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Petrographic and Geochemical Variations within the Songo Pluton, Western Maine

David Gibson
Daniel R. Lux
Department of Geological Sciences
University of Maine
Orono, Maine 04469

ABSTRACT

Field and petrographic investigations of the 382 Ma old Songo pluton, western Maine, have revealed that it can be subdivided into two petrographic varieties. A typical I-type granodiorite containing biotite, ± hornblende, and sphene crops out in the northwestern, northern, and northeastern parts of the pluton. Biotite-granodiorites containing Ti-rich biotite occur in the central and southern areas. The distribution of the latter facies appears to be spatially associated with the outcrop pattern of the 325 Ma Sebago two-mica granite and with numerous pegmatites. A gradational boundary is inferred between the two petrographic varieties of the Songo pluton.

Microprobe data confirm that biotites from the two petrographic varieties differ in TiO_2 and to a lesser degree MnO wt.%. These biotite analyses show a trend of decreasing Mn and increasing Ti within the pluton. Continuous variation in biotite compositions also corroborates the gradation between the two Songo types.

Major element geochemical data show that the petrographic varieties overlap in composition but that, on average, the biotite-hornblende-sphene granodiorites are less felsic (i.e. lower SiO_2 and higher TiO_2, Fe_2O_3(T), CaO and P_2O_5 wt.%) than their biotite-granodiorite counterparts. Whereas the major element data define linear, continuous trends with SiO_2, the trace elements do not. Some of the biotite-granodiorites are mildly peraluminous, with A/CNK ratios greater than 1:1.

The combined field, petrographic, and geochemical evidence suggest that parts of this I-type granodiorite may have been modified by the subsequent intrusion of the Sebago granite. The dual effects of reheating and fluid migration associated with the emplacement of the latter may have produced the mineralogical variation in those parts of the Songo pluton adjacent to the Sebago granite and the pegmatites. This thermal event may also have caused open-system behavior of trace elements in the Songo pluton. The major element geochemistry of the pluton appears to have remained largely unchanged.

INTRODUCTION

The Songo granodiorite pluton is one of a number of post-Acadian granitic intrusions presently exposed on the northwestern limb of the Kearsarge - central Maine synclinorium in western and northwestern Maine (Fig. 1). It covers an area of approximately 300 km^2 in the Bethel and Bryant Pond 15' quadrangles and intrudes metasedimentary rocks of Silurian and early Devonian age. It is truncated to the southeast by the Moll Ockett normal fault and is intruded by the Speckled Mountain quartz monzonite, which is the northern extension of the Sebago two-mica granite. The Songo pluton was originally mapped by Fisher (1962) and Guidotti (1965) and has been assigned to the New Hampshire plutonic series of Billings (1956).

U-Pb zircon (Lux and Aleinikoff, 1985) and Rb-Sr whole rock isochron results (Lux et al., this volume) indicate a crystal-

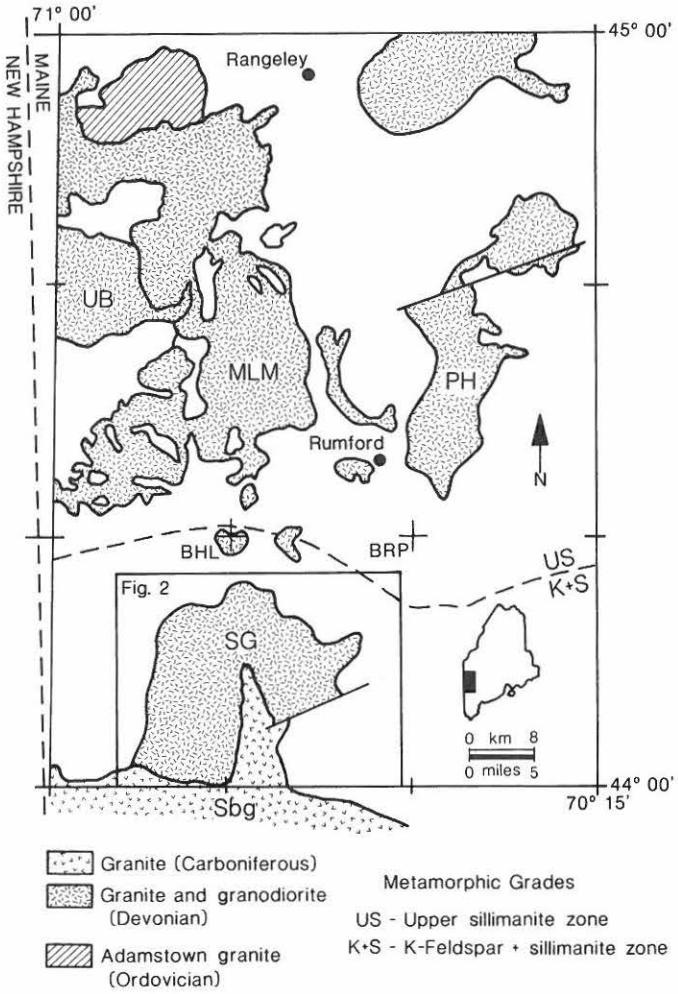

Figure 1. Map showing the distribution of granitic plutons in part of western Maine. (UB - Umbagog; MLM - Mooselookmeguntic; PH - Phillips; SG - Songo; Sbg - Sebago). The Bethel (BHL) and Bryant Pond (BRP) quadrangles are also labeled.

lization age of 382 Ma for the Songo pluton. This is comparable to ages of other plutons in this area, for example 371±6 Ma for the Mooselookmeguntic pluton (Moench and Zartman, 1976) and 382±3 Ma for the Umbagog pluton (Moench, 1984). However, $^{40}Ar/^{39}Ar$ dating of hornblende from the Songo pluton reveals that they have disturbed argon release spectra and plateau ages, averaging at 304 Ma, which are significantly younger than the crystallization age (see Lux et al., this volume).

These young, reset hornblende ages and petrographic data from the metamorphic rocks of the area led Lux and Guidotti (1985) to suggest that some of the high-grade metamorphism in western Maine was closely related in time and space to the emplacement of the Sebago granite. The latter has been dated at 325 Ma by both the Rb-Sr whole rock isochron (Hayward and Gaudette, 1984) and the U-Pb zircon methods (Aleinikoff, 1984). This suggests that this metamorphic event is Carboniferous in age rather than Devonian as previously believed (Holdaway et al., 1982, and Guidotti et al., 1983). Further evidence from calculated thermal models by De Yoreo et al. (1989) strongly suggests that the Sebago pluton was an adequate heat source for this metamorphism, given that it is a thin (ca. 1 km), north-dipping sheet-like intrusion (Hodge et al., 1982).

The initial reconnaissance sampling for the argon dating study (D. R. Lux) revealed certain petrographic variations within the Songo pluton. In some areas the granodiorite contains biotite, hornblende, and sphene, a mineral assemblage characteristic of I-type granites (Chappell and White, 1974). In other parts of the pluton the granodiorite lacks hornblende and sphene and contains biotite as the only mafic phase. In addition, preliminary petrographic observations revealed that this biotite has a distinctive red/brown pleochroism indicative of high TiO_2 contents. This is a mineralogical feature often associated with peraluminous S-type granites (see Table 1 of Pitcher, 1982). Thus the Songo pluton presents an opportunity to investigate a seemingly individual intrusion within which internal petrographic varieties are present.

This contribution presents field, petrographic, and geochemical data for the Songo granodiorite and associated rocks within the pluton. The aims of this study are, (1) to elucidate the field relations of the two petrographic varieties and hence ascertain whether the Songo pluton is zoned or composite, (2) to investigate the origin of this internal variation, and (3) to examine the effects on the Songo pluton of the later emplacement of the Sebago granite.

ANALYTICAL METHODS

Geochemical bulk rock analyses of 41 samples from the Songo pluton were performed at the Department of Geology, The Queen's University of Belfast, N. Ireland. The whole rock analyses were performed on a Phillip's PW 1410/20 X-ray fluorescence spectrometer with interchangeable W and Cr X-ray tubes. Most major elements were analyzed off fused glass discs except for MgO and CaO, which along with the trace elements, were determined on pressed powder pellets. A set of international silicate standards, along with some internal laboratory standards, were employed to construct calibration lines. SiO_2 and Al_2O_3 analyses were duplicated for each sample and these varied usually by <0.1% and <0.17% respectively from the averages. Precisions for SiO_2, Al_2O_3, TiO_2, Fe_2O_3 (as total), CaO, Na_2O and K_2O were less than 1% of the total concentrations and less than 3% for MgO, MnO, and P_2O_5. Trace element precisions were less than 1% for Rb, Sr, Ba, Zr, and Y and <5% for Th, Zn, Nb, and Ni.

Biotite microprobe analyses were performed at the University of Maine on a MAC 400S system with an accelerating potential of 15 Kv and a beam current of 0.03 micro-amps. Silicate mineral standards were utilized and the matrix correction factors employed are those of Bence and Albee (1968).

FIELD RELATIONS AND PETROGRAPHY

The Songo granodiorite is typically medium grained and equigranular although some variations in grain size and texture are observed. The granodiorite is commonly foliated and in some outcrops it is intensely banded (see below). The outer contacts of the pluton are fairly well exposed and are often associated with migmatites. No contact aureole is evident around the Songo pluton nor would one be expected because of the high grade of regional metamorphism (Ksp + Sill). Metasedimentary xenoliths, probably of local origin, are preserved in the Songo pluton, but nowhere are they abundant. Igneous type enclaves are also recognized at some localities as well as biotite-rich schlieren.

Field and petrographic investigations have confirmed that two varieties of granodiorite are present within the Songo pluton. One facies is characterized by the presence of red/brown, Ti-rich biotite and is referred to here as the biotite-granodiorite. In contrast, the other granodioritic variety contains black biotite, and usually hornblende and sphene (referred to as the BHS-granodiorites). However, more extensive sampling of the pluton has revealed that, in some parts of this facies, there is variation in this standard mineral assemblage (see below). Usually, the two petrographic varieties can be identified in the field either by the presence of hornblende and/or sphene, or by the color of the biotite. In particular, the red/brown sheen of biotite from the biotite-granodiorites is distinctive.

Recent field mapping has revealed that the two petrographic varieties crop out in discrete areas (Fig. 2). The BHS-granodiorites crop out in the northwestern, northern, and northeastern parts of the pluton with a small subsidiary area northeast of East Stoneham. The biotite-granodiorites are observed in the central and southern parts of the pluton and close to the northern extension of the Sebago granite. Indeed, there appears to be a strong spatial association between the biotite-granodiorite facies of the Songo pluton and the contact of the latter with the Sebago granite. In addition to the main area, biotite-granodiorite is also observed close to major pegmatite bodies and adjacent to large metasedimentary xenoliths.

A gradational boundary is inferred between the two Songo varieties and no intrusive contact has been observed. Evidence from petrographic observations, biotite mineral chemistry, and whole-rock geochemical data (as detailed below) appears to support this proposed gradation.

In the BHS-granodiorite, black biotite is the most abundant mafic phase and is ubiquitous throughout this facies. In thin section it is typically brown-green and inclusions of zircon and apatite are common. Hornblende is sub- to euhedral and up to 5 mm in length. Preliminary microprobe analyses suggest they are a calcic variety. Plagioclase is generally unzoned, sub- to euhedral and occasionally has sericitized cores. It greatly exceeds K-feldspar in abundance with the latter being sub- to anhedral and interstitial. Quartz often exhibits evidence of being strained with undulose and sectorial extinction. Of the accessory phases, sphene is the most abundant and is usually euhedral. Apatite is also present, occurring both as inclusions in biotite and as discrete grains (up to 0.2 mm). Zircon occurs generally as inclusions in biotite and appears to lack any petrographic characteristics of an inherited component (e.g. rounded cores or zonal growth lines). Magnetite, the primary Fe-Ti oxide phase, and allanite are also present in minor amounts. Myrmekitic intergrowths of plagioclase, K-feldspar, and quartz are common. Some muscovite is also observed, but its characteristics strongly suggest that it is secondary. Therefore, on petrographic grounds, the BHS-granodiorites have an I-type mineralogy.

However, there is some variation of the characteristic mineral assemblage of the BHS-granodiorites, with a decrease in the abundance of hornblende and sphene. In some parts of this facies hornblende is absent, but the presence of both black biotite and sphene confirm that these samples are part of this petrographic variety. Therefore there is a gradation from biotite-hornblende-sphene granodiorites to biotite-sphene granodiorites within this facies.

In the biotite-granodiorite, biotite is the only mafic silicate present. It has a distinctive red-brown pleochroism in thin section which is usually indicative of high TiO_2 contents (Deer et al., 1975). Plagioclase is sub- to euhedral and unzoned. Commonly its twin planes are warped and diffuse and, in highly deformed samples of the biotite-granodiorite, it is heavily sericitized. K-feldspar is generally subhedral and interstitial. The quartz in the biotite-granodiorite appears highly strained and is often cracked, embayed, and exhibits sectorial extinction. Apatite and zircon are the most abundant accessory phases and commonly occur as inclusions in biotite. Fe-Ti oxides (mag-

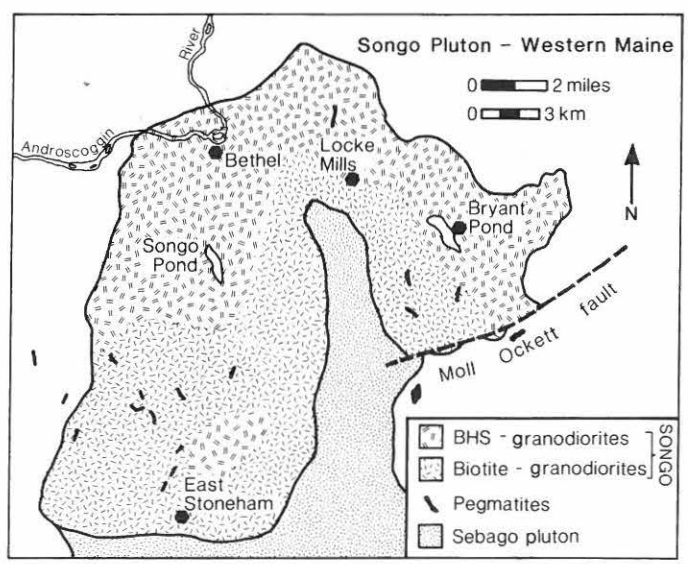

Figure 2. Generalized map of the Songo pluton showing the disposition of the two petrographic varieties. The Sebago granite and some of the larger pegmatites are also shown.

netite + ilmenite, some of which may be secondary) and allanite are present in minor amounts. Myrmekitic intergrowths are also observed in this facies. Subsidiary amounts of muscovite are present and although the majority of grains appear to be secondary, there is evidence to suggest that a small amount of primary muscovite is present in this part of the pluton. In contrast to the BHS-granodiorites, the biotite-granodiorites exhibit some S-type characteristics.

The petrographic characteristics described above are fairly constant for each Songo type. Variations are observed however, and in some biotite-granodiorite samples the biotites have less extreme red/brown pleochroism (cf. to normal examples of this facies) and some resorbed anhedral sphene, possibly of a secondary origin, is observed. In addition, biotites from some BHS-granodiorites occasionally show incipient development of red/brown pleochroism. These "intermediate" petrographic characteristics are observed in samples from outcrops geographically between the two main Songo varieties and may be evidence of a gradation between them.

Modal analyses reveal that most samples from the two petrographic varieties of the Songo pluton plot in the granodiorite field of the Streckeisen (1976) classification diagram (Fig. 3b), though some are more strictly termed tonalites. There is a large degree of overlap between the two varieties on the Q-A-P triangle with an overall trend of increasing quartz contents and decreasing plagioclase contents. Similarly, there is a large degree of overlap in total mafic content between the BHS-granodiorites (15-28%) and the biotite-granodiorites (13-25%), as illustrated by Figure 3a. The modal data also show that both plagioclase and total mafic content decrease with increasing quartz levels (see Figs. 3a and c).

The Songo pluton is cut by numerous pegmatitic bodies, most of which have a simple mineralogy (i.e. quartz, K-feldspar, muscovite ± biotite ± garnet), although some also contain beryl, tourmaline, and apatite. They commonly occur as dikes or larger irregular masses, and field relations suggest that there may have been more than one generation of pegmatite emplacement. The pegmatites appear to be more abundant in the central part of the pluton, coincidental with the area of biotite-granodiorite. Guidotti et al. (1986) suggest that their general preponderance in western Maine is due to the emplacement of the Sebago pluton from which they may have been derived. Small bodies of leucocratic two-mica ± garnet granite are commonly associated with some of the larger pegmatites. The field relations of the former are ambiguous. They may be contemporaneous with the pegmatites, or younger. These leucocratic granites may also be related to the Sebago granite. Geochemical data presented in Table 4 may shed further light on this idea.

Deformation features are not only observed at a microscopic scale as described above, but also on a macroscopic scale within the Songo pluton. In the field, the granodiorite is commonly foliated. This is usually defined by the mafic phases + plagioclase and generally trends between 30°W to 30°E of N. At some localities plagioclase phenocrysts up to 3 cm in length are aligned parallel to the foliation. Commonly, the foliation is crenulated and is especially well developed in the central area of biotite-granodiorite. Indeed, the latter is often highly deformed and in many outcrops distinct mafic and felsic banding is observed. In addition to this banding, large plagioclase grains are developed, giving the rock the general appearance of an augen gneiss (e.g. 3 miles southwest of Songo Pond).

In summary, two main petrographic varieties are observed within the Songo pluton, each of which crops out in distinct parts of the intrusion. The BHS-granodiorites have an I-type mineralogy, whereas the biotite-granodiorites have some S-type characteristics. Pegmatites are regionally abundant, but within the Songo pluton they are especially common in the areas underlain by the biotite-granodiorite. Similarly, deformation features are better developed in this area, although foliations are observed over much of the Songo pluton.

BIOTITE MINERAL CHEMISTRY

The variation in biotite petrography is one of the most important parameters on which the subdivision of the Songo granodiorite is based. To elucidate the origin of the observed petrographic variations, it was important to investigate the mineral chemistry of biotites from the Songo pluton. Seventy-four biotites, from nine samples, were analyzed by electron microprobe. The samples chosen for analysis are from both petrographic varieties including possible intermediate types, spanning the range of whole-rock compositions (see Table 3). The results are given in Table 1 as averages +/- one standard deviation for each sample and are displayed graphically in Figure 4.

Most geochemical parameters do not distinguish between biotite from either Songo type (Table 1). Significantly, TiO_2 and to a lesser extent MnO are the exceptions to this generalization. Biotites from the BHS-granodiorite have, on average, lower

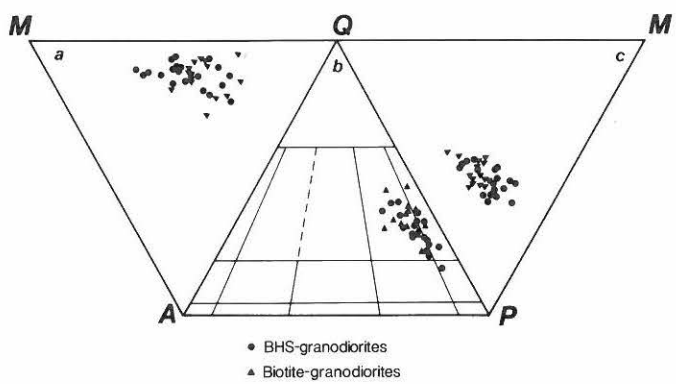

Figure 3. (a,b,c) Variations in modal mineral abundances within the Songo pluton plotted on quartz-alkali feldspar - plagioclase - total mafic content (Q-A-P-M) diagrams. 3b also shows the granitoid classification fields of Streckeisen (1974). (Some data points omitted due to overlap).

TABLE 1. AVERAGE MICROPROBE ANALYSES AND STRUCTURAL FORMULA UNITS (± ONE STANDARD DEVIATION) OF BIOTITES FROM SELECTED SAMPLES OF THE SONGO PLUTON.

Samples SG-7, 38, 10, 18, and 23 are BHS-granodiorites and are arranged, from left to right, in order of increasing SiO_2 values of their host whole-rocks (see Table 2). SG-34, 5, 16, and 40 are biotite-granodiorites. Number of biotites analysed per sample is given in brackets.

	SG-7 (8)	SG-38 (10)	SG-10 (8)	SG-18 (8)	SG-23 (6)	SG-34 (9)	SG-5 (9)	SG-16 (8)	SG-40 (8)
SiO_2	36.34 ± 0.29	36.93 ± 0.61	36.39 ± 0.78	36.29 ± 0.50	36.33 ± 0.12	36.35 ± 0.17	35.93 ± 0.60	35.66 ± 0.40	35.93 ± 0.39
Al_2O_3	16.75 ± 0.34	16.33 ± 0.67	16.06 ± 0.24	16.31 ± 0.45	17.02 ± 0.17	16.49 ± 0.31	16.48 ± 0.20	18.83 ± 0.36	17.63 ± 0.52
TiO_2	2.80 ± 0.17	2.78 ± 0.46	2.43 ± 0.19	2.50 ± 0.43	3.10 ± 0.19	3.23 ± 0.16	3.43 ± 0.19	3.60 ± 0.17	3.60 ± 0.16
MgO	10.55 ± 0.17	11.11 ± 0.26	11.42 ± 0.13	10.61 ± 0.39	11.23 ± 0.23	11.19 ± 0.17	11.30 ± 0.19	10.01 ± 0.24	10.52 ± 0.22
MnO	0.25 ± 0.06	0.26 ± 0.04	0.27 ± 0.03	0.37 ± 0.04	0.39 ± 0.05	0.16 ± 0.03	0.29 ± 0.02	0.08 ± 0.02	0.28 ± 0.07
FeO	18.33 ± 0.19	18.47 ± 0.18	18.85 ± 0.13	19.36 ± 0.28	17.83 ± 0.13	18.81 ± 0.15	18.10 ± 0.23	18.00 ± 0.24	17.62 ± 0.37
BaO	0.25 ± 0.27	0.07 ± 0.08	0.06 ± 0.11	0.11 ± 0.11	0.54 ± 0.15	0.26 ± 0.15	0.49 ± 0.13	0.03 ± 0.04	0.15 ± 0.10
K_2O	9.77 ± 0.15	9.45 ± 0.29	9.80 ± 0.14	9.68 ± 0.19	9.77 ± 0.18	9.43 ± 0.34	9.67 ± 0.19	9.80 ± 0.13	9.27 ± 0.28
Na_2O	0.19 ± 0.04	0.14 ± 0.03	0.14 ± 0.03	0.17 ± 0.04	0.12 ± 0.02	0.12 ± 0.03	0.14 ± 0.04	0.17 ± 0.02	0.14 ± 0.08
Fe/(Fe+Mg)	0.494±0.004	0.483±0.006	0.481±0.007	0.506±0.12	0.471±0.007	0.486±0.004	0.473±0.006	0.502±0.006	0.484±0.008
FORMULA UNITS ON THE BASIS OF 22 OXYGENS									
Si	5.541±0.039	5.590±0.087	5.550±0.066	5.549±0.028	5.477±0.013	5.497±0.018	5.456±0.047	5.355±0.038	5.543±0.058
Al^{IV}	2.459±0.039	2.410±0.087	2.450±0.066	2.451±0.028	2.523±0.013	2.503±0.018	2.544±0.047	2.645±0.038	2.568±0.058
Al^{VI}	0.551±0.035	0.504±0.051	0.437±0.039	0.488±0.084	0.500±0.024	0.435±0.051	0.405±0.048	0.689±0.047	0.574±0.036
Ti	0.321±0.018	0.317±0.051	0.278±0.023	0.288±0.048	0.352±0.021	0.367±0.018	0.391±0.024	0.406±0.020	0.409±0.017
Mg	2.398±0.037	2.508±0.070	2.596±0.041	2.418±0.100	2.523±0.053	2.522±0.041	2.557±0.049	2.241±0.046	2.370±0.050
Mn	0.032±0.007	0.033±0.005	0.035±0.003	0.048±0.006	0.049±0.006	0.021±0.004	0.037±0.003	0.010±0.001	0.035±0.009
Fe	2.338±0.029	2.339±0.033	2.404±0.037	2.476±0.044	2.248±0.016	2.379±0.020	2.299±0.043	2.261±0.030	2.227±0.049
Ba	0.015±0.016	0.005±0.005	0.004±0.007	0.006±0.006	0.032±0.009	0.015±0.009	0.029±0.008	0.002±0.001	0.009±0.006
K	1.901±0.022	1.824±0.057	1.907±0.029	1.889±0.044	1.878±0.033	1.819±0.066	1.874±0.035	1.879±0.028	1.885±0.047
Na	0.059±0.010	0.040±0.008	0.042±0.008	0.052±0.013	0.036±0.007	0.036±0.008	0.042±0.012	0.048±0.007	0.042±0.023

TiO_2 wt.% (2.4 - 3.1%) than those from the biotite-granodiorite (3.2 - 3.6%). The highest TiO_2 biotite values are observed in those samples (SG-16 and 40) which are geographically closest to the Sebago granite. In addition to the variation in TiO_2, there is also good discrimination between biotites from both petrographic types based on their MnO concentrations. Biotites from the BHS-granodiorite have, on average, higher MnO wt.% (0.25 - 0.39%) than their counterparts in the biotite-granodiorite (0.08 - 0.29%).

Further conclusions from the biotite data given in Table 1 are: (1) Samples SG-23 and 34, which may be intermediate varieties, have biotite TiO_2 values in between those of biotite from the two main Songo types. (2) Within the BHS-granodiorite there is a trend of decreasing biotite TiO_2 values with increasing SiO_2 contents of the host whole-rock (see also Fig. 5). (3) Fe/Fe+Mg ratios for all the biotites from the Songo pluton are fairly constant and have a restricted range of values (0.473-0.506).

Figures 4a-d are plots of individual biotite oxide pairs on a series of variation diagrams. It is apparent from these plots that there is overall continuous variation in the composition of biotites from the Songo pluton. This would tend to support the suggestion that there is a gradation between the two Songo types. It is significant, however, that the data plot in two distinct groups, each corresponding to the petrographic varieties. This distinction is primarily based on differences in TiO_2 concentrations. For example, Figure 4d shows that for a given Fe/Fe + Mg ratio, biotites from the biotite-granodiorite have significantly higher TiO_2 levels than those of the BHS-granodiorite. Only when Ti and Mn are considered jointly (Fig. 4c) is there almost complete separation of the two sets of biotite data. Furthermore, there is a general trend of decreasing Mn with increasing Ti through the entire biotite sequence.

The general relationship between biotite chemistry and whole-rock compositions is shown on a plot of biotite TiO_2 versus SiO_2 wt.% of the host rock (Fig. 5). As noted above, there is a general decrease of biotite TiO_2 with increasing SiO_2 of the host within the BHS-granodiorites, except for SG23 which is possibly an intermediate sample. In contrast, biotite TiO_2 levels remain fairly constant in the biotite-granodiorites and even SG-40, which has one of the most evolved whole-rock compositions of the entire Songo pluton (SiO_2 = 71%), has biotite TiO_2 wt.% similar to SG-5 which has a SiO_2 whole-rock value of 64 wt.%.

The electron microprobe data for the biotites confirm the petrographic subdivision described above. Biotites from the biotite-granodiorite have significantly higher TiO_2 concentrations and lower MnO values than those from the BHS-granodiorite. The data also support the suggestion that there is a gradation between the two varieties of the Songo pluton.

WHOLE-ROCK GEOCHEMISTRY

Whole-rock geochemical data for 39 Songo granodiorites are presented in Table 2 and also in summarized form in Table

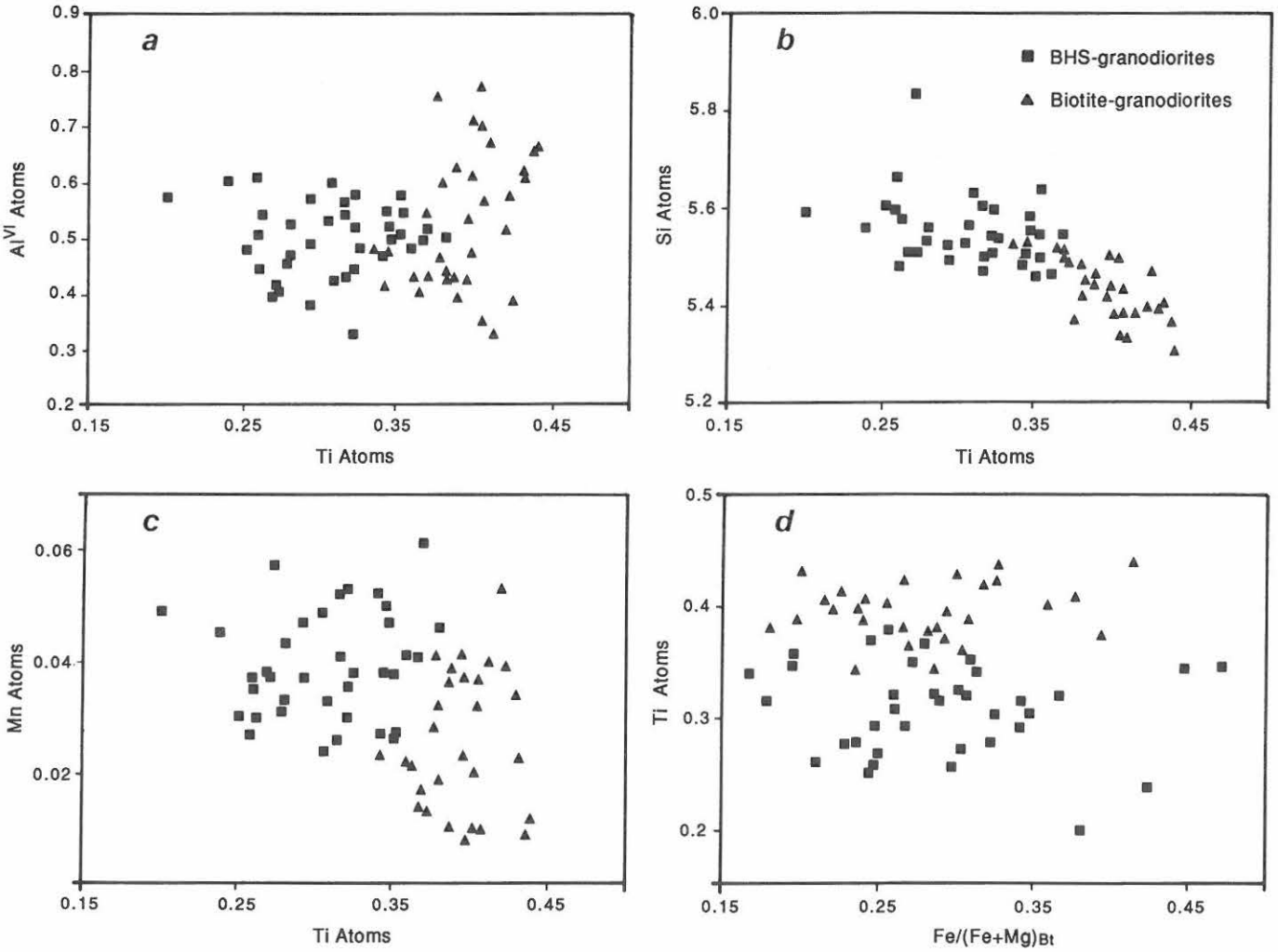

Figure 4. Bivariate plots of individual biotite oxide pairs. Figures 4a,b and c are of Al^{vi}, Si, and Mn atoms per formula unit versus Ti atoms per formula unit; 4d is of Ti atoms per formula unit against Fe/(Fe+Mg)Biot. Note the overall continuous trends in biotite composition on all the diagrams and the distinction between biotites from the BHS-granodiorites and the biotite-granodiorites.

3. Results for samples of the two-mica granite, which is associated with the pegmatites within the Songo pluton and data for the Sebago granite, are given in Table 4 and discussed below. The major and trace element data for the Songo granodiorites are plotted on a series of bivariate diagrams (Fig. 6 and 8) using SiO_2 as a fractionation index.

Table 3 shows that there is a significant amount of major element compositional variation within the Songo pluton. SiO_2 levels range from 57.5 to 71 wt.%, though the majority of samples fall within the range 61 to 68 wt.%. TiO_2, Fe_2O_3 (total), and CaO also vary significantly within the pluton. The data show that there is considerable compositional overlap between the two petrographic varieties. The BHS-granodiorites have generally less evolved chemistries. On average they contain lower SiO_2 and higher Al_2O_3, TiO_2, Fe_2O_3 (total), MnO, MgO, CaO, and P_2O_5 wt.% compared to the biotite-granodiorites. Furthermore, the BHS-granodiorites have generally lower Larsen Index and molecular A/CNK values than their biotite-granodiorite counterparts (see Table 3).

From examination of the whole-rock analyses and accompanying sample localities, it does not appear that the Songo pluton is zoned in any regular fashion. That is to say it does not display comparable systematic petrographic and geochemical variations observed in many symmetrically zoned plutons, e.g. the Loch Doon pluton, Scotland (Tindle and Pearce, 1981) or the Center Pond pluton, Maine (Scambos et al., 1986). Nevertheless, samples from the central and southwestern part of the pluton (e.g. SG-59, -2, -14 and -11), independent of their petrographic variety, do have more evolved chemistries (SiO_2 > 65%, TiO_2 <0.75%, L.I. > 15) compared to samples from the north and northeastern outcrops of the intrusion (e.g. SG-19, -6, -7 and -36). The latter, which are all BHS-granodiorites, have distinctly

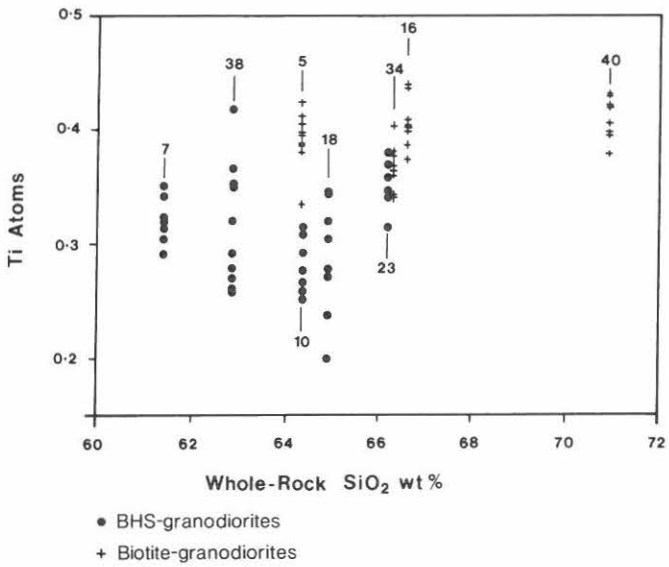

Figure 5. Plot of Ti atoms per formula units for biotites against SiO_2 wt. % of their host whole-rocks. Sample numbers are the same as those given in Table 2.

less evolved compositions. Therefore, it does appear that the central and southwestern parts of the Songo pluton are more felsic, at least on the basis of major element geochemistry.

The major element Harker diagrams (Fig. 6) reveal that the Songo granodiorites define single, essentially continuous compositional trends that have linear correlations with SiO_2. All the major elements (except for Na_2O and K_2O) decrease as SiO_2 levels increase through the series, with correlation coefficients ranging from -0.71 for MnO to -0.92 for CaO. Na_2O increases slightly through the series as SiO_2 rises, but K_2O does not appear to vary systematically through the pluton. Figure 6 also illustrates the extent to which the BHS-granodiorites and biotite-granodiorites overlap in composition, and the more evolved chemistry of some samples of the latter facies.

Figure 7, a plot of molecular A/CNK against SiO_2 wt.%, again shows that the two Songo varieties overlap in composition. The majority of samples have values between 1 and 1.1, but some biotite-granodiorites have ratios >1.1. There appears to be a slight, overall increase in A/CNK ratios with increasing SiO_2 wt.% through the Songo series.

In addition to the major element compositional variation described above, there are also differences in trace element concentrations within the Songo pluton. Table 3 reveals, however, that there is even less geochemical discrimination between the two petrographic varieties when the trace elements are considered, with many parameters almost totally overlapping. There is some trace element distinction between the two Songo types with the BHS-granodiorites having higher Sr and Ba ppm contents and slightly higher levels of Rb, Zr, Zn, and Ni ppm than the biotite-granodiorites. Nb, Th, and Y ppm are fairly constant throughout the pluton.

Trace element concentrations were also plotted on variation diagrams, but they generally lack systematic variation when plotted against SiO_2 wt.% or indeed any other fractionation index (e.g. Larsen Index or K/Rb ratios). Only plots of Rb, Sr, Zr, and Zn are presented here (Fig. 8), as the other trace elements are either fairly constant or lack any coherent trends. Figure 8 shows that Rb generally increases through the BHS-granodiorites, but that there is greater scatter in many of the more evolved biotite-granodiorite samples. In general, Sr ppm is constant in the BHS-granodiorites, but declines in some biotite-granodiorites. Only Zr and Zn vary systematically with SiO_2, both decreasing in abundance through the Songo sequence as SiO_2 increases. In general therefore, these trace element trends are in marked contrast to the linear trends observed on the major element bivariate diagrams.

DISCUSSION

The petrographic and geochemical variations of the Songo pluton may have been produced by a magmatic process(es) at the time of emplacement, as a result of post-crystallization modification, or by a combination of these mechanisms. The most likely cause of any post-crystallization modification would be the metamorphic event associated with the emplacement of the Sebago granite at around 325 Ma. The possibility that the petrographic and geochemical variations were produced independently (at different times) must also be explored. The main factors in assessing the origin of the internal variations of the Songo pluton are, (1) the disposition of and relationship between the petrographic varieties, (2) the nature of the geochemical variations within the pluton, and (3) the possible effects of the intrusion of the Sebago granite.

The distribution of the two Songo petrographic varieties has been described above. The major observation is that the biotite-granodiorites are spatially related to the outcrop pattern of the Sebago granite (Fig. 2). Away from the latter, biotite-granodiorites occur near the larger pegmatites.

The relationship between the Sebago granite and the pegmatites is unclear. The preponderance of the latter in western Maine has been linked to the proposal that the Sebago granite underlies much of the area (Guidotti et al., 1986). A model which depicts pegmatitic fluids streaming off the upper (top) surface of the Sebago magma is reasonable, but difficult to test. A possible solution might be to examine the leucocratic two-mica granites which are often associated with the pegmatites. These may be small pockets of "Sebago-type" magma, associated with the pegmatitic fluids or alternatively they may be batches of local anatectic melt. Table 4 presents analyses of two samples of leucocratic granite and for comparison the range of analyses for 21 samples of the Sebago granite. The data for the leucocratic granites usually fall within the range of the Sebago analyses and there is some geochemical affinity. However, this is not proof that they are comagmatic with the Sebago granite. Investigation

TABLE 2. MAJOR AND TRACE ELEMENT ANALYSES (XRF) OF THE SONGO GRANODIORITES.
$Fe_2O_3(T)$ = total iron measured as Fe_2O_3; L.I. - Larsen Index (= 1/3 SiO_2 + K_2O - Fe_2O_3 + MgO + CaO) (Larsen, 1938);
A/CNK = Molecular Al/Molecular Ca + Na + K; N + K wt % = total alkalis. BDL - below detection limits. Samples with an asterisk are biotite-granodiorites.

	SG-1	SG-2	SG-3	SG-6	SG-7	SG-10	SG-15	SG-17	SG-18	SG-19	SG-20	SG-23	SG-29
SiO_2	63.84	65.86	57.53	60.61	61.39	64.35	62.23	61.84	64.9	61.9	63.86	66.17	62.32
Al_2O_3	16.97	16.79	19.03	18.65	17.8	16.27	17.56	17.47	16.66	17.04	17.04	16.75	17.75
TiO_2	0.755	0.643	1.048	0.896	0.921	0.801	0.954	0.905	0.696	0.83	0.793	0.688	0.848
Fe_2O_3T	4.12	3.72	5.87	4.51	5.13	4.38	4.52	4.89	3.77	5.02	4.49	3.74	4.95
MnO	0.072	0.07	0.079	0.066	0.08	0.08	0.063	0.079	0.067	0.079	0.074	0.074	0.071
MgO	1.78	1.63	3.14	2.45	2.47	1.93	2.21	2.41	1.53	2.31	2.06	1.63	2.07
CaO	4.09	3.64	5.16	4.29	4.66	4.01	4.67	5.05	3.67	4.72	4.43	3.49	4.5
Na_2O	3.77	4.09	3.39	3.67	3.53	3.51	3.64	3.34	3.63	3.58	3.49	3.94	3.51
K_2O	2.99	2.24	2.9	3.19	2.4	3.36	2.38	2.37	3.8	2.85	2.14	2.39	2.44
P_2O_5	0.24	0.179	0.736	0.383	0.315	0.219	0.352	0.28	0.272	0.295	0.261	0.232	0.315
Total	98.63	98.86	98.88	98.72	98.69	98.91	98.58	98.63	98.99	98.62	98.64	99.1	98.77
L.I.	14.28	15.2	7.91	12.14	10.6	14.49	11.72	10.63	16.46	11.43	12.45	15.59	11.69
A/CNK	1.005	1.065	1.052	1.079	1.055	0.974	1.029	1.013	0.994	0.971	1.058	1.087	1.069
N+Kwt%	6.76	6.33	6.29	6.86	5.93	6.87	6.02	5.71	7.43	6.43	5.63	6.33	5.95
Rb ppm	112	103	146	164	130	109	75	83	112	100	100	129	111
Sr	610	496	609	609	631	598	1030	672	645	627	803	543	645
Ba	848	527	772	978	676	925	965	820	935	883	1056	545	1028
Zr	171	143	152	161	208	180	197	191	173	196	189	157	259
Th	11	7	4	BDL	10	12	7	8	14	7	8	15	16
Zn	64	61	118	79	86	65	70	68	58	70	67	67	84
Y	21	18	22	14	19	27	19	32	20	20	19	20	16
Nb	14	15	14	14	15	18	14	19	15	11	13	14	10
Ni	21	16	30	24	24	29	19	44	15	23	20	14	4

	SG-30	SG-35	SG-36	SG-38	SG-47	SG-48	SG-52	SG-53	SG-59	SG-4*	SG-5*	SG-8*	SG-9*
SiO_2	64.72	66.23	61.6	62.83	67.72	63.15	63.36	66.88	66.68	63.7	64.29	70.18	64.24
Al_2O_3	17.74	16.32	16.88	16.87	16.66	16.62	16.45	16.39	16.06	17.67	16.67	15.53	17.69
TiO_2	0.693	0.685	0.975	0.874	0.644	0.904	0.926	0.704	0.715	0.72	0.803	0.404	0.671
Fe_2O_3T	4.12	3.82	5.33	5.12	3.28	5.06	5.06	3.53	3.8	4.25	4.44	2.48	3.83
MnO	0.072	0.065	0.086	0.079	0.054	0.082	0.085	0.059	0.067	0.064	0.072	0.044	0.062
MgO	1.9	2.15	2.57	2.16	1.52	2.3	2.43	1.55	1.55	2.53	2.55	1.12	1.59
CaO	4.19	3.91	4.91	4.67	3.36	4.49	4.55	3.53	3.69	4.3	4.36	2.69	3.77
Na_2O	3.35	3.34	3.24	3.51	3.55	3.56	3.31	3.68	3.47	3.25	3.06	3.56	3.56
K_2O	2.21	2.65	2.77	2.6	3.25	2.65	2.32	2.94	3.27	2.17	2.15	3.25	3.23
P_2O_5	0.251	0.205	0.323	0.291	0.224	0.316	0.329	0.249	0.246	0.227	0.262	0.129	0.234
Total	99.25	99.38	98.68	99.0	100.26	99.13	98.82	99.51	99.55	98.88	98.66	99.39	98.88
L.I.	13.57	14.85	10.49	11.59	17.66	11.85	11.4	16.62	16.46	12.32	12.23	20.35	15.45
A/CNK	1.143	1.055	0.978	0.988	1.077	0.984	1.014	1.047	1.007	1.139	1.091	1.089	1.092
N+Kwt%	5.56	5.99	6.01	6.11	6.8	6.21	5.63	6.62	6.74	5.42	5.21	6.81	6.79
Rb ppm	115	96	92	88	108	95	105	115	111	90	94	124	110
Sr	617	548	669	672	802	627	671	617	649	544	602	381	604
Ba	1122	846	938	825	1042	653	1054	661	893	346	858	700	1416
Zr	245	154	214	217	152	210	217	156	189	146	176	121	192
Th	16	9	12	5	12	12	6	17	14	6	16	12	16
Zn	76	63	76	75	54	82	75	57	60	73	67	43	72
Y	18	17	21	22	10	16	19	24	20	30	21	16	14
Nb	12	8	12	15	11	11	12	16	15	11	17	11	10
Ni	5	22	31	20	13	26	25	12	14	29	33	15	3

TABLE 2. CONTINUED.

	SG-11*	SG-12*	SG-13*	SG-14*	SG-16*	SG-33*	SG-34*	SG-40*	SG-43*	SG-46*	SG-49*	SG-51*	SG-58*
SiO_2	69.65	64.19	65.51	65.16	66.58	66.35	66.29	70.9	64.73	67.05	64.34	64.88	66.83
Al_2O_3	15.78	17.04	17.07	17.54	16.19	17.05	16.74	14.77	16.56	15.66	17.21	17.63	16.39
TiO_2	0.581	0.817	0.678	0.601	0.658	0.598	0.767	0.505	0.871	0.764	0.805	0.706	0.694
Fe_2O_3T	3.07	4.42	3.8	3.68	3.88	3.35	4.04	2.89	4.57	4.14	4.66	3.89	4.12
MnO	0.053	0.073	0.062	0.056	0.052	0.048	0.056	0.058	0.069	0.066	.0.69	0.062	0.045
MgO	1.25	2.19	1.45	1.45	1.71	1.2	2.08	1.43	2.33	2.03	1.85	1.78	1.72
CaO	3.25	4.42	3.75	3.96	3.29	3.51	3.95	2.76	4.28	3.72	4.26	4.06	3.21
Na_2O	3.58	3.35	3.6	3.64	3.72	3.61	3.74	3.41	3.13	3.47	3.35	3.43	3.95
K_2O	2.29	2.25	2.69	2.59	2.36	3.39	1.83	2.78	2.34	1.99	2.3	2.57	1.99
P_2O_5	0.129	0.245	0.263	0.248	0.312	0.278	0.256	0.139	0.315	0.239	0.246	0.251	0.23
Total	99.63	98.99	98.87	98.93	98.75	99.38	99.75	99.64	99.2	99.13	99.09	99.26	99.18
L.I.	17.94	12.62	15.53	15.22	15.67	17.45	13.86	19.33	12.74	14.45	12.98	14.47	15.22
A/CNK	1.105	1.066	1.091	1.097	1.105	1.067	1.093	1.083	1.071	1.071	1.093	1.116	1.312
N+Kwt%	5.87	5.6	6.29	6.23	6.08	7.0	5.57	6.19	5.47	5.46	5.65	6.0	5.94
Rb ppm	93	111	112	108	121	140	85	97	110	108	109	109	123
Sr	512	644	629	606	544	530	689	475	683	480	489	618	398
Ba	501	947	1001	1240	466	1043	925	1054	911	264	372	989	249
Zr	139	161	174	193	149	130	182	141	200	225	211	201	167
Th	BDL	3	10	5	10	4	9	7	7	4	3	12	10
Zn	53	66	63	64	68	54	55	44	74	77	76	70	84
Y	13	23	22	12	18	20	15	16	19	10	12	12	15
Nb	11	16	14	10	14	15	13	10	15	11	12	11	16
Ni	7	24	9	4	19	5	18	25	23	18	6	8	15

of the isotopic systematics of these leucocratic granites might further constrain their origin, especially because the Sebago granite has distinctive Sr and O isotopic values. It is, however, reasonable to expect that at least some of the pegmatites were derived from the Sebago magma.

Much of the data presented above strongly suggest that the two petrographic varieties grade into each other - no intrusive contact is observed. Several lines of evidence support this view: (1) Petrographic observations detailed above reveal that certain samples from localities in between the main Songo types have "intermediate" petrographic characteristics. (2) There is continuous variation of biotite TiO_2 values (Fig. 4) from samples of both petrographic varieties, including data for the intermediate examples. (3) There is a lack of compositional hiatuses on any major or trace element bivariate plots (Figs. 6 and 8). The likelihood that the boundary between the two Songo types is gradational, rather than an intrusive contact, implies that the petrographic varieties do not represent the crystallized products of separate intrusive magma batches and thus the Songo pluton is not a composite body.

The geochemical data for the Songo pluton provide further insight into the origin of the internal variations of this intrusion. As noted above, the BHS-granodiorites and the biotite-granodiorites are generally not geochemically distinctive and there are continuous major element trends. Thus it appears that the Songo pluton probably crystallized from a single magma batch. The fact that there is no major distinction between the petrographic varieties and their geochemistry may also suggest that the process(es) which produced them were temporally distinct.

Compositional variation within granitoid plutons has been assigned to a variety of processes such as (1) fractional crystallization of a primary basic/intermediate magma, (2) assimilation of crustal material by a primary magma, (3) mixing of two independently derived magmas, or (4) a restite unmixing process as described by White and Chappell (1977). Distinction between these mechanisms often relies heavily on the levels and variations of the trace elements as they are more sensitive indicators of fractionation processes than the major elements. In the case of the Songo pluton any discussion of these magmatic processes is seriously restricted by the general lack of regular trace element trends within the pluton.

Nevertheless, the restite unmixing process can be largely ruled out. The Songo pluton lacks many of the recognized petrographic characteristics of this mechanism such as abundant dioritic inclusions, mottled plagioclase cores, and acicular apatites (see White and Chappell, 1977). Furthermore, it is difficult to explain both the distribution of petrographic variations within the pluton and the lack of coherent trace element trends by a magma mixing process.

Fractional crystallization may be the most favorable process responsible for the geochemical variations of the Songo pluton. The declining levels of CaO, TiO_2, and P_2O_5 with increasing SiO_2 contents may represent the fractionation of plagioclase, sphene + Fe-Ti oxides, and apatite respectively. The only systematic variation in trace element levels, Zr and Zn, might be

TABLE 3. SUMMARY OF MAJOR AND TRACE ELEMENT, L.I. AND MOLECULAR A/CNK RESULTS FOR THE SONGO PLUTON. Mean and standard deviation values on top line, min.-max. in brackets.

	SONGO GDs (N=39)	BHS-GDs (N=22)	Bt.-GDs (N=17)
SiO_2 wt%	64.74 ± 2.60	63.64 ± 2.38	66.17 ± 2.14
	(57.53 70.90)	(57.53 67.72)	(63.7 70.9)
Al_2O_3	16.89 ± 0.81	17.08 ± 0.74	16.66 ± 0.82
	(14.77 19.03)	(16.06 19.03)	(14.77 17.69)
TiO_2	0.76 ± 0.13	0.81 ± 0.12	0.69 ± 0.12
	(0.40 1.05)	(0.64 1.05)	(0.40 0.87)
Fe_2O_3T	4.19 ± 0.71	4.47 ± 0.67	3.85 ± 0.59
	(2.48 5.87)	(3.28 5.87)	(2.48 4.66)
MnO	0.067 ± 0.011	0.073 ± 0.008	0.059 ± 0.009
	(0.044 0.086)	(0.054 0.086)	(0.044 0.073)
MgO	1.95 ± 0.45	2.08 ± 0.41	1.78 ± 0.44
	(1.12 3.14)	(1.52 3.14)	(1.12 2.55)
CaO	4.03 ± 0.59	4.26 ± 0.52	3.74 ± 0.53
	(2.69 5.16)	(3.36 5.16)	(2.69 4.42)
Na_2O	3.53 ± 0.21	3.55 ± 0.19	3.49 ± 0.22
	(3.06 4.09)	(3.24 4.09)	(3.06 3.95)
K_2O	2.62 ± 0.46	2.73 ± 0.43	2.48 ± 0.45
	(1.83 3.80)	(2.14 3.80)	(1.83 3.39)
P_2O_5	0.269 ± 0.093	0.296 ± 0.108	0.235 ± 0.054
	(0.129 0.736)	(0.179 0.736)	(0.129 0.315)
L.I.	14.02 ± 2.62	13.14 ± 2.47	15.17 ± 2.35
	(7.91 20.35)	(7.91 17.66)	(12.23 20.35)
A/CNK	1.06 ± 0.05	1.03 ± 0.04	1.09 ± 0.02
	(0.97 1.14)	(0.97 1.14)	(1.07 1.14)
Tot. Alk.	6.15 ± 0.53	6.28 ± 0.48	5.98 ± 0.51
	(5.21 7.43)	(5.56 7.43)	(5.21 7.00)
Rb ppm	109 ± 17	109 ± 20	108 ± 14
	(75 164)	(75 164)	(85 140)
Sr	611 ± 111	654 ± 106	555 ± 88
	(381 1030)	(496 1030)	(381 689)
Ba	828 ± 261	863 ± 163	781 ± 344
	(249 1416)	(527 1122)	(249 1416)
Zr	180 ± 31	188 ± 31	171 ± 29
	(121 259)	(143 259)	(121 225)
Th	9 ± 4	10 ± 4	8 ± 4
	(BDL 17)	(BDL 17)	(BDL 16)
Zn	69 ± 13	72 ± 13	65 ± 11
	(43 118)	(54 118)	(43 84)
Y	19 ± 5	20 ± 4	17 ± 5
	(10 32)	(10 32)	(10 30)
Nb	13 ± 2	14 ± 2	13 ± 2
	(8 19)	(8 19)	(10 17)
Ni	18 ± 9	21 ± 9	15 ± 9
	(<5 44)	(<5 44)	(<5 33)

explained by the continuous removal of zircon and perhaps hornblende. The fact that the Songo pluton lacks any obvious combined petrographic and geochemical variations, which are commonly observed in zoned plutons and would probably result from this process, is a drawback to this model. However it may be that the later emplacement of the Sebago granite overprinted/destroyed any systematic petrographic and compositional variation. The more felsic central and southwestern parts of the pluton as described above might be the remnants of such combined variations.

It is difficult, however, to explain both the geochemical and petrographic variations of the Songo pluton by a fractional crystallization mechanism alone. The fact that the petrographic varieties overlap geochemically argues against the biotite-granodiorites being differentiates of the BHS-granodiorites. However, this does not rule out the possibility that the mineralogical variations may have been superimposed on a fractional crystallization series.

An alternative model is that the Songo pluton represents a fractionally crystallizing I-type magma which had been con-

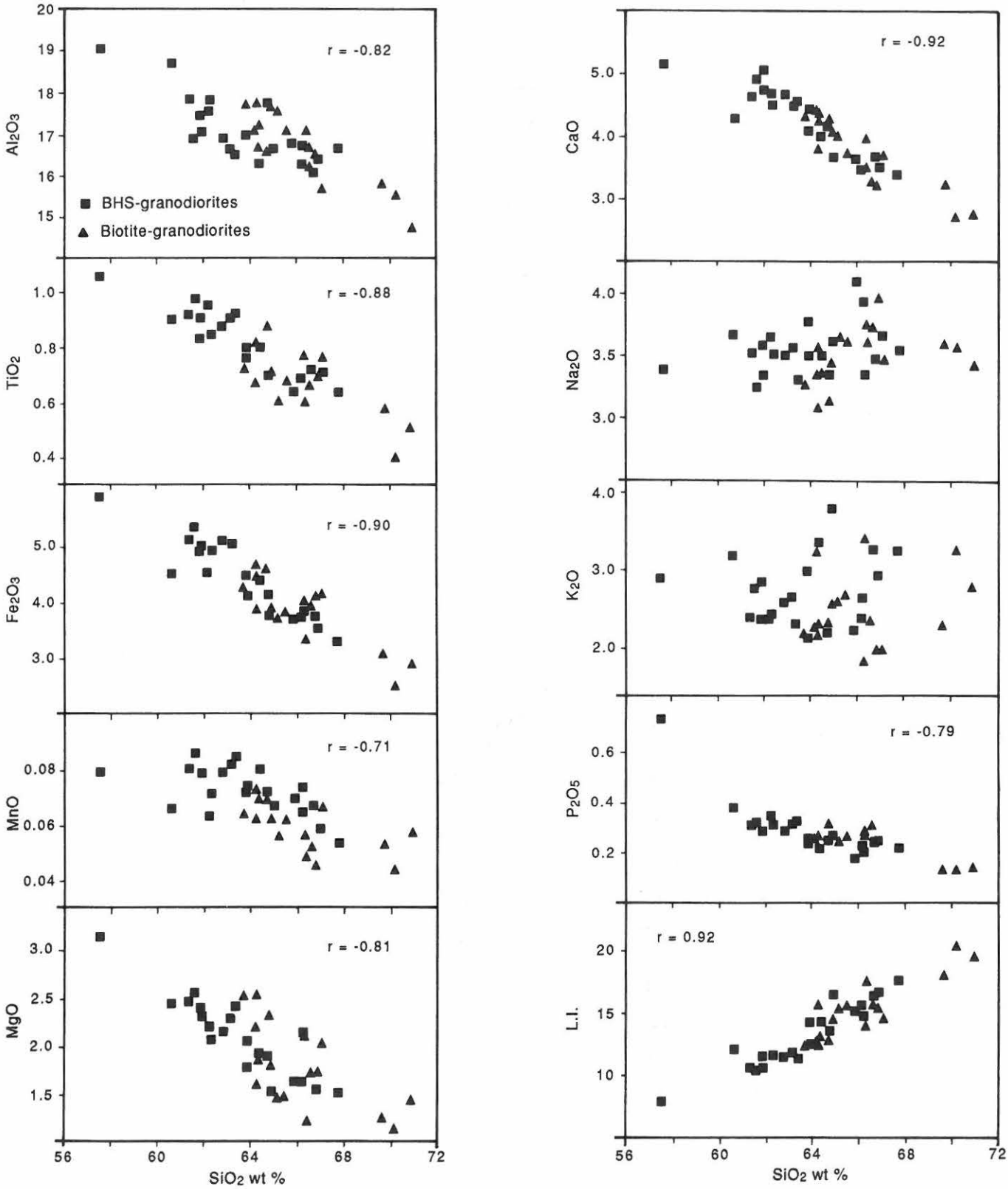

Figure 6. Major element Harker diagrams for the Songo granodiorites. The correlation coefficient (r) is given for each of the oxides (except Na_2O and K_2O). L.I. = Larsen Index (i.e. 1/3 SiO_2 + K_2O - Fe_2O_3(T) + MgO + CaO) (Larsen, 1938). (Some data points omitted due to overlap).

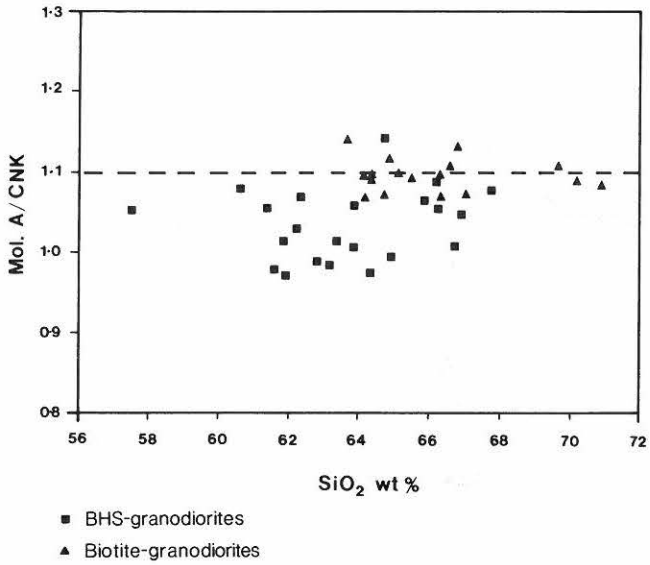

Figure 7. Molecular Al/molecular Ca + Na + K (A/CNK) plotted against SiO_2 wt. % for the Songo granodiorites. Note that some biotite-granodiorites have A/CNK > 1.1.

TABLE 4. GEOCHEMICAL DATA FOR TWO SAMPLES OF THE LEUCOCRATIC GRANITE OBSERVED WITHIN THE SONGO PLUTON AND, FOR COMPARISON, THE RANGE IN COMPOSITION OF 21 SAMPLES OF THE SEBAGO GRANITE (GIBSON, UNPUBLISHED DATA).

	85-45	85-50	SEBAGO DATA MIN.	MAX.
SiO_2	73.58	75.5	71.31	75.83
Al_2O_3	14.53	15.03	14.62	16.11
TiO_2	0.285	0.076	0.082	0.362
Fe_2O_3T	1.33	0.68	0.66	2.35
MnO	0.013	0.012	0.016	0.097
MgO	0.52	0.12	0.15	0.64
CaO	0.9	0.52	0.78	2.66
Na_2O	2.94	4.22	2.71	4.49
K_2O	6.24	4.49	2.84	6.41
P_2O_5	0.103	0.13	0.058	0.434
Total	100.44	100.78	--	--
L.I.	28.02	28.34	21.22	27.76
A/CNK	1.099	1.179	1.00	1.46
N+Kwt%	9.18	8.71	6.20	9.39
Rb ppm	211	332	91	434
Sr	207	19	48	455
Ba	526	BDL	13	879
Zr	225	28	53	250
Th	33	3	BDL	41
Zn	53	45	<5	80
Y	14	12	BDL	42
Nb	10	11	<5	36
Ni	BDL	BDL	BDL	BDL

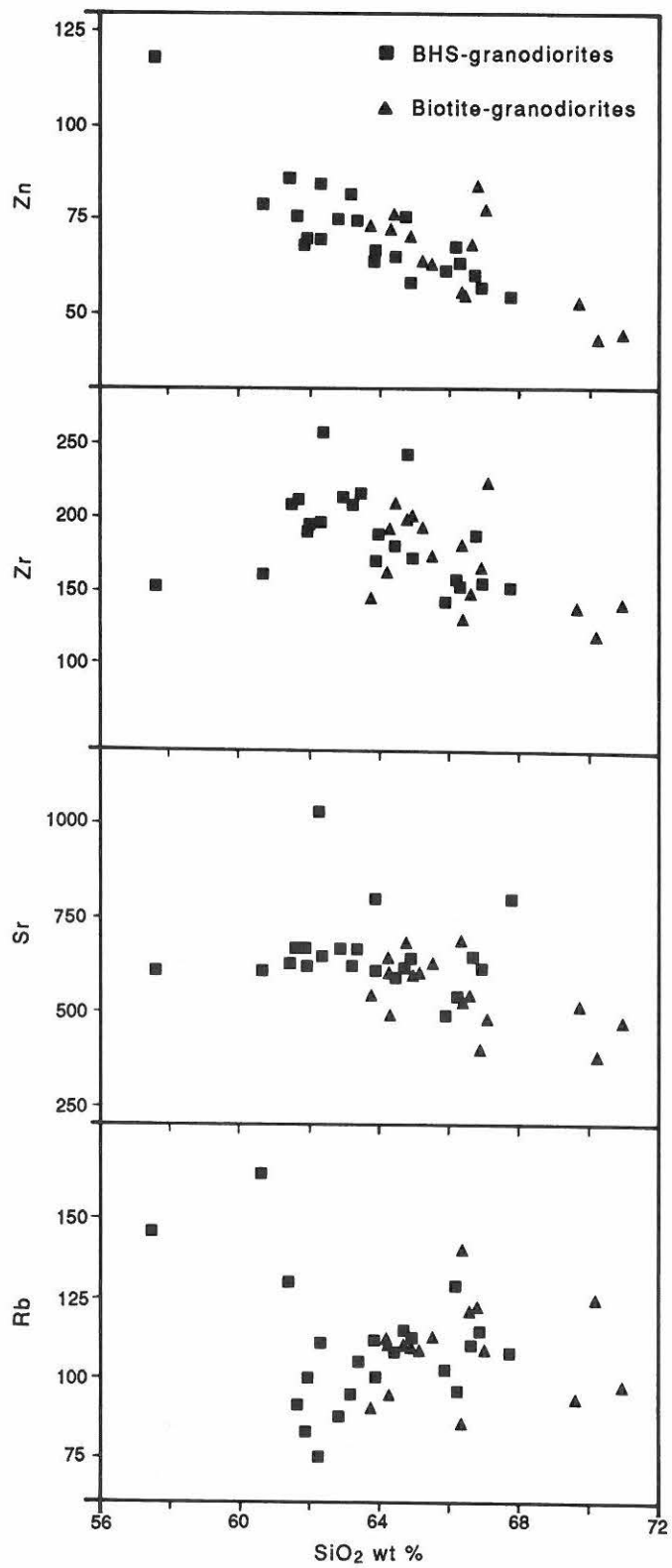

Figure 8. Plots of Rb, Sr, Zr, and Zn ppm versus SiO_2 wt. % for the Songo granodiorites.

taminated with crustal material. This might explain both the geochemical and petrographic variations, in that assimilation of aluminous metasedimentary xenoliths could increase the A/CNK ratio and also increase the stability field of biotite relative to hornblende. The increase in TiO_2 in biotite from the biotite-granodiorite may indicate that there was not another Ti-bearing phase crystallizing from the melt in certain parts of the pluton. This, however, does not explain the overall spatial distribution of the biotite-granodiorite or indeed the irregular trace element trends. It is hoped that ongoing research of the Sr and O isotopic systematics of the Songo pluton will help to further test this model.

One of the main problems in discussing the geochemical aspects of the pluton is the different behavior of the major and trace elements. Whereas the major elements vary regularly through the Songo pluton, the trace elements generally lack coherent trends. Any magmatic process such as fractional crystallization or restite unmixing which produced major element variations would invariably have resulted in systematic changes in trace element levels. Assuming this was the case, it appears therefore that the distribution of trace elements within the Songo pluton may have been subsequently altered.

Another model which should be considered is the effect of changes in the intensive variables (pH_2O, fO_2, T, and P) during crystallization on biotite composition. Speer (1987) has shown that petrographic variations in the Liberty Hill pluton, South Carolina can be explained by changes in the intensive variables as opposed to differentiation or multiple intrusion mechanisms. Significantly though, Speer states that biotites from the Liberty Hill pluton are generally similar in composition. This is in contrast to the compositional variation observed in the Songo biotites. Indeed, the variation of biotite composition within the BHS-granodiorites may point to a differentiation mechanism (see Fig. 5 and Table 1). However, more detailed electron microprobe data for the Fe-Ti oxides and hornblende would be necessary to examine any changes of the intensive parameters during the crystallization of the Songo pluton.

The effects of the emplacement of the thin (ca. 1 km), laterally extensive Sebago granite resulted in widespread metamorphism in western Maine (Lux and Guidotti, 1985). Temperatures within the Songo pluton were raised above the argon closure temperature for hornblende (500°C) as evidenced by their reset $^{40}Ar/^{39}Ar$ ages (Lux et al., this volume). In addition, abundant pegmatites, which were probably derived from the underlying Sebago magma, intruded the Songo pluton. Evidently there was considerable fluid migration through the pluton. It is suggested that this combination of reheating and widespread fluid migration may have resulted in the formation of the biotite-granodiorites in those parts of the Songo pluton closest to the Sebago granite or the pegmatites. In effect, the Sebago granite could have modified parts of this essentially I-type granodiorite by a process similar to that which produced K-feldspar + sillimanite-grade metamorphism in the country rocks.

Two further lines of evidence suggest that the thermal effects of the Sebago granite might have produced the petrographic variations evident in the Songo pluton. Firstly, Lux et al. (this volume) have shown that the Rb-Sr whole-rock isotopic systematics for the Songo pluton have been disturbed. They suggest that scatter in $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ data, especially among the biotite-granodiorites (see their Fig. 2), could be due to open-system trace element mobility coincidental with the thermal event associated with the emplacement of the Sebago granite.

Secondly, the variation in biotite chemistry within the Songo pluton may also point to the Sebago granite as the cause of the petrographic variations. Specifically, Figure 4c identifies a general trend of decreasing MnO and increasing TiO_2 contents in the biotites of the pluton. In fact these parameters almost discriminate between biotites from both petrographic varieties. Deer et al. (1975) state that the composition (and color) of biotite varies with metamorphic grade, and frequently a decrease in MnO (and Fe^{2+}, Fe^{3+}) and an increase in TiO_2 and MgO can be correlated with increasing metamorphic grade. This is the trend which is observed on a localized scale within the Songo pluton, as the highest Ti-lowest Mn biotite values are observed adjacent to the contacts with the Sebago granite. In fact, Guidotti (1984) recognized a general trend of increasing Ti in biotites with increasing grade of metamorphism from the rocks of western Maine. It would appear that this trend is also recognized from within the Songo pluton itself.

SUMMARY

The important conclusions of this study are as follows:

(1) The pluton can be subdivided into two petrographic varieties. The BHS-granodiorite has an I-type assemblage (biotite, + hornblende and sphene), whereas the biotite-granodiorite contains only Ti-rich biotite. Several lines of evidence suggest that there is a gradation between these two petrographic varieties.

(2) The two facies of the Songo pluton outcrop in distinct areas. The biotite-granodiorites are exposed in the central and southern parts of the pluton adjacent to the Sebago granite and also occur near large pegmatitic bodies. It is inferred that at least some of the latter were derived from the Sebago granite.

(3) Biotite mineral chemistry supports the petrographic subdivision of the Songo pluton and the gradation between the two Songo types. In addition, the trend of decreasing MnO with increasing TiO_2 values for the Songo biotites is similar to that observed for metamorphic rocks with increasing grade of metamorphism.

(4) Geochemical data reveal that neither petrographic variety is distinct, and therefore the Songo pluton is probably not a composite intrusion. The major elements vary systematically, having linear continuous trends with SiO_2. The trace elements, however, generally lack coherent trends and may have experienced open-system mobility.

The main conclusion of this study is that parts of the Songo pluton may have been subsequently modified by the later emplacement of the Sebago granite and pegmatites derived therefrom. A combination of reheating and fluid migration could have resulted in changes in biotite chemistry, thus producing the observed petrographic variation. In addition, this thermal event may have caused open-system mobility of trace elements and disturbance of the Rb-Sr isotopic system. The uncoupled nature of the petrographic and compositional variations suggests that they were produced at different times. In effect, the major element geochemistry of the pluton has been largely preserved but the mineralogy of parts of the Songo pluton has been altered.

The Songo pluton may therefore represent an I-type granodiorite which has been modified by a later thermal event. A similar situation may also have occurred in the southern parts of the Mooselookmeguntic pluton which also contains red/brown biotites and has suffered the metamorphic effects of the Sebago granite.

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