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The Commingling of Diverse Magma Types in the Flagstaff Lake Igneous Complex

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ABSTRACT

The Flagstaff Lake Igneous Complex is a member of an array of Acadian plutons which extend from the Katahdin batholith in the northeast to New Hampshire in the southwest. It is characterized by four major rock types: (1) gabbro, (2) granite, (3) garnet tonalite, and (4) trondhjemite. Field, petrographic, and geochemical evidence support the hypothesis that these diverse rocks existed as contemporaneous liquids, and that extensive mixing occurred at the time of emplacement.

The dominant mafic mineral pairs in the gabbros are olivine-clinopyroxene, two pyroxenes, and pyroxene-hornblende. The high Fe, low Ni and Cr contents of most of the gabbro sampled imply that it underwent substantial fractional crystallization prior to and during emplacement. The granitic rocks of the Flagstaff Lake Igneous Complex are heterogeneous, ranging from two-mica granites with equal amounts (~30%) of orthoclase, plagioclase, and quartz, to mafic diorites. These K-feldspar-bearing silicic rocks are exposed over ~40% of the areal extent of the complex.

Trondhjemite containing biotite, plagioclase, cordierite, and quartz, with minor muscovite and K-feldspar, is located along the margins of the intrusion, particularly in areas where the contact between the gabbro and granite intersects aluminous metapelitic wall rocks.

The garnet tonalite is generally located in sections of the complex where the wall rocks are sulfidic, graphitic metasedimentary rocks. The tonalite is characterized by up to 60% almandine garnet, and oscillatory-zoned plagioclase, biotite, quartz, apatite, and zircon. The bodies of garnet tonalite are commonly, but not exclusively, located near the contacts between gabbro and country rock, and truncate the local strike of the country rocks.

Irregular, fine-grained mafic enclaves with biotite-rich rims are common throughout the granite, trondhjemite, and tonalite. This is especially true near the edge of the intrusion, in contrast to many occurrences of gabbro "pillows" (Wiebe, 1973; Taylor et al., 1980; Furman and Spera, 1985) where the mafic enclaves are generally restricted to dike-like chains. Other observations, such as phenocryst trains, schlieren, and large-scale chemical and mineralogical heterogeneity of the igneous body are common along the contacts between the four observed rock types.

INTRODUCTION AND REGIONAL GEOLOGY

The Flagstaff Lake Igneous Complex is one of a series of Acadian plutons that extends across western Maine from New Hampshire northeast to the Katahdin batholith in northern Maine. Along this array of plutons, the depth of emplacement increases from northeast (1-3 km at Katahdin -- Loiselle et al., 1983) to southwest (7-10 km at Pierce Pond -- Lyttle, 1976; and Flagstaff Lake -- Boudette, 1973, 1978). A crosscutting relationship with Acadian isoclinal folds, and isotopic dating of the nearby slightly younger Lexington pluton (Gaudette and Boone, 1985) fix the age of the complex at approximately 400 Ma, after the major tectonic events of the Acadian orogeny.

The Flagstaff Lake Igneous Complex is situated at the southern end of the Lobster Mountain anticlinorium, flanked on the southeast and northwest by the Kearsarge-central Maine and Moose River synclinoria, respectively (Osberg et al., 1985). Major metamorphic units surrounding the complex are the lower Paleozoic Dead River, Carrabassett and Seboomook Formations around the northeastern portion of the complex (Vehrs, 1975), and the Ordovician Quimby and Greenvale Cove Formations around the southwestern part. Regional Acadian chlorite-grade metamorphism is overprinted by a narrow (2 km) contact aureole. Geobarometry on minerals from the contact zone yields pressures in the range of 2-3 kbar (Vehrs, 1975; Lyttle, 1976). The igneous rocks show little evidence of deformation or metamorphism.

The complex can be divided into four main rock types: gabbro, granite, trondhjemite, and garnet tonalite. Gabbroic rocks are concentrated in the northern and southern ends of the complex, covering approximately 60% of the areal extent (Fig. 1), while granitic rocks and trondhjemites dominate the middle third.

Contacts between gabbroic and granitic rocks are gradational and irregular. The granite contains mafic enclaves and gabbro-cored biotite schlieren, while the gabbros contain large (2 cm) xenocrysts of sodic plagioclase feldspar (An_{25-40}) and an overall increase in amphibole and biotite near the contact. Trondhjemite is found exclusively where the gabbro-granite contact intersects the edge of the intrusion, in contact with aluminous metamorphic rocks of the Dead River, Seboomook and Carrabassett Formations.

The garnet tonalites are also generally located at gabbro-country rock contacts, particularly at the extreme northern (Pierce Pond) and southern ends of the complex. These are areas where the gabbro is in contact with Fe-rich, sulfidic, graphitic metasiltstones and metagraywackes of the Quimby and lower Dead River Formations.

From Figure 1, one can see that the complex is crudely zoned. There are many processes which have been called upon to explain individual cases of zonation such as marginal accretion/assimilation (Holmes, 1932; DePaolo, 1981; McBirney, 1980), fractional crystallization and accumulation, autointrusion by a magma of different composition (Ayuso, 1984), and thermo-gravitational diffusion (Hildreth, 1981). Each of these processes place chemical and textural signatures on the suite of rocks produced. In this paper we shall present field, petrographic, and geochemical evidence that shows several of these processes were active in the formation of the present form of the Flagstaff Lake Igneous Complex.

FIELD RELATIONS

In general, the Flagstaff Lake Igneous Complex is concordant with the northeast-southwest regional strike of the metamorphosed sedimentary rocks (Moench, 1971). However, detailed mapping shows that parts of the intrusion truncate the strike of the country rock (Boone, 1973). In those areas, the shape of the contacts appear irregular on a scale of tens to hundreds of meters. An example from the southern end of the complex is illustrated in Figure 2. The scale of the irregularity of the contact varies greatly, from none, to that shown in Figure 2. However, the largest bodies of both tonalite (Fig. 2) and trondhjemite (Boone, 1973) are found in areas with the most convolute contacts.

Within a few tens of meters of the contact, the metamorphic rocks show progressive development of migmatites together with veins of granite or trondhjemite. The proportion of leucosome to melanosome, and the incidence of veins, increases steadily as one approaches the complex. At approximately 40-60% leucosome, the rock becomes a breccia and grades into the igneous body (Fig. 3a,e). Stoped blocks of metamorphic rocks, generally less than 4 m in size, are common within a few hundred meters of the contact. However, they are almost totally absent from the center of the complex. In addition, unlike many of the surrounding intrusions (Boone et al., 1970; Vehrs, 1975; Lyttle, 1976) the Flagstaff Lake Igneous Complex contains few large roof pendants or large stoped blocks.

Mafic enclaves are pervasive in the complex, particularly near (100-200 m) where the gabbro-granite, gabbro-

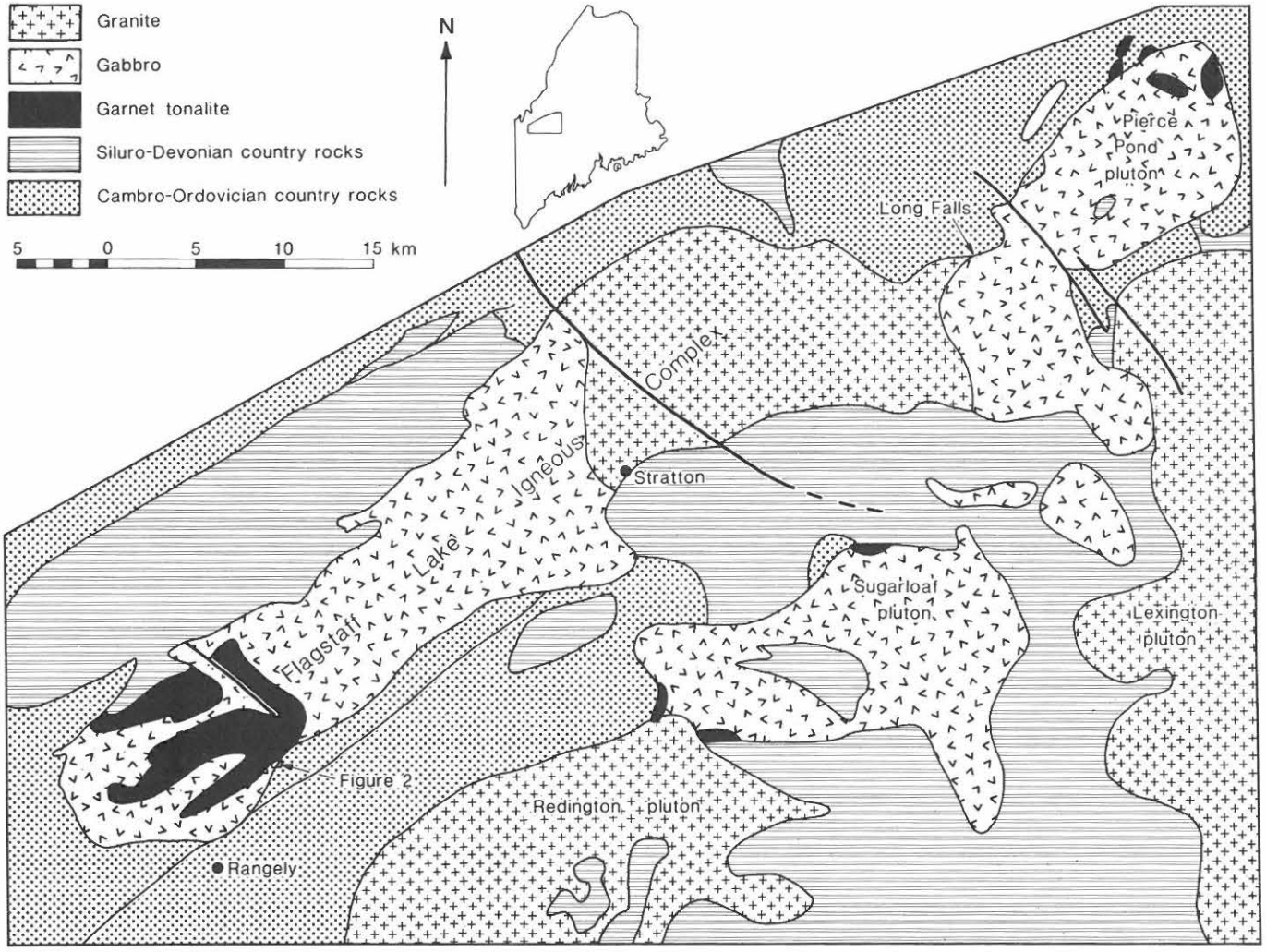

Figure 1. Location and geologic maps of the Flagstaff Lake Igneous Complex (modified after Moench et al., 1982).

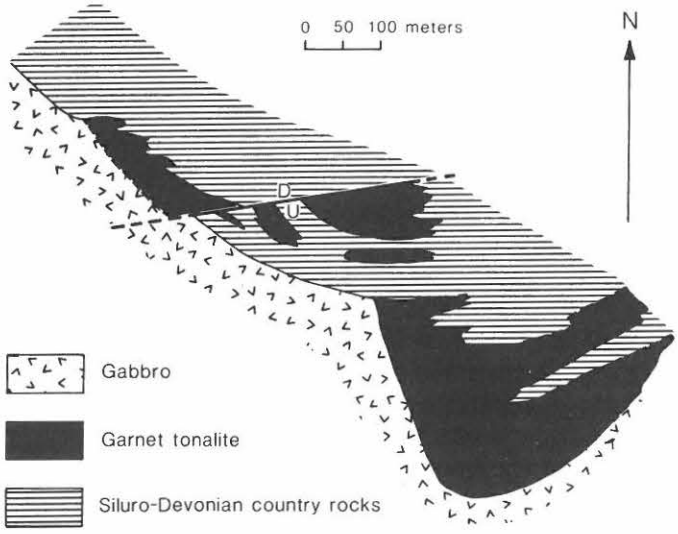

Figure 2. Map of the details of the field relationship of the gabbro, garnet tonalite, and metamorphic country rock.

Figure 3. Field evidence of magma mixing and partial melting. (a) Migmatites and contact breccias, Dead River Formation at Long Falls, 2 m from metasediment-trondhjemite contact.

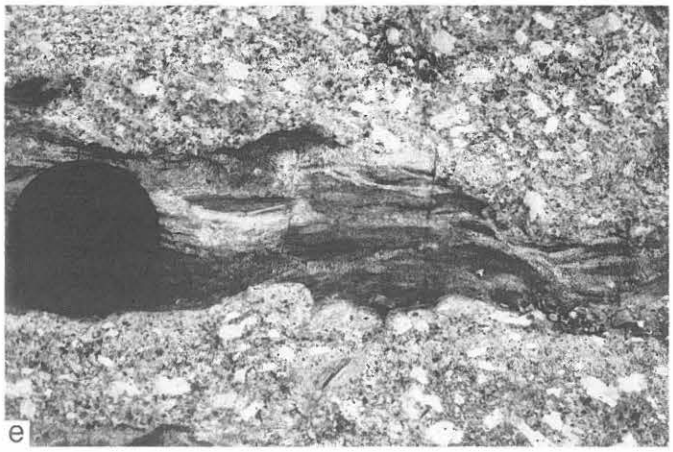

Figure 3 (continued). Field evidence of magma mixing and partial melting. (b) Xenoliths (quartz-cordierite hornfels) in garnet tonalite near Rangeley. (c) Biotite-rimmed gabbro inclusions, Long Falls. (d) Mixing interface between quartz monzonite porphyry and fine-grained diorite showing plagioclase phenocryst trains in diorite. (e) Biotite schlieren (metasediment derived) in quartz monzonite porphyry, near Stratton. (f) Biotite-rimmed gabbro inclusion in garnet tonalite, Pierce Pond. (g) Cuspate gabbro enclave-granite contact, Long Falls.

trondhjemite, or gabbro-tonalite contacts intersect the edge of the intrusion (e.g. Long Falls - Fig. 1). These enclaves have irregular morphologies (Fig. 3c,f,g), are fine grained, and have biotite-rich rims. Angular blocks and breccia, evidence of brittle behavior, are rarely observed away from the immediate vicinity (<10 m) of the edge of the intrusion. The thickness of the biotite rims increases roughly as a function of the distance from the edge of the complex. The rims of the enclaves are often crenulate (Fig. 3g). As one proceeds toward the center of the complex, the mafic enclaves become more ellipsoidal in shape and dioritic in composition (Fig. 3d). Eventually, in the center of the intrusion, the gabbro-granite and gabbro-tonalite contacts become gradational. There, the only remaining evidence of the mafic enclaves is biotite schlieren.

In other reported cases of mafic enclaves in granitic bodies, the enclaves are largely restricted to dike-like clusters (Taylor et al., 1981; Furman and Spera, 1985). In most recent investigations this has been attributed to the injection of gabbro into a granitic body which was largely crystalline. In the Flagstaff Lake Igneous Complex, the mafic enclaves commonly occur in a wide band along the boundary separating the granitic and gabbroic sections of the intrusion. This observation suggests that the enclaves may have originated in a boundary layer between two different magma types. The dip or orientation of this boundary is too irregular for any determination of its nature.

In the southern part of the complex, weakly metamorphosed sulfidic, graphitic, Fe-rich metasiltstones and metagraywackes are the dominant lithologies near occurrences of garnet tonalite. At Pierce Pond, in the far northern end of the intrusion, similar metamorphic rocks are present in the middle and lower sections of the Dead River Formation (Lyttle, 1976; Moench et al., 1982). These rocks are also associated with garnet tonalites (Boone, 1985). Randomly oriented blocks of metamorphic rocks and biotite-rimmed gabbro enclaves are present in both locations (Fig. 3b,c,f,g). Garnet tonalites do not occur in contact with either trondhjemite or granite. The garnet tonalite-gabbro contact ranges from sharp (4 m wide) to gradational (1 km wide). A full suite of intermediate rock types can be observed in the field, from garnet tonalites with 35-70% garnet to garnet-free gabbro. The garnet tonalite exhibits no foliation or mineral layering, on either a large or small scale.

ANALYTICAL METHODS

Bulk major and trace element chemistry of the samples from the Flagstaff Lake Igneous Complex was determined by XRF analysis using fused pellets and pressed powder preparations (Johnson, 1984). Standards included both USGS standards, BHVO-1, W-2, GSP-1, RGM-1, and a set of synthetic standards for Fe, Y, and Zr which were calibrated by ICP and XRF analysis at the USGS. Error on the major elements is approximately 2.2% relative and ±5% for the trace elements.

Mineral chemistry was determined by electron microprobe at the facilities of the Mineral Sciences Department, Smithsonian Institution (ARL SEMQ), and the Department of Engineering, University of Maryland (JEOL 840a). Precision is approximately 1% for the major components.

PETROGRAPHY AND MINERAL CHEMISTRY

The four major igneous rock types present in the Flagstaff Lake Igneous Complex can be readily distinguished on the basis of their mineralogy and modal proportions (Table 1). All rock types were named using the IUGS (Streckheisen, 1976) classification. The two-mica granite (Fig. 4a) is medium to coarse grained and contains approximately equal amounts of orthoclase, quartz, and plagioclase (An_{20-40}). In several locations, the granite is characterized by large (>5 cm) orthoclase phenocrysts. Biotite is the major mafic phase, although minor garnet and cordierite are also present (Boone, 1973). The modal proportion of muscovite is variable, but is always less than that of biotite. Diorites, both north and south of the central granite body, are finer grained than the granites (Fig. 4b) and contain local orthoclase with abundant biotite and amphibole (Table 1). These intermediate composition rocks are often heterogeneous, grading continuously from mafic diorite to granite in a space of 100 meters. They also contain large (>1 cm) resorbed sodic feldspar (An_{20-40}) and quartz crystals, many with biotite halos. Biotite is also present as discrete clusters in both the diorites and in some of the more silicic rocks.

The trondhjemites are characterized by a medium to fine grained texture, and plagioclase, quartz, and biotite with occasional trace amounts of cordierite, and garnet. Muscovite and K-feldspar are rare. Most of the plagioclase phenocrysts exhibit patchy zoning, particularly those in trondhjemite near the mafic enclaves. Samples near the metamorphic contact contain the most cordierite and garnet, both of which commonly show textural evidence of resorption and/or re-equilibration (rounded crystal forms, biotite reaction rims). A large fraction (>1/2) of the biotite in the trondhjemite is present in schlieren or clusters. It is therefore difficult to determine the modal percentage of biotite that is representative of the trondhjemite itself. Thus, in this case it is clear that the bulk composition of the trondhjemite does not represent a liquid composition.

The rims of the mafic enclaves are fine grained (Fig. 4c) but coarsen toward the center of the enclaves. As one proceeds inward from the rim of an enclave (Fig. 4c,d) the proportion of amphibole increases and biotite decreases. Texturally, biotite appears to be the product (Fig. 4e) of a reaction involving amphibole (and melt?). The centers of the larger enclaves (>3 m) are mineralogically similar to the olivine-pyroxene-amphibole-bearing gabbros found elsewhere in the complex, away from contacts with granitic rocks (Table 1). Many of the mafic enclaves contain feldspar phenocrysts, some of which have patchy zoning, resorbed rims, and sodic compositions (An_{25-40}) compared to the groundmass plagioclase compositions (An_{55-70}), and are thus probably xenocrystic.

Biotite schlieren fall into two mineralogic groups. The first is characterized by the almost total absence of any mineral but biotite. The biotite is medium grained (1-2 mm) and devoid of inclusions. The other type of schlieren contain quartz and cordierite in addition to biotite. These schlieren are finer grained (~200 microns) and biotite frequently contains abundant inclusions of monazite and zircon. Toward the center of the intrusion, the schlieren appear to break down into smaller and smaller units. The end products are clusters of biotite, 1-5 mm in diameter, made up of 5-50 individual crystals of biotite. Some of these clusters contain monazite and zircon inclusions, while others contain few or none. A few clusters are characterized by a single grain of biotite containing inclusions, surrounded by inclusion-free biotite. There is no consistent textural or color difference between the two biotite types. Some of these clusters contain inclusions characteristic of the biotite in the metamorphic rocks. Others are devoid of inclusions, as is the biotite associated with the mafic enclaves.

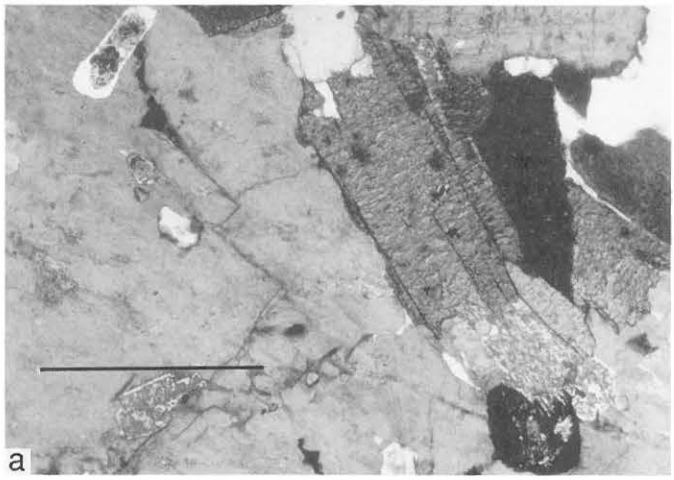

Figure 4. (a) Two-mica granite from Hedgehog Hill, 1 mi south of town of Stratton. Bar scale 1 mm.

TABLE 1: MODES OF REPRESENTATIVE SAMPLES FROM THE FLAGSTAFF LAKE IGNEOUS COMPLEX AND ITS AUREOLE

	86081 White granite	86020 Pink granite	EW-53 Diorite	86001A Hornfels	86087A Gabbro enclave	86087B Gabbro bt. rim	86087B Host granite
alk.fld	30-40	20-30	5	–	–	–	–
plag.	20-30	40-50	40	40-50	35-40	50	55
quartz	10-20	10-20	5	5	–	0	35
biotite	10	5-10	5	10	5-10	45	10
opaques	Tr	Tr	5	–	5-10	5	1
amphibole	–	–	50	40-50	35-40	–	–
muscovite	5	5	–	–	–	–	–
zircon	Tr	Tr	–	–	–	–	–
apatite	Tr	Tr	–	–	–	–	–
sphene	–	–	–	Tr	–	–	–
epidote	–	–	–	–	–	–	Tr
monazite	Tr	Tr	–	–	–	–	Tr
mean grain size	1-2mm pheno-3mm	1-3cm	2mm	400-600 m	200 m-1mm	50 m	1-2mm

	18 Garnet tonalite	146 Garnet tonalite	145 Garnet gabbro	226 Garnet gabbro	2 Gabbro	10 Gabbro	183 Hornfels incl.	193 Mafic incl.
plag	20	5	45	35	50	44	60	50
quartz	15	20	5	5	–	–	33	–
biotite	5	10	5	3	1	1	4	1
opaques	3	Tr	3	5	5	10	2	10
amphibole	–	–	–	–	15	–	–	–
garnet	45	65	5	10	–	–	–	–
pyroxene	–	Tr	35	40	–	45	–	35-40
cordierite	15	–	–	–	–	–	–	–
olivine	–	–	–	–	30	–	–	–
chlorite	Tr	–	–	–	Tr	–	–	–
apatite	Tr	Tr	Tr	Tr	–	–	Tr	–
zircon	Tr	Tr	Tr	Tr	–	–	–	–
mean grain size	0.8mm	1.9mm	0.1-2.5mm	1mm	1.3mm	1mm	0.3mm	0.5mm

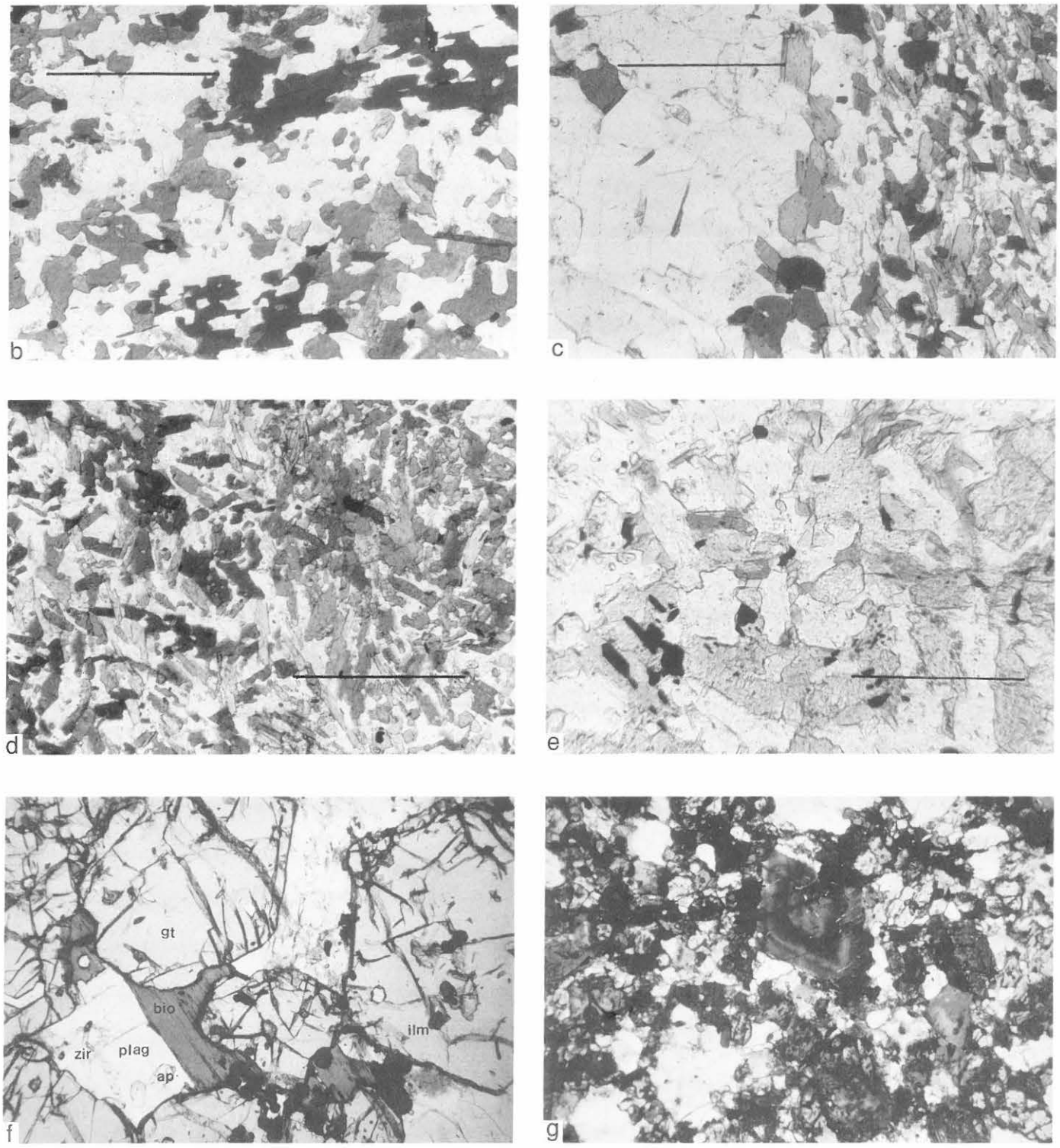

Figure 4 (continued). (b) Diorite from center of pluton on north shore of Flagstaff Lake. Note lack of zircon or monazite inclusions in biotite. Bar scale 1 mm. (c) Biotite rim on mafic enclave, Long Falls, 20 meters from granite-metamorphic contact. Bar scale 1 mm. Note fine grain size and absence of any mafic material except biotite in the rim. (d) Mafic enclave 2 cm from rim - same enclave as 4c. Bar scale 1 mm. Note acicular form of opaques (ilmenite), increase in amphibole content and grain size. (e) Mafic enclave 10 cm from biotite rim. Note reaction relationship between biotite and amphibole, equant habit of oxides, acicular apatites. Bar scale 200 microns. (f) Garnet tonalite - Bar scale 1 mm. gt - garnet; plag - plagioclase; zir - zircon; ap - apatite; bio - biotite; ilm - ilmenite. (g) Oscillatory zoned plagioclase in garnet gabbro (garnet excluded from field of view), xpl. Bar scale 1 mm.

This observation suggests the possibility that a significant proportion of biotite in the Flagstaff Lake Igneous Complex was inherited and does not represent a primary crystallization product of a granitic melt. This hypothesis is currently being investigated in detail in order to gain the information necessary to constrain the chemical, modal, and textural variation of biotite in the complex. If a significant proportion of biotite is the inherited reaction product of assimilation or reaction of granite with the mafic enclaves, then the granites do not represent liquid compositions. This could be of special importance when considering the evolution of the Flagstaff Lake Igneous Complex using the systematics of components added by the inclusions in the biotite (e.g. REE, Th, Zr, U, Pb). Two possibilities are currently being considered as working hypotheses. The first is that biotite was included as an already re-equilibrated reaction product. In this case, the rock composition would lie on a straight line between the biotite composition (plus inclusions) and the granitic magma plus crystals. The second possibility is that biotite was included as xenolithic or enclave material that reacted with the granitic magma producing the biotite and an altered granitic magma. In this case, the observed composition of the rock would reflect the biotite composition, plus the original granite magma composition, plus the added components derived from the xenoliths or enclaves. The observed suite of rocks would then exhibit a complex pattern of compositions, dependent on the nature and amount of the contaminant.

Rocks at the southern end of the Flagstaff Lake Igneous Complex form a continuous suite of compositions ranging from olivine gabbro to garnet tonalite. The garnet tonalites are equigranular rocks composed of 25-70% unzoned garnet (Table 1,2), oscillatory zoned plagioclase (~An_{50}, Fig. 4g), quartz, biotite, ilmenite, pyrrhotite, apatite, and zircon (Fig. 4f). Mineral grains tend to be euhedral, and the garnets in particular contain inclusions of the other phases present in the rock. They exhibit no foliation or lineation in thin section or hand specimen.

While the garnet tonalites are mineralogically similar to one another, percentages of phases (most notably garnet) are variable. With the exception of the xenoliths and mafic enclaves, there are no sharp contacts within the garnet tonalite body. The transition from garnet tonalite containing 25-30% garnet to that containing up to 70% garnet is gradational. The tonalites with the highest garnet contents (~50%) have a cumulate texture, but a mappable cumulate pile or zone has not been identified.

The garnet tonalite-gabbro contact is transitional, marked by an "intermediate" garnet gabbro. Since the series is continuous, the boundary between garnet tonalite and garnet gabbro is arbitrarily set at 25% garnet. Rocks with less garnet generally contain pyroxene, and those with more garnet generally contain quartz.

The garnet gabbros are characterized by orthopyroxene, oscillatory zoned plagioclase, and local cordierite. The garnet in these "intermediates" tends to be larger (up to 1 cm), less euhedral, and more magnesian as the modal percentage declines. The decrease in percent garnet is directly proportional to distance from the garnet tonalite toward the gabbro. This transition zone in the Rangeley area ranges in width from several to hundreds of meters. In addition, garnet sporadically appears as an accessory mineral throughout the gabbros of the southern part of the Flagstaff Lake Igneous Complex. The fact that garnets present in the transitional rocks are compositionally different from those in the garnet tonalite suggests the possibility that the 1-cm garnets are not xenocrysts from the tonalite. The major phases present as groundmass minerals in the garnet gabbros also occur as compositionally similar garnet inclusions, suggesting simultaneous crystallization (Table 2).

TABLE 2. MINERAL CHEMISTRY OF REPRESENTATIVE SAMPLES FROM THE RANGELEY AREA.

	Ferro-gabbro			*Diorite*	
	Ortho-pyroxene	Clino-pyroxene	Ilmenite	Biotite	Plagioclase
SiO_2	46.32	50.33	–	34.78	62.04
Al_2O_3	1.15	5.72	–	16.85	24.06
FeO	40.42	15.42	46.13	22.52	–
MgO	9.20	12.52	0.07	4.34	–
CaO	0.56	13.27	–	0.01	5.32
K_2O	–	–	–	9.49	0.09
Na_2O	–	0.77	–	–	6.94
TiO_2	0.20	1.07	50.33	3.54	–
MnO	0.97	0.34	0.78	0.11	–
H_2O	–	–	–	3.81	–
Total	98.82	99.55	98.39		

	Garnet tonalite (18)				
	Garnet grain traverse				
	Rim	Core	Rim	Biotite	Ilmenite
SiO_2	37.48	37.00	36.86	33.57	–
Al_2O_3	20.86	20.55	21.27	16.71	–
FeO	37.29	36.95	37.86	26.71	46.82
MgO	2.54	3.30	2.77	6.34	0.08
CaO	1.34	1.38	1.44	0.21	–
K_2O	.04	.02	.01	8.93	–
Na_2O	.01	.02	.01	0.07	–
TiO_2	.08	.11	.03	2.64	52.60
MnO	1.65	1.32	1.54	0.10	0.43
H_2O	–	–	–	3.73	–
Total	101.30	100.65	101.78	98.98	100.04

	Garnet gabbro (145)				
				Pyroxene	
	Garnet	Cordierite	Biotite	in garnet	gdmass
SiO_2	37.74	47.23	34.13	48.04	48.28
Al_2O_3	21.37	32.00	15.75	2.54	2.75
FeO	36.26	10.95	25.28	35.89	36.74
MgO	3.84	6.52	7.24	12.02	11.91
CaO	1.21	0.00	0.06	0.31	0.31
K_2O	.02	0.00	8.57	–	0.02
Na_2O	.01	.76	0.16	0.04	0.04
TiO_2	.07	0.00	4.20	0.19	0.04
H_2O	–	2.23	3.79	–	–
Total	101.87	99.07	99.22	99.95	100.67

TABLE 3: MAJOR AND TRACE ELEMENT ANALYSES ON REPRESENTATIVE ROCKS FROM THE RANGELEY AREA.

	14 Gabbro main body	145 Garnet gabbro	18 Garnet tonalite	140 Gabbro	LF14a Gabbro	PP 13 Gabbro enclave	FL 4 Grano-diorite
SiO_2	51.2	46.0	41.5	49.5	49.76	47.99	65.82
TiO_2	2.22	2.65	3.5	3.2	1.86	1.78	0.56
Al_2O_3	18.25	17.25	18.0	16.0	16.87	14.50	16.66
FeO	14.4	21.3	28.8	15.1	11.17	12.65	4.78
MnO	0.2	0.25	0.7	0.23	0.20	0.20	0.08
MgO	3.8	4.20	1.9	5.66	7.81	9.41	0.97
CaO	5.6	3.6	2.67	8.5	10.12	9.98	2.60
K_2O	0.65	0.39	0.63	0.19	0.99	1.10	4.98
Na_2O	2.61	2.51	1.61	2.35	2.25	2.39	3.66
Total	98.97	98.15	99.31	100.63	101.03	100.01	100.11
Cr	–	–	–	–	–	301	250
Ni	19	50	11	31	67	65	–
Cu	16	30	27	7	51	42	17
Zn	116	118	106	88	115	102	76
Rb	25	14	5	4	27	36	134
Sr	308	230	84	226	185	160	121
Y	270	490	1538	125	51	14	30
Zr	813	1058	1750	145	131	127	186
Nb	28	35	40	19	4	7	11

GEOCHEMISTRY

The geochemistry of the gabbros of the complex indicates that they have been significantly fractionated. They characteristically contain low amounts of Ni and Cr (Table 3) and high amounts of Fe. The gabbros with the highest Ni and Cr and lowest Y and Zr are still fractionated compared to liquids in equilibrium with the mantle. Absence of cumulates in the complex suggests that crystal fractionation probably occurred prior to emplacement.

The most distinctive rocks from the complex are the garnet tonalites. They are characterized by low Si, Ca, and K, and very high Fe, Y, and Zr (Table 3). Trace element abundances (especially Y and Zr) are quite variable and directly correlate with the amount of zircon and garnet in each sample.

Preliminary microprobe mapping reveals that Y is concentrated in a separate (as yet unidentified) phase within fractures in garnet. This could be caused by low-grade metamorphism or perhaps hydrothermal alterations immediately following the emplacement of the complex. Since the Y phase is not dispersed throughout the rocks, but is localized within garnets, we feel that the whole-rock analyses represent original Y concentration, which has been locally redistributed.

The continuity of the gabbro-tonalite suite can be demonstrated by considering the compositional range of rocks collected from the area shown in Figure 2. The distribution of Ca and Fe (Fig. 5) in the suite indicates that not only is the suite continuous, but it is characterized by a wide range of Ca contents at a specific Fe concentration. This cannot easily be explained as the product of any single set of processes.

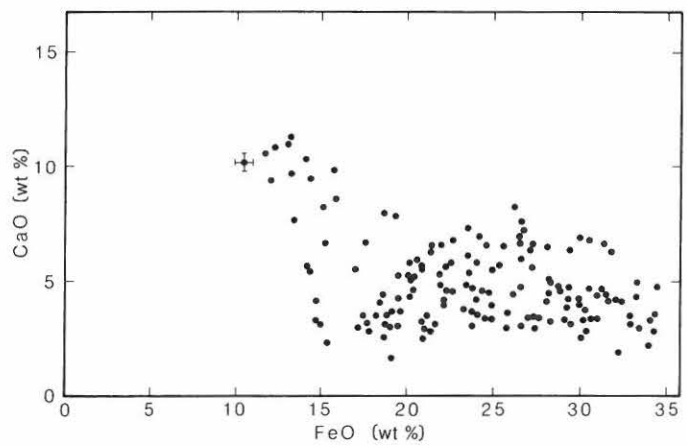

Figure 5. Ca vs. Fe for gabbros and garnet tonalites from the southwest third of the Flagstaff Lake Igneous Complex.

The incompatible elements (e.g. Y vs. Zr, Fig. 6) also exhibit a wide range of concentrations. In the case of Y and Zr, the gabbro-garnet tonalite suite exhibits a 20-500 fold increase in concentration. As with Ca and Fe, the data set exhibits a wide range of Y values at any given Zr value.

DISCUSSION AND CONCLUSIONS

From the information presented above, it is evident that many different, interacting processes are responsible for the phenomena observed in the Flagstaff Lake Igneous Complex.

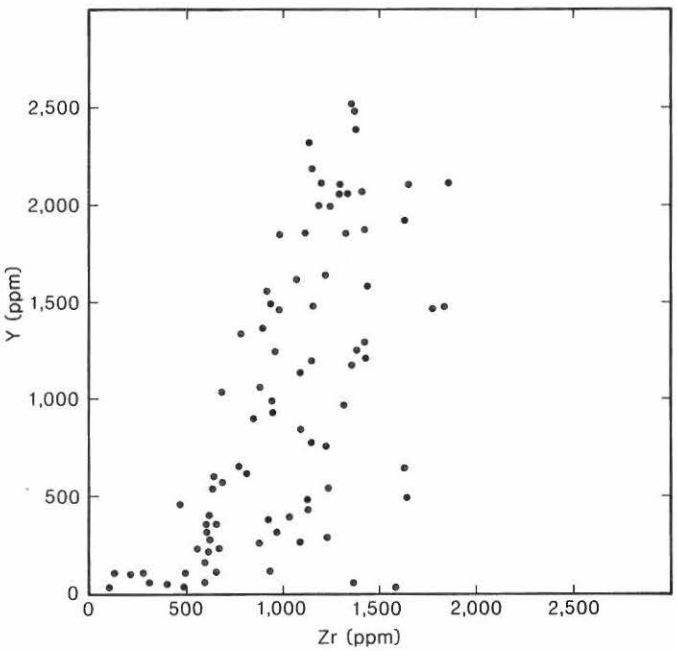

Figure 6. Y vs. Zr for gabbros and garnet tonalites from the southwest third of the Flagstaff Lake Igneous Complex.

These include the processes responsible for (1) the origin of the mafic enclaves; (2) the origin of the garnet tonalite; (3) the observed continuous chemical and mineralogic series between garnet tonalite and gabbro; and (4) the significance of the monazite and zircon inclusions in biotite in the granite.

There are two potential explanations for the origin of the mafic enclaves found in the granite, tonalite, and trondhjemite. They either originated as blocks of gabbro, broken off and swept up as the granite intruded a previously solidified gabbroic pluton, or they represent quenched "pillows" of gabbro, injected as a liquid into a partially solidified granite body (Taylor et al., 1980; Furman and Spera, 1985). It is important to distinguish the two hypotheses in order to establish the relative timing of the emplacement of the major rock types. The irregular, ameboid shape of the enclaves, the inclusion of patchy zoned sodic feldspar, the fine grained rims and inward-coarsening texture, and the cuspate interface with the host rock all point to the enclaves originating as liquids injected into a low temperature crystal mush. Therefore we feel that granitic and gabbroic magmas coexisted during the major emplacement event of the complex. The rough zoning pattern of the intrusion itself suggests the possibility that the magma chamber was zoned, with granite lying above a larger body of gabbro. With the information presently available, two intrusion histories seem possible. The first scenario is that granite originally filled the entire magma chamber and was then partially pushed out by an influx of gabbroic magma. Alternatively, the magma system rose through the crust as a unit with the granitic magma being produced from melting of the wall rock as the composite pluton rose through the crust (McBirney, 1980).

There are several hypotheses that could explain the origin of the garnet tonalite. The first point to be addressed is whether the rocks are igneous or metamorphic in origin. Previous workers have called them (1) restites of partial melting (Boone, 1973; Vehrs, 1975); (2) reaction hornfels (Boudette, 1978); (3) products of igneous differentiation (Lyttle, 1976); or (4) restites mixed with their own partial melts (e.g. similiar to cases described by Clark and Lyons, 1986; Plank, 1987).

Restites of partially melted metapelite could produce a rock mineralogically similar to the garnet tonalite (Gribble, 1970), but the body would not cut the regional strike as the tonalites invariably do. Neither would one find oscillatory zoned plagioclase, or the equigranular texture exhibited by the tonalites. If the partial melt were not removed, but remained to mix with the refractory phases, some of these problems would be eliminated (oscillatory plagioclase, crosscutting relationship). However, garnet of metamorphic origin is usually free of inclusions and often zoned (Clark and Lyons, 1986). The garnets from tonalite and gabbro samples are both full of inclusions, identical to the matrix assemblage, and are unzoned. This suggests that the garnet co-precipitated with the other phases in the rocks. We do not eliminate the possibility that the tonalite magma was partially crystalline at the time it mixed with the gabbro, but we feel the evidence is not compelling. This is in contrast to the pervasive evidence that the granitic magma was partially crystalline when it interacted with the gabbro.

The mobilization of Y, represented by its concentration in fractures in the garnet, indicates that some late-stage metasomatism did occur. Large bodies of apparently metasomatically generated garnet-rich rock (skarns) are associated with the contacts of many plutons. However, garnets associated with skarns are different in most characteristics from those from the Flagstaff Lake Igneous Complex. Garnets from skarns are usually andradite-grossular rich, strongly zoned, inclusion-free, and the bodies occur in veins. In addition, skarns are characterized by rocks with a small number of phases and variable phase proportions. The garnet tonalite is characterized by a large number of major phases and relatively constant phase proportions. An origin by metasomatism also would not account for the angular, randomly oriented blocks of hornfels or mafic enclaves as observed in the garnet tonalite bodies. Finally, it would be difficult to explain the continuous series of rocks from gabbro to tonalite by metasomatism.

An igneous origin for the tonalites implies two possible source areas and processes: differentiation of mantle-derived magmas (gabbro) or anatexis of the country rock. To date, no source has been identified in the country rock to produce a Fe-rich, alkali- and silica-poor melt. The coincidence of garnet tonalite with sulfidic, graphitic, Fe-rich metapelite and the numerous xenoliths strongly suggests a petrogenetic relationship between them. If, however, the country rocks cannot be

demonstrated to be related to the tonalite-gabbro series, it does not rule out the possibility of assimilation or anatexis at depth.

The wide range of both major and trace element compositions in the tonalite-gabbro suite provides great difficulty in specifying a petrologic process or set of responsible processes. Fe-rich, Ca-poor magma compositions could potentially be produced from gabbro by fractional crystallization of augite. The low but variable Cr and Ni contents of the gabbros indicate that at least some fractional crystallization has occurred. However, the increasing amount of garnet in the suite as Fe increases negates fractional crystallization as a major process in the origin of the tonalites. This is a consequence of the high partition coefficient for Fe, Y, and Zr in garnet. Fractional crystallization of garnet would prevent the evolution of the magma system to the observed high Fe, Y, and Zr contents. In addition, even if the partition coefficient for those elements was 0, over 99% fractional crystallization would be needed to raise Y from 20 to 2500 ppm. Alternatively, the observed distribution could be explained as due to the accumulation of igneous garnet derived from an Fe-rich magma, assimilation of metamorphic garnet, or to the mixing of two liquids, one gabbroic and the other Fe-rich. The theory of garnet accumulation or assimilation is supported by two observations. First, in a few locations, tonalite contains almost 70% garnet and has a cumulate texture. Second, garnets in the garnet gabbro often have rims of biotite, suggesting that they have reacted with the gabbroic magma. On the other hand, garnets in tonalite and gabbro in general have mineral inclusions similar to those in the groundmass of the rock in which they are found. Also, there is a correlation of the Mg-content of the garnet with the Mg-content of the igneous rock. This would not necessarily be the case if the garnet was assimilated from a garnet-bearing metasedimentary rock or crystallized in an Fe-rich magma prior to magma mixing. The biotite rims on the garnets could be a result of a change in the crystallizing assemblage, analogous to orthopyroxene rims on olivine. Therefore, it is our preliminary conclusion that the observed distribution is due to a series of interacting processes: (1) the fractional crystallization of the gabbro; (2) garnet accumulation, at least in the most garnet-rich tonalites; and (3) mixing of gabbroic and Fe-rich tonalite magmas.

The proportion of the biotite in the granites, trondhjemites, and tonalites that was inherited from either the mafic enclaves or metamorphic stope blocks is a critical point from several perspectives. All of these center around the determination of the extent to which these rock types represent liquid compositions. Inherited biotite could add Th, Zr, Pb, and U to the bulk rock from monazite and zircon inclusions, in addition to the exchange of Mg, Ti, and Fe from re-equilibration of biotite itself.

The proportion of schlieren in the granite, trondhjemite, and tonalite ranges from 0 to 20%, with the highest percentage being found in the trondhjemites. It is certain that at least some of the biotite crystallized from the magma and was not incorporated in the solid state as enclaves, xenoliths, or schlieren. It is not unreasonable to suggest that monazite was a crystallizing phase during a large part of the crystallization history of the Flagstaff Lake Igneous Complex granites and trondhjemites. Therefore, it is extremely difficult to distinguish the origin of individual biotite crystals in the granites. However, several approaches could provide useful information and are presently being applied to these rocks. First, a statistical evaluation could be made of the number of inclusion-bearing biotites vs. inclusion-free biotites in a given size range. Second, a detailed study is presently being conducted of the range of biotite compositions in the biotite rims, metamorphic stope blocks, and schlieren of both types. Third, the range in monazite and zircon compositions in biotite in the same rock types, in addition to those in granite, tonalite, and trondhjemite is being determined by microprobe to evaluate any possible correlations.

In summary, on the basis of the data presently available, we feel that the processes responsible for the observed suite in the Flagstaff Lake Igneous Complex were dominated by magma mixing of at least three discrete end members: fractionated mantle-derived gabbro, granite, and garnet tonalite. The specific mechanism driving the mixing is as yet unclear. However, the available evidence is consistent with autointrusion as suggested for the Bottle Lake Complex by Ayuso (1984) or with the creation of a granitic cap on a rising gabbroic magma system by anatexis of the wall rock (DePaolo, 1981; McBirney, 1979, 1980). Fractional crystallization played a relatively minor role after emplacement, although the gabbroic rocks show evidence of significant olivine and pyroxene fractionation.

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