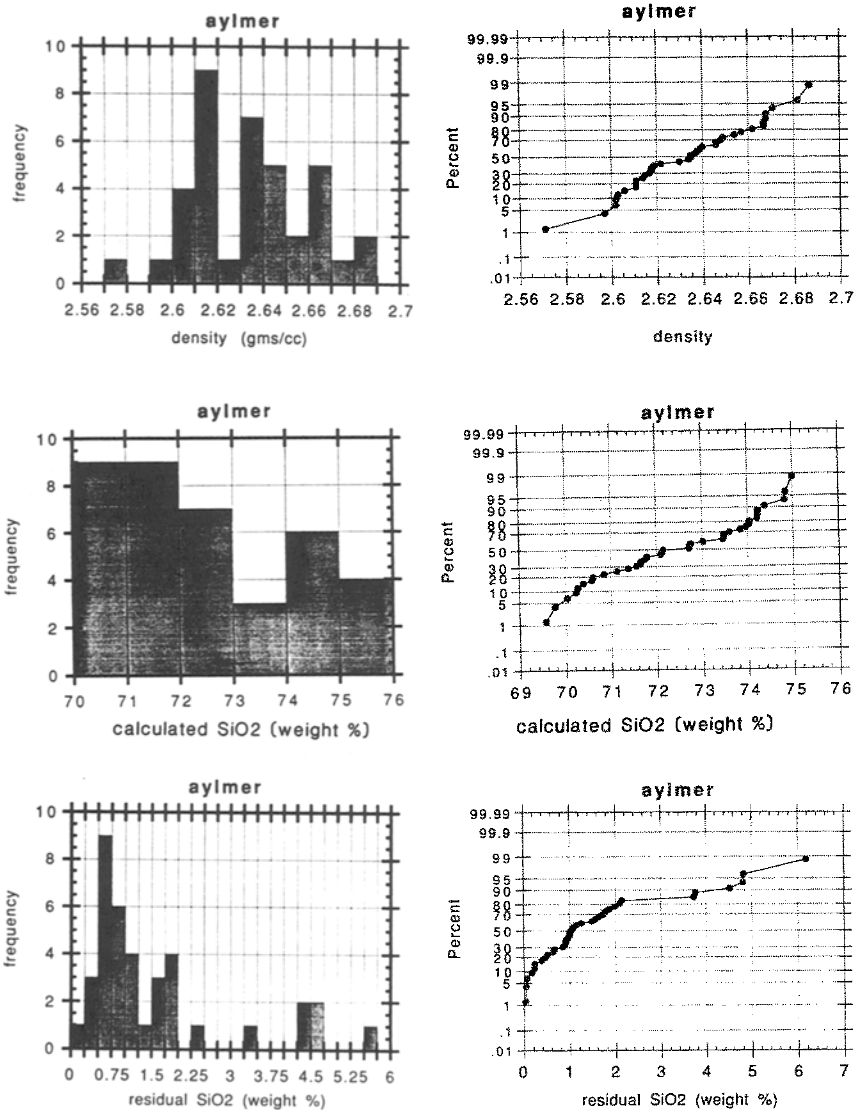

Fig. 2. Histograms and cumulative frequency plots for variabales used in the multiple regression equation (legend as in Table I).

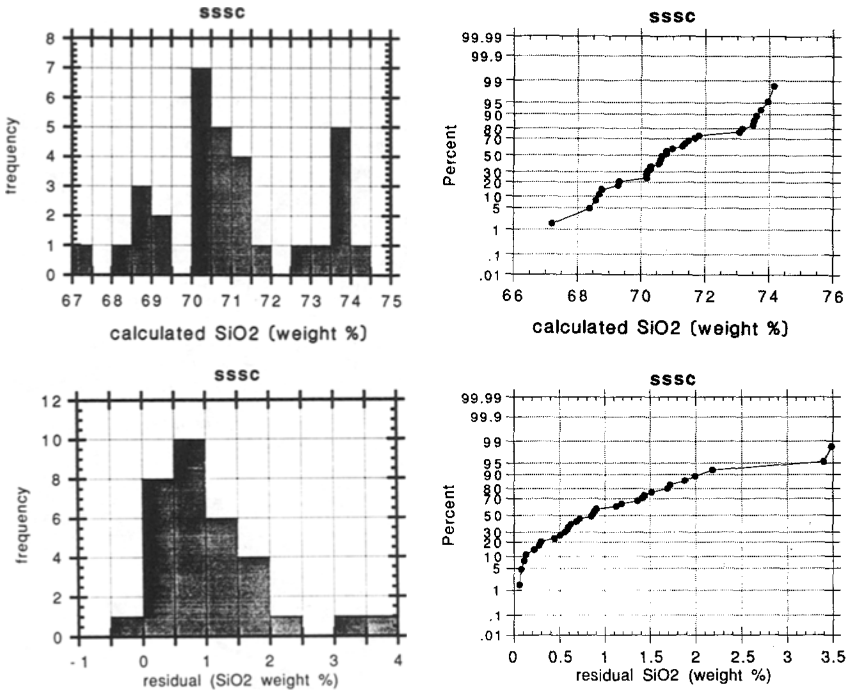

Fig. 2. Continued

(Table I) is considered as a function of density, magnetic susceptibility, and ppf ratio simultaneously, yield polynomial equations which can be used to estimate SiO_2 contents of unanalyzed samples. For example, using the Aylmer data (Table I) and the SAS multiple regression program, the relationship between these four variables is calculated to be:

$$SiO_2\ (calc) = -0.0771\ K - 6.4193\ ppf - 4.913\ dens + 90.42 \quad (1)$$

and using the SSSC data:

$$SiO_2\ (calc) = -0.00145\ K - 10.914\ ppf + 79.92 \quad (2)$$

Because the three variables used to estimate SiO_2 are not statistically independent of one another, these equations cannot be used to *accurately predict* SiO_2 values, however, they can be used them to *empirically estimate* SiO_2 values of unanalyzed samples. To evaluate how accurate such estimates might be, Eqs. (1) and (2) are used to calculate an estimated SiO_2 value for each sample in Table I and then compare them to the actual SiO_2 value. The difference between the two values (the residual) represents that portion of the SiO_2 variation which

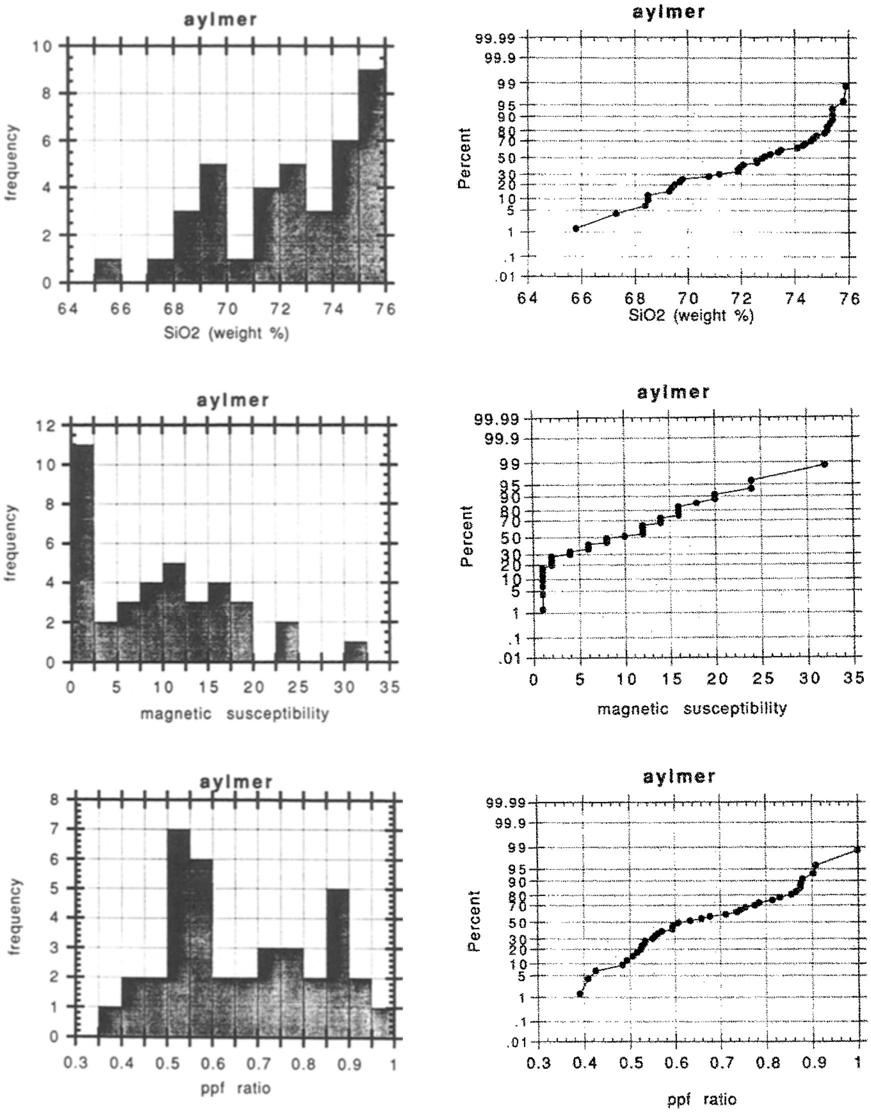

Fig. 2. Continued

is not explained by the adopted model. Plots of the chemically determined SiO_2 value against the calculated value for this variable (Fig. 3) show calculated SiO_2 values falling between 69% and 73% are generally within 1% of their analytical value. Because the uncertainty envelope for regression equations features an

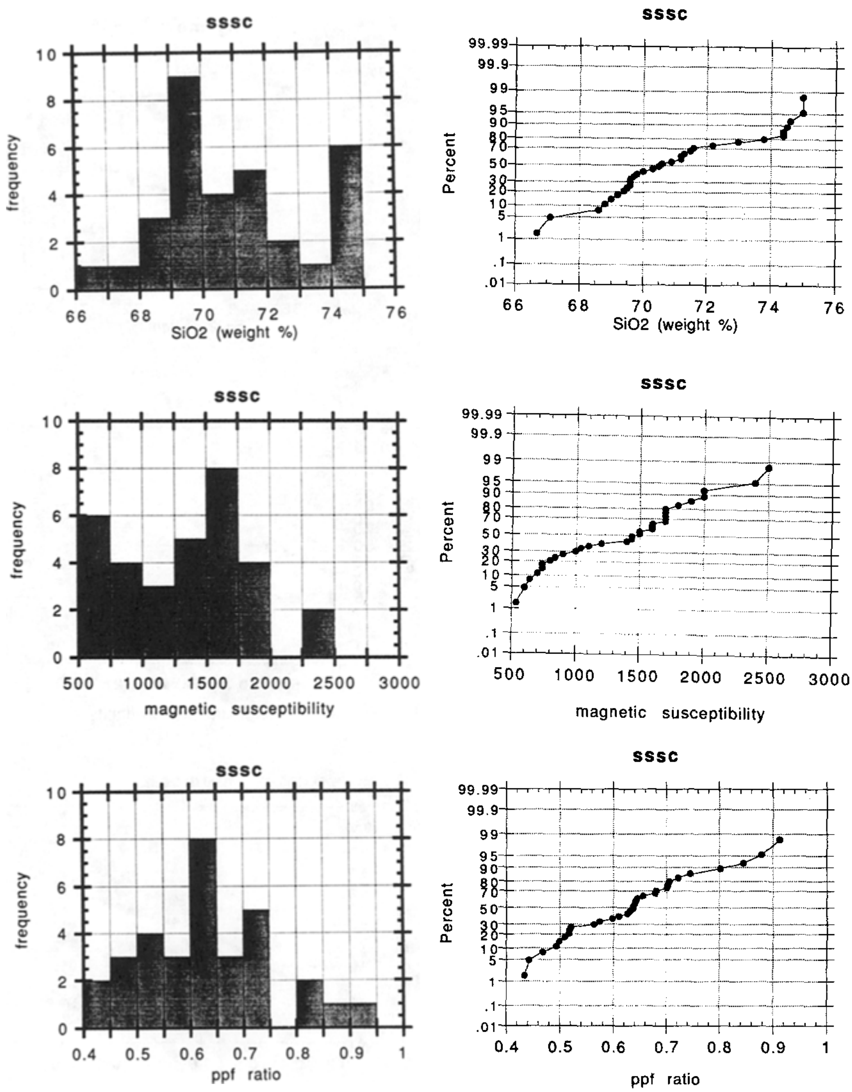

Fig. 2. Continued.

hourglass-like form (LeMaitre, 1982), it is reasonable to expect that larger uncertainties may arise for the extreme SiO_2 values, and that the residuals would be smaller for mid-range SiO_2 values. The average discrepancy is 1.02 wt. % for the complete SSSC data set and 1.57 wt. % for the Aylmer data set.

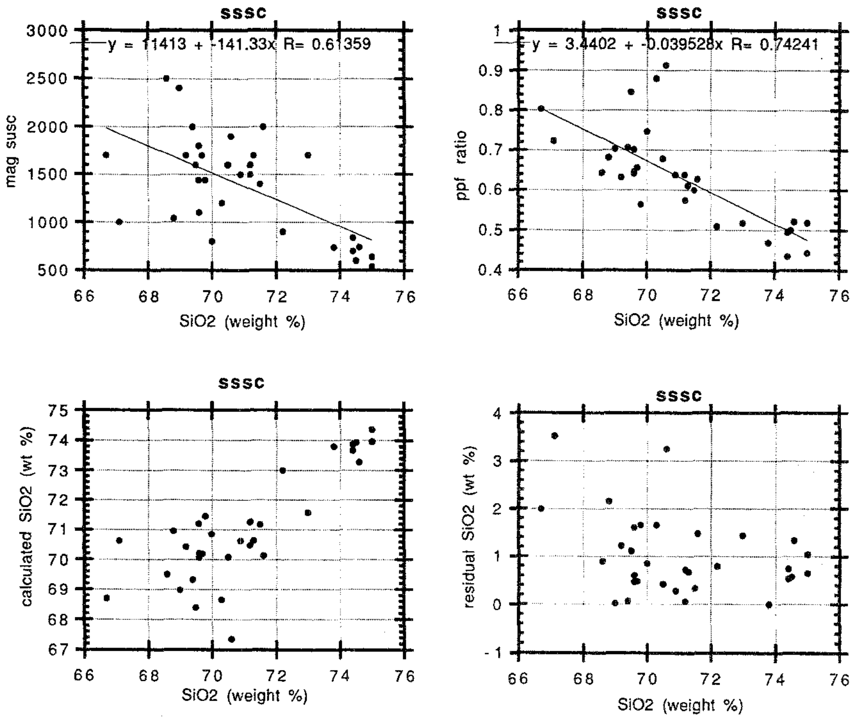

Fig. 3. Bivariate plots of physical parameters against SiO_2 (legend as in Table I). SiO_2C = calculated SiO_2 value using Eqs. (1) or (2).

DISCUSSION

Contoured diagrams showing the distribution of the SiO_2 data, ppf ratios, magnetic susceptibility values, density, and the calculated SiO_2 distributions are shown for both plutons (Figs. 4–8). Sample locations of the rocks submitted for chemical analysis and sample locations of all rocks collected during the study are shown in Figs. 4 and 8, respectively, but not in Figs. 5–7 for reasons of clarity. Rocks situated near the extremities of the SSSC pluton and within a broad arc along the western and northern margins of the Aylmer pluton have the greatest SiO_2 values whereas rocks near the center of each intrusion have smaller SiO_2 concentrations. These plots show unequivocally that the two plutons are reversely zoned. This distribution is mirrored in Figs. 5–7. Samples with the least density, magnetic susceptibility value, and ppf ratio are in those portions of the plutons with the largest SiO_2 values. These diagrams provide visual confirmation of the statistical data presented above. Calculated SiO_2 values obtained from the two polynomials presented earlier (Fig. 8), show a very

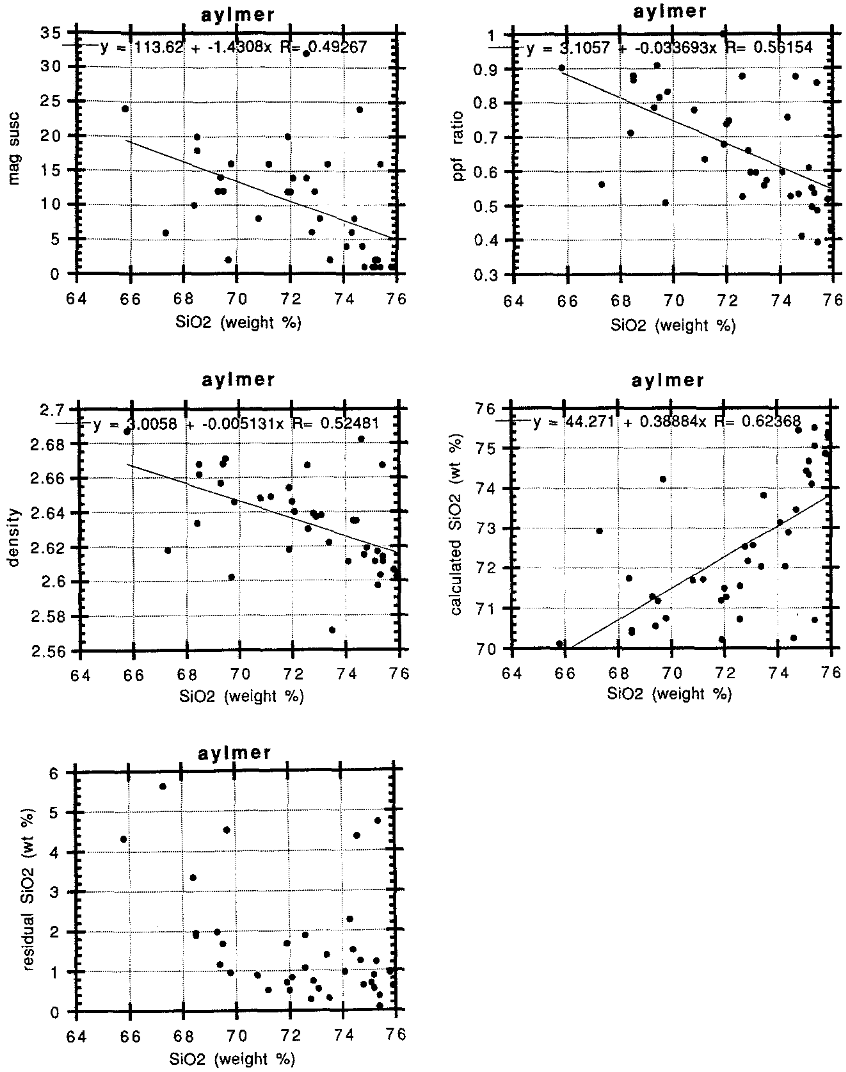

Fig. 3. Continued.

good spatial correlation with the analytical results, however, in detail, minor differences exist. The greater SiO_2 value zones found in the northeastern and northern corners of the Aylmer pluton (Fig. 8) are more clearly defined than in Fig. 4. In addition, a small, crudely circular zone of smaller SiO_2 values in the west-central portion of the Aylmer pluton (not present in Fig. 4) might reflect the emplacement of a separate pulse of magma. Similar slight, although poten-

Table II. Spearman Rank-Correlation Coefficients for the Aylmer Dataset (to the Lower Left of the Diagonal) and the SSSC Dataset (Upper Right of the Diagonal)

	SiO_2	K	ppf	Dens
SiO_2	1.0	−0.58	−0.78	—
K	−0.61	1.0	0.50	—
ppf	−0.61	0.70	1.0	—
Dens	−0.57	0.77	0.70	1.0

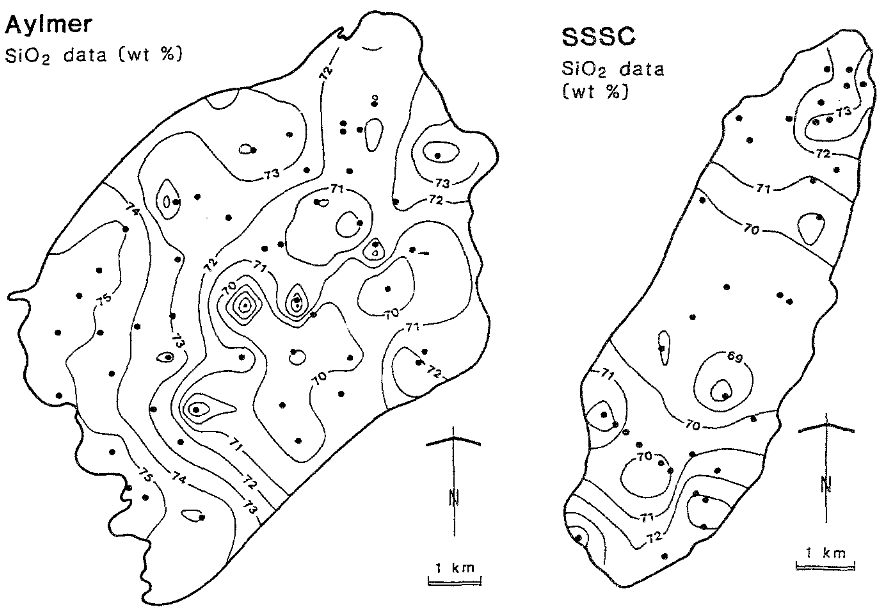

Fig. 4. Maps of SiO_2 (wt.%) distribution for the SSSC and Aylmer plutons. Contours on this and the following figures were calculated using the GRAPHER computer program. The value at each point on the contoured grid was calculated using data from the seven "nearest neighbors" weighted by inverse square of the distance from the grid point. The actual form of the contours will vary slightly depending on the computer program used and the parameters chosen.

tially useful differences, are apparent elsewhere. Thus the approach described herein can serve as a supplement to geochemical studies and provides a method for easily extracting additional useful information from ALL samples collected during the course of a mapping project.

An additional benefit is that the physical parameters can be used to check for possible errors in the chemical data set. Consider analysis 35 of the Aylmer suite, for which the reported SiO_2 value is 75.4 wt.%. The ppf, density, and

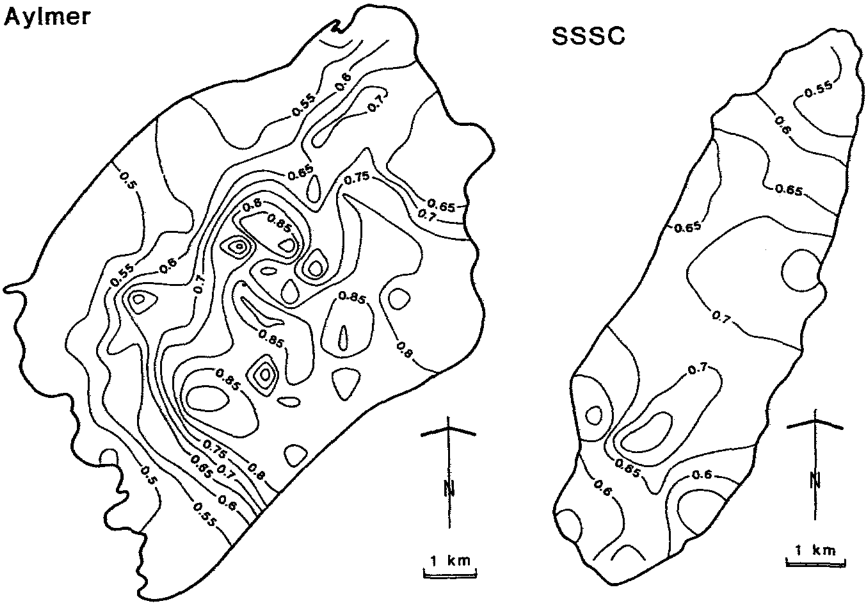

Fig. 5. Maps of ppf ratios for the SSSC and Aylmer plutons.

magnetic susceptibility values for this sample all suggest that this SiO_2 value may be too large. Therefore, the accuracy of analysis 35 should be viewed with suspicion and it would be wise to re-analyse this specimen.

CONCLUSIONS

1. Density, magnetic susceptibility, and stained slab data, all of which were collected in the field, correlate well with SiO_2 values as determined subsequently in the laboratory.
2. Polynomial equations relating measured SiO_2 to these physical parameters may be used to calculate approximate SiO_2 values (or values for any other oxide) for all collected rock specimens.
3. Plots of calculated SiO_2 values may provide a more detailed picture of the chemical variability of the intrusion which can then be incorporated into the petrogenetic interpretation of the mass.

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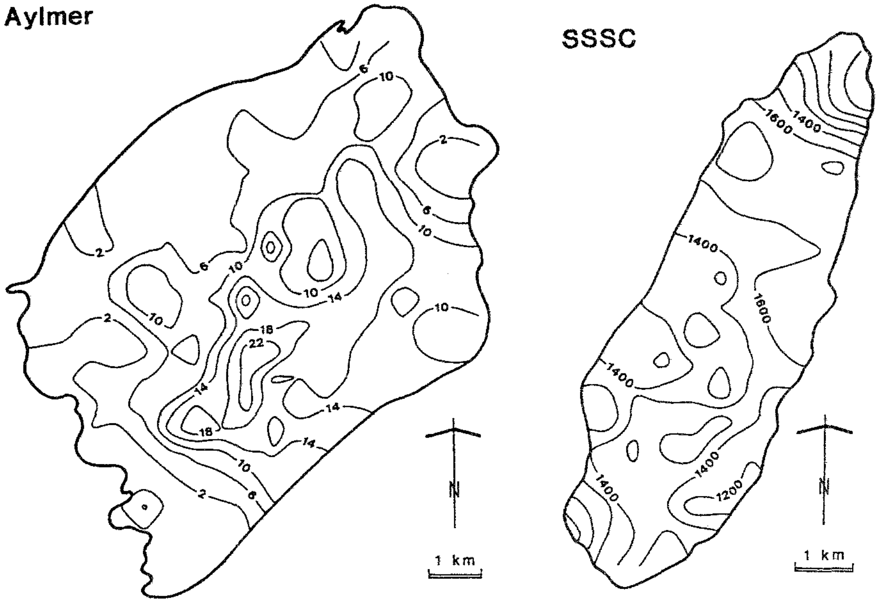

Fig. 6. Maps of magnetic susceptibility values for the SSSC and Aylmer plutons. Values of the contours are in 10^{-5} SI units.

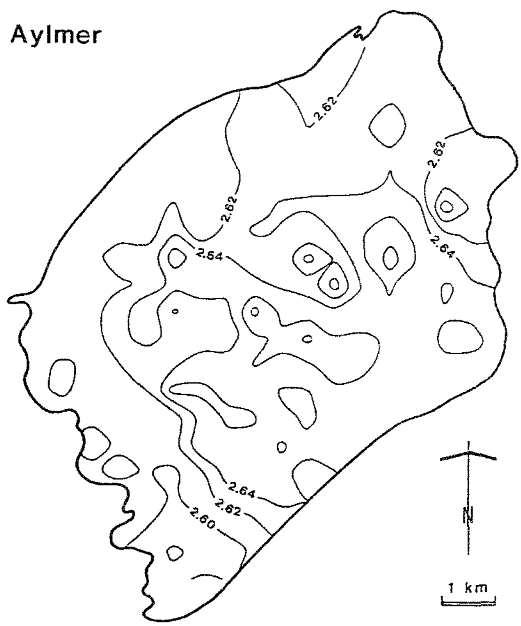

Fig. 7. Map of density data (gm/cc) for the Aylmer pluton.

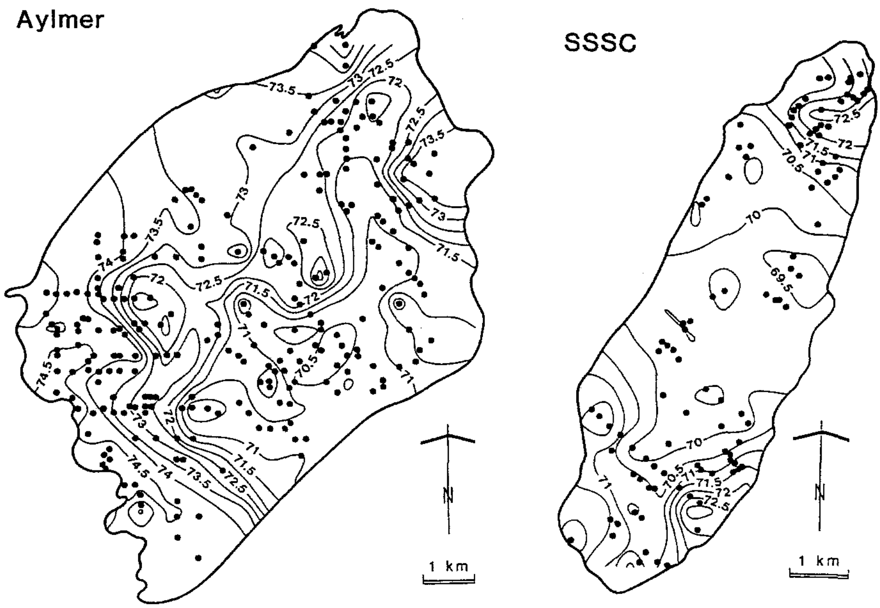

Fig. 8. Maps of calculated SiO_2 (wt.%) values for the SSSC and Aylmer plutons.

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