The chemistry, mineralogy, and petrology of the George Ashley Block pegmatite body

WALLACE D. KLECK[1,*] AND EUGENE E. FOORD[2,†]

[1]23940 Basin Harbor Court, Tehachapi, California 93561, U.S.A.
[2]U.S. Geological Survey, Denver Federal Center, Denver, Colorado 80225, U.S.A.

ABSTRACT

The George Ashley Block (GAB) is a rockslide block located in the Pala pegmatite district of Southern California. It is layered, asymmetric, pocket containing, and peraluminous. The GAB consists of quartz (42 vol%), Na-rich plagioclase (27%), potassium feldspar (24%), muscovite (7%), Mn-rich garnet (2%), biotite (1%), and a trace of tourmaline and gahnite. It contains only small amounts of the incompatible elements that characterize differentiated pegmatite bodies. P_2O_5, MnO, and F are present in amounts of <1 wt% each; B, Be, Ce, Li, Nb, Nd, and Th are <100 ppm each.

More than 90% of the garnet grains in the GAB are zoned toward Mn-rich rims, and a symmetrical change in garnet-core composition occurs across the body. The mean X site contents for garnet (in at%) are 57% Fe, 40% Mn, 3.1% Mg, and 0.4% Ca. The Mn contents of garnet range from 30 to 55 at%; Fe contents vary inversely with Mn and range from about 66 to 43 at%.

It is concluded that the bulk chemistry yields little information about fractionation, but the garnet, muscovite, and biotite mineral chemistry is more useful. There may have been two separate injections of magma to form the GAB.

INTRODUCTION

For many pegmatite bodies, underground and surface exposures are limited. Even if the pegmatite body is currently being mined, mine workings follow the economically valuable zones. For example, the Stewart Mine (Pala pegmatite district, San Diego Co., California) has tens of miles of tunnels that are confined primarily to the central parts of the pegmatite body, and little is known about the lower contact and lower parts of the body. The "interesting" pegmatite bodies, in many cases, are large with complex interpenetrating zones, making representative samples difficult to collect. In addition, more attention has been given to the pockets and the unique minerals contained therein than to the mundane rock that makes up the bulk of the pegmatite body. As a result, little of the fundamental chemical and mineralogical information about pegmatite bodies is available, particularly for the Southern California pegmatite districts.

With the facilities available to E.E. Foord and with a cross section of the George Ashley pegmatite block fully exposed, this lack could be partly rectified. The George Ashley Block (GAB for brevity) is a rockslide block that was a part of a larger pegmatite body on Heriot Mountain. It represents a cross section of a pegmatite, including one long pocket or a series of connected pockets. This is not an entire pegmatite, but it provides a detailed look at a significant part of a zoned pegmatite body.

This study was in progress when Eugene E. Foord died on January 8, 1998. Analyses of all the samples were complete but not formalized, and the interpretation of the data had just started. The conclusions reached in this paper reflects ideas from both persons but are the sole responsibility of W.D. Kleck.

LOCATION AND PREVIOUS WORK

The GAB is located in the NE1/4, sec. 25, T. 9 S., R. 2 W., Pala, California quadrangle at the southwestern base of Heriot Mountain, approximately 50 m south and behind the former residence of George Ashley (Fig. 1). The name "Hiriart Moun-
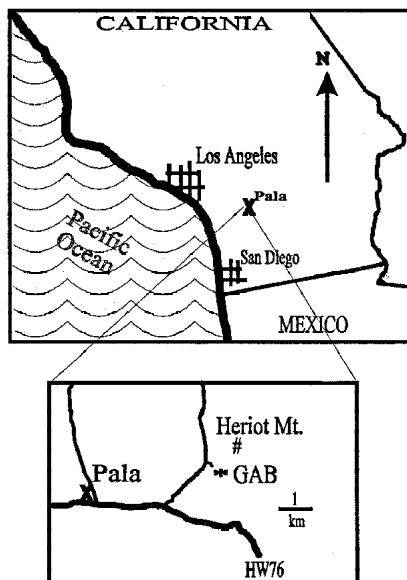

FIGURE 1. Location map for the George Ashley Block pegmatite.

*E-mail: wkleck@lightspeed.net
†Deceased: January 8, 1998.

tain" was used by Jahns and Wright (1951), but the name "He-riot Mountain" appears on the most recent Pechanga Quad-rangle for the same geographic feature. This area is within the Pala pegmatite district, San Diego Co., California. The Pala Indian Tribe now controls most of Heriot Mountain and is ac-quiring (or has acquired) the George Ashley property. At present, access has been closed to these tribal properties.

Preliminary, bulk-chemical compositions and a description of some line-rock features of the GAB were published by Webber et al. (1997). Kleck (1994, 1996) presented a brief de-scription of the GAB and some preliminary chemical data. Simpson (1965) reported one analysis and a composition com-puted from modal mineralogy for pegmatites in the Ramona pegmatite district. Jahns and Tuttle (1963) presented norma-tive mineralogy (but not the actual oxide analyses) for the Katerina dike, Pala district, California; Himalaya dike, Mesa Grande district, California; and the Upper Mack dike, Rincon district, California. Jahns and Tuttle (1963) also described some of the structures in the pegmatite bodies of Southern Califor-nia pegmatite districts. Jahns and Wright (1951) described the Pala pegmatite district (which includes Heriot Mountain) and provided a basic description of many pegmatite bodies in this district. That work emphasized structures, petrology, and min-eralogy; no analyses of the rocks and no systematic chemistry

of the minerals were reported. Analyses of minerals from South-ern California pegmatite bodies (mainly pocket minerals) were reported in several publications; representative references can be found in Jahns (1955) and in Foord et al. (1989).

METHODS

Because the GAB has a relatively smooth surface and has a cross section of the pegmatite body exposed in nearly a hori-zontal position, a diamond saw could be used for sampling. After the initial examination of the rock, a detailed description was made and a line of section established. Sample areas were marked every 60 cm along the measured line of cross section; 15 samples were collected and identified as sample A through O (from base to top) (Fig. 2). Samples approximately 3 by 7 by 6 (deep) cm were cut with a circular-bladed diamond saw ex-cept for sample G, which was broken from the pocket. Four additional samples (B2, C2, D2, and E2) were also cut along the line of section, and one sample (P) was cut off the line of section. Six other samples were taken from the edge of the block and cut into slabs for further examination of textures.

Major- and trace-element whole-rock chemical analyses were made of the fifteen samples (A through O), but only a major-element chemical analysis was made of sample P. Each sample (as well as the rock along the line of section) was ex-amined using a hand lens, and several sawn slabs from the margin of the block were examined with a binocular micro-scope. Thin sections and polished sections were prepared from samples A through P (excluding G, B2, C2, D2, and E2); the thin sections were examined by standard optical methods, and the polished sections were used for microprobe analysis of the minerals. Part of each sample block (except sample G, which lacked garnet) was coarse crushed, and 2–10 garnet grains were extracted for electron microprobe analysis; about 80% of the garnet grains recovered were single, euhedral crystals.

Garnet was considered the most ubiquitous mineral and the most likely to reflect the changing chemical conditions in the magma. It was also considered one of the less likely minerals to be subject to reequilibration. Therefore, garnet was chosen as the mineral for detailed examination.

All analyses were conducted at the U.S. Geological Survey laboratory in Lakewood (Denver), Colorado. Electron micro-probe studies of the minerals (polished rock samples and mounted-grain separates of garnet) were conducted by E.E. Foord. Thirteen elements—Na, Mg(0.01), Al, Si, Ca(0.01), Ti(0.01), Cr(0.01), Fe(0.01), F(0.01), Mn(0.01), K, P(0.02), and Rb(0.02)—were determined at each analytical location; esti-mated limits of detection in weight percent of the oxide (ex-cept F) are indicated after each element. In addition, Ba(0.02) was determined for potassium feldspar. A beam diameter of 20 μm was used with an accelerating voltage of 15 kV and a probe current of 20 nA. The level of detection for an element is indi-cated by <0.0x, where 0.0x represents the estimated detectable concentration. Counting precision is indicated in the appropri-ate tables, where the number in parentheses represents one stan-dard deviation.

Major elements were determined by X-ray fluorescence (XRF) analysis (PW-1606 instrument) using fused Li-tetraborate disks by the method of Taggart et al. (1987). Trace
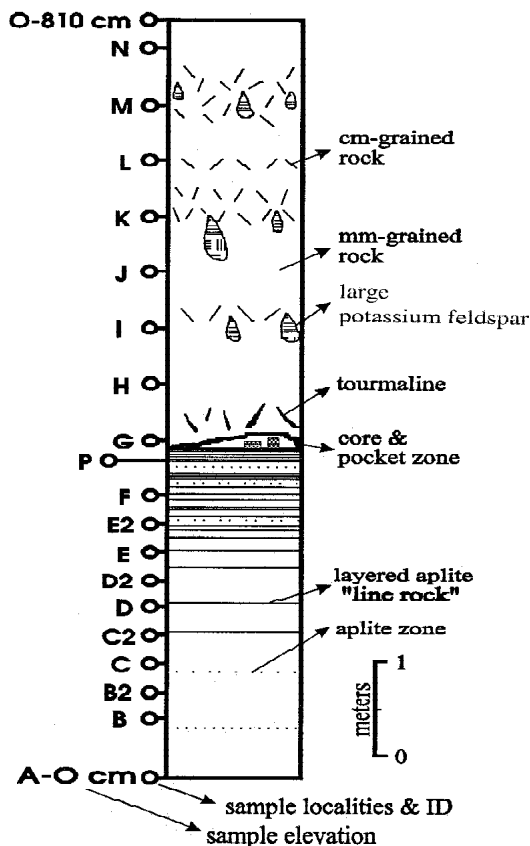

FIGURE 2. Sketch of a cross section of the George Ashley Block pegmatite body.

elements were determined by inductively coupled plasma mass spectrometry (ICP-AES) using the method of Lichte et al. (1987). Two separate major-element analyses of the rock samples were conducted; these were made on powders prepared from different portions of the same sample block (see Table 1 in the chemistry section). The two different analyses show only the minor differences expected from separate parts of the same pegmatite sample. Because some of the samples were taken at the edge of the block and at intervals of other than 60 cm, weighted means were also calculated; this was done by weighting each sample for the proportion of the cross section attributable to that sample, i.e., half the distance to the adjacent samples. In spite of the inhomogeneous nature of the rock, weighted means differ only slightly from the simple means.

One hundred to 150 random points were counted for each thin section for determination of the mineral abundances. More points would have given a greater precision for each thin section but, considering the small size of a thin section, the inhomogeneous nature of pegmatites, and the drastically different textures in the GAB, more points would not have resulted in a greater accuracy for overall mineral abundances. Three thin sections were stained to facilitate identification of the potassium feldspar.

OCCURRENCE, FEATURES, AND PETROLOGY

The pegmatite dikes in the Pala pegmatite district dip to the west by an average of 20° and range between 10–35° (Jahns and Wright 1951). Several studies have indicated that the entire Southern California Batholith has been rotated to the west since emplacement. Ague and Brandon (1992) indicated that the tilt to the west is 19 ± 5.4 or 17 ± 4.8° (depending on the technique used). It is probable, then, that the Pala district pegmatite dikes were within a few degrees of horizontal at the time of emplacement and solidification.

For the purposes of this paper, it is assumed that the terms "top" and "bottom" apply to the GAB and to the tabular, pegmatite body from which the GAB was derived. Jahns and Tuttle (1963) determined that the vast majority of layered aplite occurs in the lower part of pegmatite bodies. It is assumed here that this is also true for the GAB. The terminology of Orville (1960) is used here in referring to the grain size of pegmatite rock, i.e., centimeter-grained means grains with the average greatest dimension between 1 and 9.9 cm, etc.

The GAB is approximately 8 m thick, 15 m long, and 3 m wide. The 8 by 15 m surface is a cross section of a tabular, pegmatite body. The block rests at the base of Heriot Mountain and is one of several rockslide blocks in this area. The parent body has not been identified, and it is not known if the GAB is representative of the entire pegmatite body. No country rock remains attached to the base or top of the GAB; it is therefore not possible to determine the nature of the adjacent country rock or the contact relationships. The margins of the GAB were determined by textural features and by a "burnt, dirty" appearance that marks such margins on other dikes in this area.

The GAB is asymmetric in texture, mineral composition, and grain size. All of the aplite is below the core, as is the majority of the sub-millimeter grains. A clear majority of the garnet lies below the core as well. Both potassium feldspar and

plagioclase are distributed asymmetrically with more potassium feldspar above and more plagioclase below the core. The compositions of the individual minerals are also asymmetric (see the description of minerals that follows). The pocket zone is likewise asymmetric, with 55% of the dike occurring above the pocket zone.

The following description is from the top of the GAB downward to the base (also see Fig. 1). A border zone (terminology of Jahns 1955), approximately 40 cm thick, occurs at the top and bottom of the block, which consists of millimeter-grained, granular quartz, potassium feldspar, Na-rich plagioclase, and muscovite. Biotite and garnet are present but occur in amounts of 1 vol% each. The upper border zone grades downward through ~3.3 m of mixed types of rock and textures. One type of rock predominates and consists of quartz, potassium feldspar (some perthitic, some not), and Na-rich plagioclase. Zones of millimeter-grained rock are intermixed with centimeter-grained rock, and these zones are crudely parallel to the walls of the dike. A second type of material makes up about 5% of this part and consists of decimeter-grained blocks of graphic potassium feldspar. These blocks are generally teardrop shaped, flare downward (inward), and are scattered sporadically, but do not appear to change in abundance in any regular way. A third type of material makes up about 5% of this part. It consists 0.1 mm grained Na-rich plagioclase, quartz, muscovite, garnet, and biotite. These grains are disseminated throughout this entire section.

A partially collapsed pocket zone (~30 cm thick) contains centimeter-sized crystals of potassium feldspar and, in one part off the line of section, massive core quartz. The pocket at the line of section is floored by aplite covered by ~1 cm of porous, granular, Na-rich plagioclase. One long pocket (or a series of smaller, connected open cavities) is present and extends across about 60% of the GAB. Some of the contents appear to have been removed by collectors—only coarse, crude, mostly broken crystals of potassium feldspar remain.

The lower half (~2.9 m thick) of the GAB is composed of aplite mixed with millimeter- to centimeter-grained, granular rock, which grades into the lower contact zone. Aplite makes up approximately one-quarter of this section and consists of granular, 0.1 mm grained quartz, Na-rich plagioclase, garnet, muscovite, and biotite; about 90% of the aplite is layered. Generally, garnet in the aplite is slightly smaller in size than the associated other minerals. In the uppermost aplite (just below the core zone), biotite is absent and traces of tourmaline and gahnite are found. Most of the aplite is intermixed with other types of pegmatitic rock, but the aplite layers become more abundant and better developed upward to near the base of the pocket zone. In the 70 cm just below the core, layered aplite predominates almost to the exclusion of other types of rock. Layering in the aplite results from alternating concentrations of garnet and quartz-feldspar-mica. The layers range from ~1 mm to a few centimeters thick depending on the minerals present—garnet-rich layers are thinner, whereas quartz-feldspar-mica layers are thicker. Garnet-rich layers may be nearly monomineralic, but may also contain up to 70% intermixed quartz, feldspar, and mica. Na-rich plagioclase is the predominant feldspar in the aplite with potassium feldspar present in

amounts of only a few percent at most.

The non-aplite rock in the lower part of the GAB is bimodal in grain size. Approximately 90 vol% is millimeter- to centimeter-grained quartz, potassium feldspar, and Na-rich plagioclase, and ~10 vol% is 0.1 millimeter-sized grains of disseminated quartz, Na-rich plagioclase, muscovite, garnet, and biotite.

Much of the GAB is granitic in texture, but it is bimodal in many (if not most) places and even trimodal in some. Large grains of potassium feldspar in the upper part create a porphyritic texture in ~10% of the rock. The range in grain size is extreme; the smallest grains (in the lower, aplitic part) are as small as 0.1 mm in diameter, and the largest grains are up to 40 cm in their maximum dimension. The quartz and feldspar are anhedral, and the mica typically forms subhedral plates. More than 70% of the garnet is euhedral and occurs as simple dodecahedra and trapezohedra. Within the layered aplite, the garnet is predominately euhedral. Although this type of fine-grained rock in pegmatite bodies is commonly referred to as aplite, it does not have the same texture as aplitic dikes. In the GAB it has a considerable range in grain size—some grains in layered aplite are up to 10 times larger than the grains in adjacent layers.

The small amount of tourmaline occurs in two forms. One consists of euhedral prisms, generally <2 mm on the *c* axis with a length:diameter ratio of ~10:1. These grains most commonly are found in the uppermost aplite and are oriented typically with the long direction approximately parallel to the layering of the aplite; measurements (n = 66) of the orientation have a standard deviation from parallel (to layering in the aplite) of 16°. The second form consists of ragged, subhedral, elongate grains up to 15 cm long. These grains are most commonly found in the rock just above the pocket zone. They are oriented randomly and, in some places, occur as two or more grains radiating from a common point.
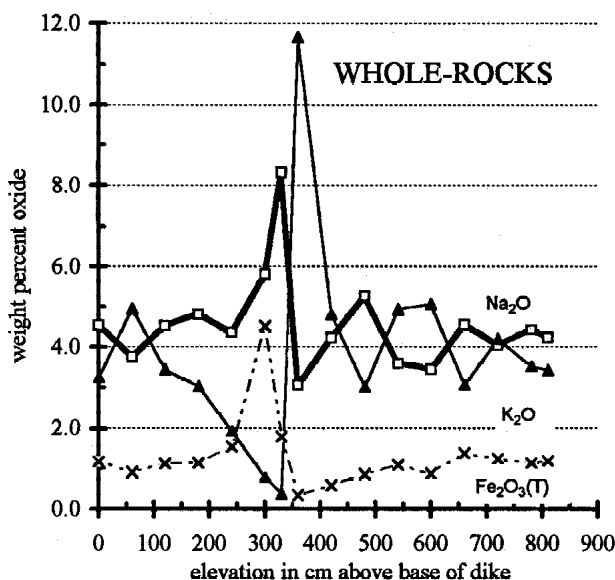
TABLE 1. Major oxide and F composition for samples of the George Ashley Block pegmatite

Sample ID	Elev. (cm)	oxides, F, and LOI (weight percent)			
		SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	MgO
O*		74.7	14.0	1.60	0.11
O	810	74.8	14.4	0.76	<0.10
N*		74.5	13.9	1.68	0.11
N	780	74.9	14.3	0.59	<0.10
M*		72.8	14.2	1.66	0.10
M	720	76.2	13.5	0.83	0.14
L*		73.9	14.0	2.09	0.11
L	660	74.7	14.6	0.68	0.11
K*		74.3	13.9	1.10	0.11
K	600	74.6	14.0	0.66	0.13
J*		75.6	13.3	1.64	0.16
J	540	74.3	14.0	0.56	0.10
I		*76.8	13.1	1.30	<0.10
I	480	73.4	14.6	0.43	<0.10
H*		70.1	15.8	0.63	<0.10
H	420	77.8	13.6	0.51	0.10
G*		64.2	18.6	0.54	<0.10
G	360	65.2	18.4	0.15	<0.10
P*	330	72.3	15.5	1.79	<0.10
F*		69.3	15.5	4.25	0.14
F	300	68.3	15.7	4.79	0.15
E*		73.9	14.7	2.12	0.14
E	240	76.7	13.7	0.96	0.13
D*		74.5	14.0	1.58	0.12
D	180	74.6	14.2	0.71	0.10
C*		74.6	14.0	1.61	0.12
C	120	74.1	14.4	0.64	0.10
B*		74.6	14.1	1.17	0.12
B	60	73.7	14.5	0.65	0.12
A*		74.2	14.1	1.55	0.11
A	0	74.9(2)	14.1(2)	0.78(2)	0.11(2)
mean		73.5	14.6	1.31	0.10
std.dev.		3.1	1.3	1.03	0.03
Wted.		73.6	14.5	1.26	0.09

Note: Analyses were by XRF; analysts were J.S. Mee and D.F. Siems, U.S. Geological Survey, Lakewood, Colorado. Elev. is the elevation of the sample above the base in centimeters; LOI is the loss on ignition at 925 °C; H$_2$O is the total water (analyst was T.R. Peacock, U.S. Geological Survey, Lakewood, Colorado); Wted. represents a mean, weighted for the amount of rock represented by that sample; F was measured by ICP-AES on a separate split of the same sample (analyst was J.H. Blullock, U.S. U.S. Geological Survey, Lakewood, Colorado); for calculation of means and ratios, below detection values (<0.xx) are assumed to be: MgO = 0.05, TiO$_2$ = 0.01, MnO = 0.00; n.d. = not determined. Amounts below the detection level are indicated by "<x.xx" where x.xx is the limit of detection. Sample G was from the core zone and was a single, large crystal of microcline. A/CNK = Al$_2$O$_3$/(CaO+Na$_2$O+K$_2$O) = peraluminus index. Total Fe is reported as Fe$_2$O$_3$.
*Analyses from a second split of the same sample.

CHEMISTRY AND MINERALOGY

Major and minor (trace) element chemistry

With few exceptions, elemental abundances in the bulk samples correlate with modal mineralogy. As a result, the individual sample compositions reflect a lack of mineralogic homogeneity among the samples (Table 1 and Fig. 3). As with the major-element analyses, individual-sample, minor-element bulk chemistry also reflects a lack of homogeneity among the samples (Table 2).

Mineralogy

All of the samples (except G) contain quartz, Na-rich plagioclase, potassium feldspar, muscovite, biotite, and Mn-rich garnet (Table 3). Tourmaline is sparse and occurs only in the most

FIGURE 3. Fe$_{total}$ as Fe$_2$O$_3$(T), Na$_2$O, and K$_2$O contents (in wt%) of bulk samples of the George Ashley Block pegmatite body vs. elevation.

TABLE 1.—*Extended*

				oxides, F, and LOI (weight percent)						molar A/
CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO	F	LOI	Total	H$_2$O	CNK
0.32	4.25	3.20	0.03	0.10	0.14	0.04	1.30	99.8	n.d.	1.27
0.29	4.19	3.66	0.04	0.07	0.20	n.d.	0.86	99.3	0.69	1.27
0.34	4.47	3.41	0.04	0.10	0.06	0.05	1.29	100.0	n.d.	1.19
0.31	4.38	3.66	0.04	0.07	0.07	n.d.	0.84	99.2	0.67	1.22
0.34	3.92	5.34	0.04	0.12	0.03	0.04	1.08	99.7	n.d.	1.11
0.39	4.16	3.05	0.05	0.07	0.04	n.d.	0.88	99.3	0.74	1.24
0.44	4.80	2.72	0.03	0.10	0.11	0.03	1.21	99.5	n.d.	1.20
0.40	4.32	3.41	0.04	0.06	0.07	n.d.	0.96	99.4	0.75	1.27
0.24	3.57	4.79	0.03	0.12	0.02	0.03	1.19	99.4	n.d.	1.21
0.22	3.33	5.33	0.04	0.09	0.02	n.d.	0.67	99.1	0.74	1.20
0.33	3.97	3.65	0.04	0.10	0.03	0.04	0.90	99.8	n.d.	1.20
0.21	3.21	6.23	0.03	0.09	0.02	n.d.	0.48	99.2	0.46	1.13
0.49	6.25	0.83	0.03	0.10	0.04	0.04	0.65	99.6	n.d.	1.09
0.29	4.28	5.19	0.03	0.08	0.03	n.d.	0.39	98.7	0.41	1.11
0.08	4.33	7.59	<0.02	0.16	0.02	0.02	0.63	99.4	n.d.	1.02
0.08	4.11	2.04	0.03	0.07	0.04	n.d.	1.03	99.4	0.96	1.49
0.03	3.21	11.50	<0.02	0.24	<0.01	0.02	0.90	99.2	n.d.	
0.03	2.90	11.80	0.03	0.22	0.02	n.d.	0.23	99.0	0.26	
0.09	8.31	0.38	<0.02	0.18	0.81	0.06	0.41	99.8	n.d.	1.09
0.15	6.07	0.81	0.03	0.14	2.91	0.04	0.55	99.9	n.d.	1.39
0.13	5.56	0.75	0.03	0.13	3.82	n.d.	0.43	99.8	0.39	1.54
0.33	4.40	1.96	0.03	0.10	0.74	0.04	1.26	99.7	n.d.	1.48
0.34	4.33	1.92	0.04	0.07	0.27	n.d.	0.76	99.2	0.74	1.40
0.46	5.05	2.74	0.04	0.12	0.05	0.03	1.00	99.7	n.d.	1.16
0.38	4.56	3.31	0.03	0.09	0.08	n.d.	0.51	98.6	0.52	1.21
0.49	4.79	2.87	0.03	0.11	0.04	0.03	1.01	99.7	n.d.	1.18
0.40	4.26	4.02	0.03	0.09	0.06	n.d.	0.51	98.6	0.56	1.19
0.30	3.98	4.36	0.03	0.14	0.15	0.03	0.78	99.8	n.d.	1.19
0.25	3.53	5.56	0.04	0.13	0.05	n.d.	0.53	99.1	0.56	1.18
0.41	4.70	3.18	0.03	0.11	0.17	0.03	1.10	99.7	n.d.	1.18
0.39(2)	4.37(4)	3.31(2)	0.04(1)	0.08(1)	0.13(2)	n.d.	0.67(5)	98.9	0.60(5)	1.23
0.29	4.44	3.98	0.03	0.11	0.35	0.04	0.81	99.4	0.60	1.20
0.13	1.05	2.68	0.01	0.04	0.87	0.01	0.30	0.4	0.19	
0.29	4.45	3.93	0.03	0.11	0.30	0.04	0.79	99.4	0.59	1.20

TABLE 2. Minor (trace) elements in samples from the George Ashley Block pegmatite body

Sample							Element (ppm)											
ID	Elev.	B	Ba	Be	Ce	Cu	Ga	Li	La	Mn	Nb	Nd	Pb	Sc	Sr	Th	Y	Yb	Zn
O	810	12	90	2	12	<1	20	50	5	1400	6	7	9	3	6	<4	10	1	21
N	780	11	110	1	14	<1	17	59	7	450	6	7	11	3	7	<4	6	<1	28
M	720	11	150	<1	11	<1	16	61	6	260	6	8	10	4	11	<4	4	<1	39
L	660	13	140	1	12	<1	18	52	6	480	6	5	10	3	10	<4	5	<1	30
K	600	11	210	1	6	<1	16	78	3	98	9	4	12	<2	10	7	<2	<1	42
J	540	9.7	140	<1	<4	<1	15	87	2	110	4	<4	17	<2	7	<4	<2	<1	32
I	480	12	160	1	<4	<1	14	99	<2	180	<4	<4	14	<2	7	<4	<2	<1	24
H	420	29	5	4	<4	<1	30	160	<2	240	16	<4	<4	<2	<2	<4	<2	<1	35
G	360	65	11	2	<4	<1	15	210	<2	130	<4	<4	8	<2	<2	<4	<2	<1	4
F	300	41	7	1	64	<1	42	68	19	26000	7	49	<4	<2	<2	29	7	<1	81
E	240	12	24	1	29	<1	23	100	11	2000	6	15	6	5	2	5	42	8	40
D	180	12	130	2	12	2	18	98	5	550	7	9	13	2	8	<4	6	<1	34
C	120	10	240	2	13	4	17	77	6	460	5	9	16	2	11	<4	5	<1	31
B	60	12	240	2	6	9	17	88	3	360	9	5	17	<2	11	<4	3	<1	47
A	0	9.8	120	2	13	29	18	54	6	1000	7	8	10	3	10	<4	11	2	35
mean		18	118	1	13	n.d.	20	89	5	2248	7	9	10	n.d.	7	n.d.	7	n.d.	35
std.dev.		16	79	1	16	n.d.	7	44	5	6592	3	12	5	n.d.	4	n.d.	10	n.d.	16

Note: Analyses were by ICP-OES; analyst was D.L. Fey, U.S. Geological Survey, Lakewood, Colorado. Elev. is the elevation of the sample above the base of the block in centimeters. For calculating means, the assumed values for amounts less than the level of detection are: Be = 0, Ce = 2, La = 1, Nb = 2, Nd = 2, Pb = 2, Sr = 1, Y = 1. Looked for but not detected (at the indicated level of detection) in any sample were: Ag<2, As<10, Bi<10, Cd<2, Co<1, Cr<1, Eu<2, Ho<4, Mo<2, Ni<2, Sn<2, Ta<40, U<100, V<2.

interior rock samples. No tourmaline was found in the pockets, and a few small (<0.5 mm) scattered grains of gahnite were found in sample P. Details on the petrography and chemistry of the pegmatite minerals appear in the following sections.

Quartz. Quartz comprises ~42 vol% of the pegmatite body and most is present as anhedral grains. Massive quartz also occurs in one section of the pocket, off of the line of traverse

and sampling; a casual examination of this quartz indicates that it is centimeter grained.

Potassium feldspar. Potassium feldspar occurs in nearly all samples, most commonly as anhedral, millimeter- to centimeter-sized grains, but also as isolated, large (~10–40 cm), tear-drop-shaped grains in the upper part of the pegmatite body. In the core, it forms large (several centimeters long), euhedral crys-

TABLE 3. Modes of samples from the George Ashley Block pegmatite body

Sample ID	Elevation (cm)	quartz	plagioclase	Potassium feldspar	muscovite	biotite	garnet	tourmaline	Total
				Minerals by volume percent					
O	810	53	20	19	7	<1	1	0	100
N	780	50	24	19	7	<1	<1	0	100
M	720	49	32	10	7	2	<1	0	100
L	660	57	16	16	11	<1	1	0	101
K	600	36	27	25	10	1	<1	0	99
J	540	36	16	44	3	2	<1	0	101
I	480	38	17	39	4	2	<1	0	100
H	420	69	18	7	6	<1	1	<1	101
G	360	0	0	100	0	0	0	<1	100
P	330	43	55	1	<1	0	1	<1	100
F	300	40	41	0	6	0	12	<1	99
E	240	52	31	<1	15	<1	1	0	99
D	180	37	48	10	4	1	<1	0	100
C	120	41	39	11	7	2	<1	0	100
B	60	29	25	36	11	<1	<1	0	101
A	0	37	24	27	10	1	1	0	100
mean		42	27	24	7	1	2	0	100
std.dev.		15	14	25	4	1	4	0	1

Note: Minerals by area percent in thin section (~vol%). Between 100 and 150 random points were counted for each thin section; the exception was sample G which was a single, pocket crystal. Analyst was W.D. Kleck. Elevation is cm above base. Assumed value of "<1" for calculating means is 0.5.

TABLE 4. Composition of potassium feldspar from the George Ashley Block pegmatite body

sample ID	elev.	SiO_2	Al_2O_3	K_2O	CaO	Na_2O	BaO	P_2O_5	FeO	Rb_2O	Total	No. grains	An	Ab	Or
					oxides by weight percent									mol%	
O	810	65.4	18.6	15.9	<0.01	0.60	<0.02	0.08	<0.01	b.l.d.	101	avg. of 2	0.0	5.4	94.6
N	780	64.9	18.6	15.2	0.02	1.33	<0.02	0.11	0.02	b.l.d.	100	avg. of 7	0.1	11.7	88.2
M	720	65.4	18.4	15.7	<0.01	0.76	0.20	0.02	0.02	b.l.d.	100	avg. of 6	0.0	6.9	93.1
L	660	65.5	18.8	15.8	0.04	0.75	<0.02	0.08	<0.01	b.l.d.	101	avg. of 2	0.2	6.7	93.1
K	600	63.1	18.7	15.7	0.03	0.96	<0.02	0.10	0.01	b.l.d.	98	avg. of 4	0.1	8.5	91.3
J	540	64.2	18.5	15.7	0.01	1.08	<0.02	0.07	0.02	b.l.d.	100	avg. of 5	0.0	9.5	90.5
I	480	65.0	18.5	15.8	<0.01	0.57	<0.02	0.11	<0.01	b.l.d.	100	avg. of 3	0.0	5.2	94.8
H	420	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.
G	360	63.9	18.3	15.6	<0.01	1.12	n.d.	0.21	0.01	0.08	99		0.0	9.9	90.1
F	300	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.				
E	240	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		n.d.	n.d.	n.d.
D	180	65.4	18.6	15.4	0.02	1.06	<0.02	0.07	0.01	b.l.d.	101	avg. of 3	0.1	9.5	90.5
C	120	64.9	18.7	15.5	0.01	0.91	<0.02	0.18	<0.01	b.l.d.	100	1 only	0.0	8.2	91.8
B	60	65.1(1)	18.6(1)	15.4(1)	0.01	1.13(3)	<0.02	0.19(3)	0.04	b.l.d.	100	avg. of 2	0.0	10.0	90.0
A	0	65.8	18.4	15.4	0.01	0.98	0.02	<0.02	<0.01	b.l.d.	100	avg. of 5	0.0	8.8	91.2
mean		65	19	16	0.0	0.9	n.d.	0.1	n.d.	n.d.	100		0.1	8.4	91.6
std. dev.		1	0	0	0.0	0.2	n.d.	0.1	n.d.	n.d.	1				

Note: analyses were by electron microprobe (except elev. 360); analyst was E.E. Foord, U.S. Geological Survey, Lakewood, Colorado; sample G (elev.360) was analyzed by XRF. Elev. is the sample elevation above the base of the block in centimeters. Letters are the sample identity. n.d. = not determined; n.p. = not present; b.l.d. = below limits of detection. Total iron is expressed as FeO. std. dev. = standard deviation.

tals. In the samples examined in thin section, the potassium feldspar was microcline, as indicated by the presence of distinctive grid twinning. The potassium feldspar averages $An_{0.1}Ab_{8.4}Or_{91.6}$ (Table 4). Only some potassium feldspar is perthitic (at 100× magnification); this is true even in the same thin section. As a result, some of the electron-microprobe analyses may reflect inadvertent sampling of the exsolved plagioclase. Figure 4 shows that potassium feldspar in the upper part of the pegmatite body ranges to lower values of Ab than the potassium feldspar in the lower part of the pegmatite. There are small amounts of Ba in two samples, and most samples contain traces of Fe and P. One sample (sample G, pocket zone) contained detectable Rb.

Plagioclase. Two types of plagioclase are present in some samples: one enclosed in alkali feldspar to form perthite and one that crystallized as distinct grains. The perthitic (exsolved?) plagioclase was not analyzed—all of the electron-microprobe analyses were of distinct, non-perthitic plagioclase grains (in retrospect, it would have proven informative to compare analy-
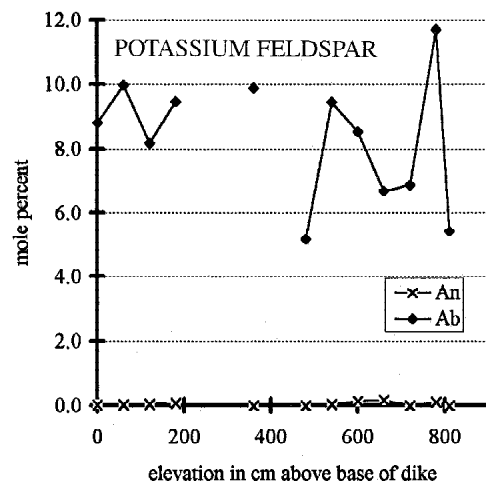

FIGURE 4. Anorthite and albite content of the potassium feldspar in samples of the George Ashley Block pegmatite body vs. elevation. Gaps are due to lack of data or absence of potassium feldspar.
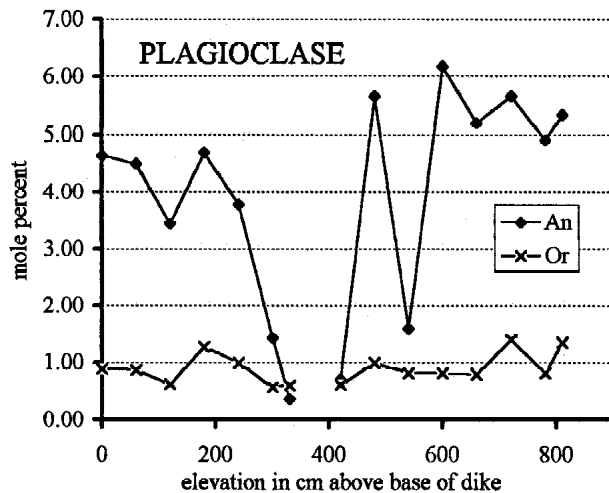
FIGURE 5. Anorthite and orthoclase content of the plagioclase in samples of the George Ashley Block pegmatite body vs. elevation.

ses of the two types). All the analyzed plagioclase is Na-rich and contains less than 2 wt% CaO+K_2O. It averages $An_{3.9}Ab_{95.2}Or_{0.9}$ (Table 5). The later (sample P, nearest the core) plagioclase is close to pure end-member albite.

There is an obvious decrease in the CaO content of the plagioclase as the core of the GAB is approached and a similar, but a less-pronounced decrease in K_2O (Fig. 5). These decreases are not smooth and regular but are accompanied by compositional oscillations. There is also compositional zoning (identified optically) in many plagioclase grains with rims being slightly more Na rich than cores.

Muscovite. Na, the most common substituting element (in the X site) for K in muscovite, shows little systematic variation across the dike (Fig. 6a). Perhaps either there was little initial variation or Na reequilibrated after crystallization. Among the substituting elements in the octahedral site (Y site), Ti and Mn are minor (and near the levels of detection), and Mg shows little variation. Fe, unfortunately, is not separable into Fe^{2+} or Fe^{3+} from electron microprobe analyses. The difference in the Fe content (expressed as FeO) across the GAB (Fig. 6a) may then reflect conditions other than concentration.

Given these things, later reequilibration may have smoothed much of the original variation in the muscovite compositions. Ti does appear to decrease, and F shows a notable (>3×) increase as the core of the GAB is approached (Fig. 6b). Several grains of muscovite contain trace amounts of P_2O_5, Cr_2O_3, and Rb_2O (Table 6), and electron microprobe analyses of grains in single polished sections reveal small compositional differences. In addition, many grains have narrow rims with a lower birefringence (and hence probably a different composition from the cores); the compositions of these rims were not specifically determined.

Biotite. Biotite is much less abundant than muscovite and is absent in parts of the pegmatite body, notably near the center and in samples that have tourmaline. In composition, it has high Fe/Mg ratios and high Al contents (compared to analyses in Deer et al. 1992) (Table 7). This biotite typically has a few
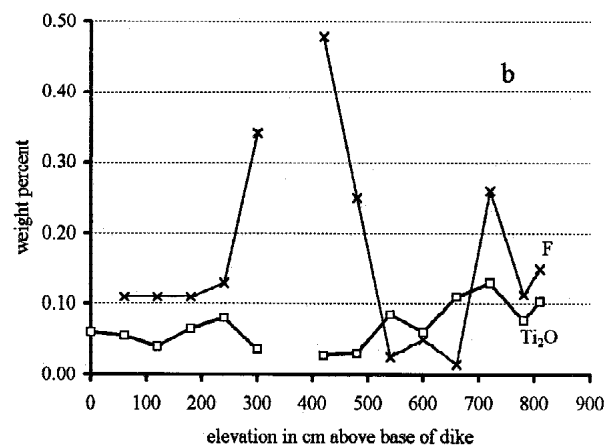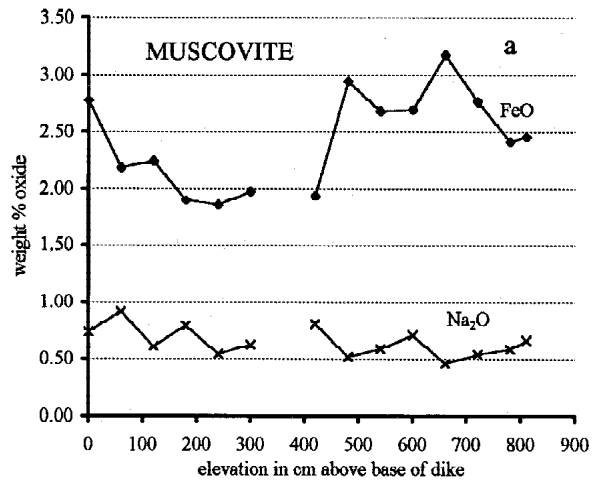
FIGURE 6. Variation of composition (in wt%) of muscovite in samples of the George Ashley Block pegmatite body vs. elevation. **(a)** Fe_{total} as FeO and Na_2O; **(b)** TiO_2 and F.

tenths wt% MnO, and some samples have trace amounts of Rb_2O. In the biotite, both MgO and TiO_2 decrease slightly and FeO increases toward the center of the pegmatite body (Table 7 and Fig. 7). Minor compositional differences were detected in individual grains by electron microprobe, but the extent of these differences was not determined.

Garnet. All samples except G contain garnet, but the total amount in any sample is small, generally 1 vol%, and the garnet grains are small (<2 mm) throughout the GAB. About 70% of the garnet grains are euhedral with well-developed crystal faces; most faces show slight etching.

The analyzed garnets are all aluminous, and the composition of the X site (at%; with considerable variation) is $Fe_{54.9}Mn_{41.5}Mg_{3.2}Ca_{0.4}$. As such, the garnet is an almandine-spessartine crystal solution in which the spessartine content (at% Mn in the X site) ranges from 28 to 54% (Table 8). Garnet compositions have a considerable range because of zoning

TABLE 5. Composition of plagioclase in the George Ashley Block pegmatite body

Sample ID	Elev.	oxides and F (wt%)										
		SiO$_2$	Al$_2$O$_3$	CaO	Na$_2$O	K$_2$O	MgO	FeO	TiO$_2$	P$_2$O$_5$	MnO	Rb$_2$O
O	810	67.7	20.8	1.16	11.15	0.25	<0.01	<0.01	<0.01	<0.02	<0.01	b.l.d.
N	780	67.4	20.4	1.08	11.41	0.15	0.01	<0.01	<0.01	0.08	0.01	b.l.d.
M	720	68.2	20.6	1.22	11.07	0.25	<0.01	<0.01	<0.01	<0.02	<0.01	b.l.d.
L	660	67.5	20.5	1.14	11.34	0.15	<0.01	0.01	<0.01	0.06	<0.01	b.l.d.
K	600	66.5	20.7	1.35	11.18	0.15	<0.01	0.01	0.01	0.07	0.01	b.l.d.
J	540	67.7	19.9	0.35	11.77	0.15	<0.01	0.03	<0.01	0.09	<0.01	b.l.d.
I	480	67.2	20.8	1.22	11.10	0.18	<0.01	<0.01	<0.01	<0.02	<0.01	b.l.d.
H	420	67.7	19.7	0.16	11.95	0.11	0.01	0.02	<0.01	0.13	<0.01	b.l.d.
P	330	69.0	19.8	0.08	11.90	0.11	<0.01	<0.01	<0.01	<0.02	<0.01	b.l.d.
F	300	68.6	19.8	0.32	11.90	0.11	<0.01	0.02	<0.01	0.13	0.01	b.l.d.
E	240	67.4	20.1	0.82	11.34	0.18	<0.01	0.02	0.01	0.09	0.01	b.l.d.
D	180	68.0	20.5	1.01	11.19	0.23	<0.01	<0.01	<0.01	<0.02	<0.01	b.l.d.
C	120	67.8	20.3	0.74	11.43	0.11	<0.01	0.01	0.01	0.12	0.01	b.l.d.
B	60	67.8(1)	20.32(8)	0.98(2)	11.42(8)	0.16(9)	<0.01	0.01	<0.01	0.09(2)	<0.01	b.l.d.
A	0	68.0	19.8	1.02	11.50	0.17	<0.01	<0.01	<0.01	<0.02	<0.01	b.l.d.
mean		67.8	20.3	0.83	11.4	0.2	n.d.	0.02	n.d.	0.10	n.d.	n.d.
std. dev.		0.6	0.4	0.43	0.3	0.0	n.d.	0.01	n.d.	0.03	n.d.	n.d.

Note: Analyses were by electron microprobe; analyst was E.E. Foord, U.S. Geological Survey, Lakewood, Colorado. Numbers on the left side are the sample elevation above the base of the block in centimeters. Letters are the sample identity; n.p. = not present; std. dev. = standard deviation; total Fe is reported as FeO; b.l.d. = below limits of detection.

TABLE 6. Composition of muscovite in the George Ashley Block pegmatite body

Sample ID	elev.	oxides and F (wt%)										
		SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO	Cr$_2$O$_3$
O	810	45.6	34.65	2.46	0.41	<0.01	0.67	10.5	0.10	<0.01	0.03	<0.01
N	780	45.2	34.97	2.41	0.39	0.01	0.59	10.8	0.08	0.01	0.03	<0.01
M	720	45.6	34.50	2.77	0.42	<0.01	0.54	10.50	0.13	0.01	<0.01	<0.01
L	660	45.2	33.75	3.18	0.48	<0.01	0.46	11.02	0.11	0.02	0.01	<0.01
K	600	43.9	34.60	2.70	0.44	0.01	0.71	10.70	0.06	0.02	0.02	0.01
J	540	44.4	34.60	2.68	0.35	<0.01	0.59	10.89	0.09	0.03	<0.01	0.01
I	480	45.3	33.93	2.95	0.48	<0.01	0.52	10.51	0.03	<0.01	0.03	<0.01
H	420	45.1	35.15	1.94	0.35	<0.01	0.81	10.41	0.03	0.01	0.06	0.01
G	360	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.
P	330	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F	300	45.8	34.72	1.98	0.35	<0.01	0.62	10.65	0.04	0.01	0.04	0.01
E	240	45.2	35.15	1.86	0.31	<0.01	0.55	10.97	0.08	0.02	0.03	0.01
D	180	45.4	35.10	1.90	0.37	0.03	0.80	10.54	0.07	0.02	0.02	0.02
C	120	45.4	35.30	2.24	0.38	<0.01	0.61	10.46	0.04	<0.01	0.01	<0.01
B	60	45.1(1)	34.85(9)	2.19(4)	0.38(1)	<0.01	0.92(2)	10.40(6)	0.06(2)	0.02	0.02	<0.01
A	0	46.3	34.60	2.78	0.39	<0.01	0.74	10.56	0.06	<0.01	0.01	<0.01
mean		45.2	34.69	2.43	0.39	n.d.	0.65	10.63	0.07	n.d.	n.d.	n.d.
std. dev.		0.6	0.46	0.44	0.05	n.d.	0.11	0.21	0.03	n.d.	n.d.	n.d.

Note: Analyses were by electron microprobe; analyst was E.E. Foord, U.S. Geological Survey, Lakewood, Colorado. Elev. is the sample elevation in centimeters above base; letters are the sample identity; n.d. = not determined; n.p. = not present; the value of SiO$_2$ for sample B at 60 cm has been adjusted (from 42.9) for a likely error; std. dev. = standard deviation; total Fe reported as FeO.

TABLE 7. Composition of biotite in the George Ashley Block pegmatite body

Sample ID	Elev.	oxides and F (wt%)												Total	No. grains
		SiO$_2$	Al$_2$O$_3$	FeO	MgO	CaO	Na$_2$O	K$_2$O	TiO$_2$	P$_2$O$_5$	MnO	Rb$_2$O	F		
O	810	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
N	780	35.7	18.57	21.92	5.25	0.15	0.14	7.67	1.27	<0.01	0.56	<0.02	0.68	92	avg. of 2
M	720	35.9	18.65	22.72	5.34	0.01	0.08	8.56	1.26	0.21	0.61	<0.02	0.34	94	ave. of 4
L	660	35.5	18.00	23.12	5.73	0.04	0.06	9.24	1.36	0.01	0.81	0.02	0.19	94	avg. of 2
K	600	34.9	18.23	22.17	5.64	0.08	0.14	8.75	1.14	0.02	0.59	0.04	0.27	92	avg. of 5
J	540	35.3	18.95	23.89	4.65	0.12	0.11	8.84	1.00	0.01	0.55	0.02	0.10	94	avg. of 4
I	480	35.1	19.09	23.97	3.92	0.03	0.08	9.01	0.85	<0.01	0.71	<0.02	0.75	93	avg. of 2
H	420	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
G	360	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.		
F	300	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.		
E	240	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
D	180	34.8	20.07	23.77	4.64	0.09	0.06	8.78	0.60	<0.01	0.50	<0.02	0.40	94	avg. of 2
C	120	35.5	19.38	24.52	4.77	0.10	0.08	8.77	0.75	<0.01	0.54	<0.02	0.54	95	avg. of 2
B	60	34.8(1)	19.59(8)	23.97(5)	4.64(4)	0.14(1)	0.09(1)	8.81(5)	0.59(3)	0.01	0.46(3)	0.06	0.27(5)	93	avg. of 2
A	0	36.3	18.54	22.79	5.63	0.11	0.11	8.67	1.10	<0.01	0.71	<0.02	n.d.	94	avg. of 3
mean		35.4	18.90	23.3	5.02	0.09	0.09	8.71	0.99	n.d.	0.60	n.d.	0.39	94	
std. dev.		0.5	0.64	0.87	0.59	0.05	0.03	0.41	0.28	n.d.	0.11	n.d.	0.22	1	

Note: Analyses were by electron microprobe; analyst was E.E. Foord, U.S. Geological Survey, Lakewood, Colorado. Elev. is the sample elevation above the base in centimeters; letters are the sample identity; n.d. = not determined; n.p. = not present; total Fe is reported as FeO; std. dev. = standard deviation.

TABLE 8. Composition of garnet (cores) in the George Ashley Block pegmatite body

Sample ID	elev.	\multicolumn{7}{c}{oxides and F (wt%)}			\multicolumn{4}{c}{atom% in X}			
		SiO$_2$	Al$_2$O$_3$	FeO	MnO	MgO	CaO	F	Total	No. grains	Fe	Mn	Mg	Ca
O	810	36.9	21.25	25.9	15.6	0.97	0.16	0.23	101	avg. of 2	59	36	4.0	0.5
N	780	36.7	21.77	27.1	13.8	1.07	0.13	0.14	101	avg. of 3	63	32	4.4	0.4
M	720	37.3	21.05	27.1	14.0	0.96	0.16	0.10	100	avg. of 2	63	33	4.0	0.5
L	660	37.0	20.90	24.9	16.6	0.82	0.16	0.18	100	avg. of 2	57	39	3.4	0.5
K	600	36.6	21.00	24.0	17.3	0.76	0.07	0.15	100	avg. of 3	56	41	3.1	0.2
J	540	37.1	21.05	26.3	14.7	0.94	0.15	0.21	100	avg. of 2	61	35	3.9	0.4
I	480	36.9	20.97	26.6	14.9	0.87	0.16	0.14	100	avg. of 3	61	35	3.6	0.5
H	420	36.4	20.97	22.7	19.6	0.37	0.02	0.15	100	avg. of 3	52	46	1.5	0.0
G	360	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	n.p.	none				
P	330	37.0	20.93	19.6	22.4	0.19	0.02	0.12	100	avg. of 3	46	53	0.8	0.1
F	300	36.7	20.75	21.6	20.2	0.44	0.00	0.07	100	avg. of 2	50	48	1.8	0.0
E2	270	36.9	21.05	20.6	21.4	0.32	0.07	0.12	100	avg. of 2	48	50	1.3	0.2
E	240	37.1	21.05	26.1	15.5	0.95	0.14	0.19	101	avg. of 2	60	36	3.9	0.4
D2	210	35.9	20.95	24.5	17.3	0.73	0.16	0.09	100	avg. of 2	56	40	3.0	0.5
D	180	37.4	21.00	26.2	15.7	0.91	0.15	0.18	101	avg. of 2	60	36	3.7	0.4
C2	150	36.7	21.35	27.4	15.0	0.90	0.17	0.24	102	avg. of 2	62	34	3.6	0.5
C	120	37.1	21.00	23.6	18.6	0.75	0.12	0.14	101	avg. of 2	54	43	3.0	0.4
B2	90	36.9	20.95	23.1	18.9	0.67	0.11	0.21	101	avg. of 2	53	44	2.7	0.3
B	60	36.0(1)	21.20(8)	24.5(1)	17.7(1)	0.80(2)	0.18(1)	0.15(1)	100	avg. of 2	56	41	3.2	0.5
A	0	36.8	21.07	24.7	17.6	0.84	0.17	0.20	101	avg. of 3	56	40	3.4	0.5
mean		36.8	21.07	24.5	17.2	0.75	0.12	0.16	101		57	40	3.1	0.4
std. dev.		0.4	0.21	2.2	2.5	0.25	0.06	0.05	1		5	6	1.0	0.2

Note: Analyses were by electron microprobe; analyst was E.E. Foord, U.S. Geological Survey, Lakewood, Colorado. Sample ID is the designation of the sample; elev. is the sample elevation above the base in centimeters; n.p. = not present; total Fe is reported as FeO; std. dev. = standard deviation; sample P was collected off of the section line.

content at 300 cm elevation (see Fig. 3) is the result of a high concentration of garnet in that sample]. Fe$_{total}$, MnO, and CaO all appear to decrease (slightly) toward the core zone of the GAB (see Table 1). However, these changes in concentration are neither regular nor distinct. Li and B are the only elements showing obvious changes across the dike. Both are concentrated in the center (see Table 2), and in the last rock to solidify (if solidification was from the margins inward).

With the exceptions of B and Li, neither the major or minor elements unequivocally show significant changes across the dike. However, the changes in composition of individual minerals are more evident and therefore may document changes in the overall chemistry of the system from the margins toward the core. For example, (1) the F content of the rock varies little across the GAB, but the F content of muscovite (see Fig. 6) indicates enrichment in the center of the dike; (2) Fe, Mn, Mg, and Ca in garnet show clear patterns of enrichment and depletion (see Fig. 10); (3) Ca in plagioclase (see Fig. 5) shows depletion; (4) TiO$_2$ and Fe$_{total}$ in muscovite (see Fig. 6) as well as MgO and TiO$_2$ in biotite (see Fig. 7) may also indicate depletion, although reequilibration of the micas may obscure the patterns.

In addition, most of the minerals from the upper parts of the GAB have compositions and compositional trends that are slightly different from, but symmetrical with, the minerals in the lower parts of the GAB (see Figs. 4–10); these varieties in mineral compositions indicate slight differences in the chemical environment. It is suggested that the escape of volatile substances was primarily upward; therefore, the chemical environment in the upper part of the pegmatite body was slightly different from the lower part (richer in F; richer in water, B, Li, and other substances partitioned into the volatile phase). As bulk-rock analyses generally fail to reflect changes during solidification in the GAB, it appears to be more efficient to monitor

changes in pegmatite bodies by means of mineral chemistry.

The presence of compositional zoning shows that equilibrium was achieved only between magma and the exteriors of grains. As a result, mineral zoning probably reflects some of the changes in the composition of the magma. Every mineral occurring throughout the GAB, with the exception of quartz, shows a change in composition across the pegmatite body; individual grains of garnet, plagioclase, and muscovite are also zoned, some significantly.

Biotite and tourmaline do not occur in the same parts of the GAB. Apparently, as the B content in the magma reached levels that resulted in the crystallization of tourmaline (in excess of about 2.5 wt% B$_2$O$_3$ for peraluminous melts, London et al. 1996), biotite became unstable. Perhaps the melt reached saturation in tourmaline, which consumed the elements that would have gone into biotite.

Potassium feldspar and Na-rich plagioclase

Whole-rock Na and K contents are near mirror images of each other across the GAB (see Fig. 3). The distribution of these elements reflects the distribution of plagioclase and potassium feldspar, so some process results in an uneven and contrasting distribution of these minerals (hence the elements Na and K) in the pegmatite body.

Garnet

The events recorded in the garnet (from the margin of the GAB inward) are an initial increase in Mn, an abrupt return to near original levels, then an increasing Mn content with maxima near the pocket zone of the GAB. Fe in garnet shows exactly the opposite pattern, and Mg has the same pattern as Fe but on a much reduced scale.

Most garnets in the GAB are zoned from a Mn-poorer core to an Mn-richer rim. Although late enrichment of either Fe or
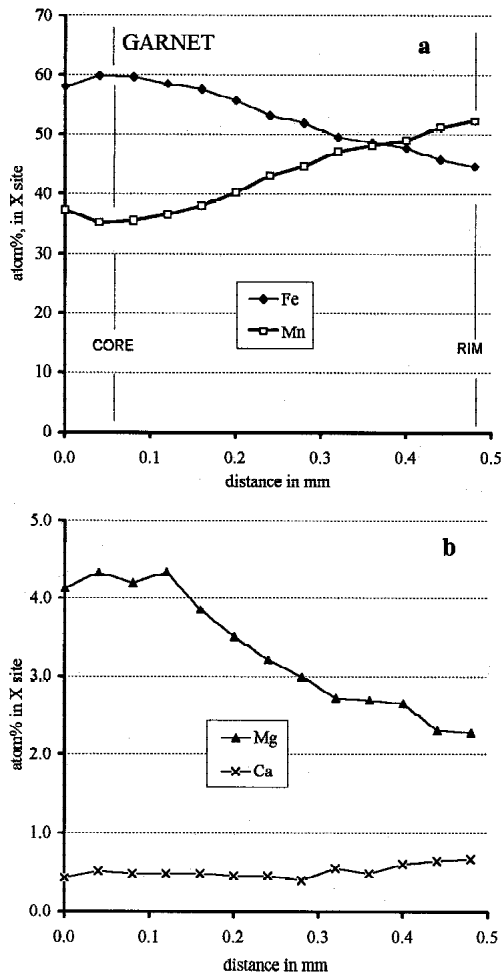
FIGURE 8. Compositional zoning in a single garnet grain from sample no. 4 (off the line of section and approximately equivalent to sample D-2) from the George Ashley Block pegmatite body. The composition is in at% in the X site. (a) Fe and Mn; (b) Mg and Ca on an enlarged scale to show detail.
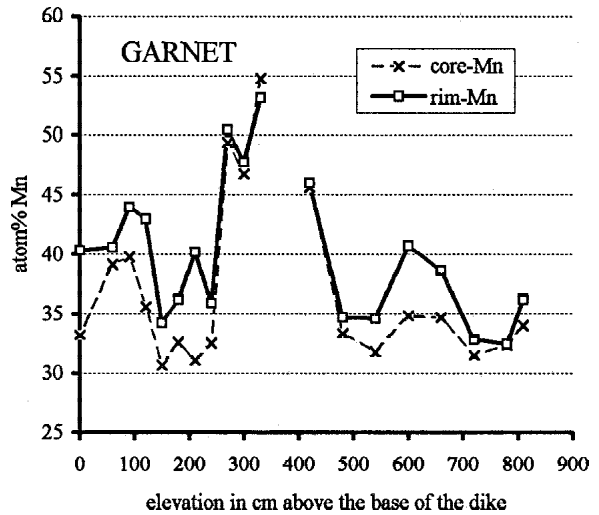

FIGURE 9. Mn composition and zoning in garnet from samples across the George Ashley Block pegmatite body.
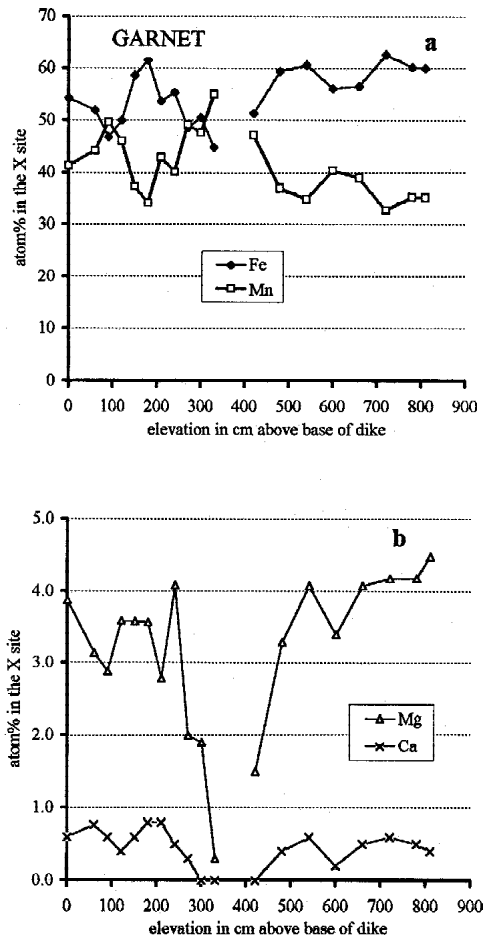

FIGURE 10. Composition (in at% in the X site) of garnet (cores only) in samples from across the George Ashley Block pegmatite. (a) Fe and Mn; (b) Mg and Ca on an enlarged scale to show detail.

Mn has been reported in igneous garnets, zoning toward Mn-poor rims is by far more common (e.g., Baldwin and von Knorring 1983; Macleod 1992; Manning 1983). Manning (1983) notes that garnet preferentially concentrates Mn and suggests that Mn-rich rims are due to retention of Mn within the garnet during resorption.

In the GAB, none of the garnets show evidence of resorption. Crystallization was probably sufficiently rapid and the temperature low enough so any evidence of resorption should be retained. It is suggested that such zoning from Mn-poorer cores to Mn-richer rims in the GAB may be due in part to the initial very low MnO content (<0.4 wt%) of the magma. The Fe_2O_3 (Fe_{total} as Fe_2O_3) content (<2 wt%) of the magma was also low, but it was about four times higher than MnO. Perhaps the Mn content becomes sufficiently high only as Fe is depleted. For example, both muscovite and biotite crystallized contemporaneously with garnet. However, the combined mica is ~4 times more abundant than garnet, and the Fe/Mn ratio for both

TABLE 9. Characteristics of the X site contents for pegmatite and aplite garnet

	Fe	Mn	Mg	Ca
median	49	50	0.9	0.8
range	2–72	25–95	0.0–5.0	0.0–10.2

Note: Contents are in at% in the X site. n = 109; 49 are from this study (38 = GAB, 4 = Little 3, 2 = Mission Dike, 5 = San Diego pegmatite). Other analyses are from Baldwin and von Knorring (1983) Harrison (1993), Leake (1976), Linnen and Williams-Jones (1993) and Whitworth (1992).

micas is much greater than the Fe/Mn ratio for garnet. Perhaps the mica preferentially utilized the Fe resulting in a magma depleted in Fe (in comparison to Mn) and therefore Mn enrichment during crystallization of the later garnet.

Some additional information comes from comparing the Fe, Mg, and Mn contents of the rock to that of the garnet. This "X-site preference" in garnet (under these conditions) is Mn>Fe>Mg in the ratio of approximately 6:1:0.2 (atom). Miller and Stoddard (1981) proposed that the Mn content of a magma is a critical factor in the crystallization of igneous, Mn-rich garnet (note that their rock and garnet compositions are nearly the same as for the GAB). They suggested that garnet begins to crystallize when the magma reaches and exceeds 0.6 wt% MnO. However, the GAB averages only 0.34 wt% MnO, and garnet crystallizes throughout. Miller and Stoddard (1981) also suggested that coexisting biotite will have MnO > 0.75 wt% whereas coexisting biotite in the GAB averages 0.60 wt% MnO. The values noted by Miller and Stoddard were derived from granites; perhaps because the GAB is a pegmatite body, the different temperature and chemical environment resulted in crystallization of garnet at lower contents of MnO.

There is now a sufficient amount of data to partially characterize pegmatitic garnet. There were 109 analyses utilized to this end (49 from this study and 60 from the literature); which are summarized in Table 9. Both the accuracy and precision of these values may be low because of several sources of data, unknown sample-selection criteria, and estimates and assumptions made in calculating the X-site occupancy. However, this information shows the approximate characteristics of Mn-rich garnet in pegmatite bodies. Because the distribution is skewed, the median is probably a better measure of the central tendency of the values.

A second injection of magma

The pattern of garnet compositions across the GAB indicates a significant event at about 40% solidification (at elevations of 120 and 600 cm; see Fig. 10). At this place garnets in the upper and lower parts show an abrupt return to nearly original compositions. It is suggested this event may have been a second injection of magma from the original source (or a chemically similar magma) with the accompanying flushing out of the residuum of the first magma; it is considered that this was a flushing rather than a mixing of the two magmas because the composition of the garnet was reset to near their original values. Such an event would restart the crystallization process for garnet at near beginning compositions. None of the other minerals show this event clearly, although both muscovite and biotite show compositional changes at about these levels. Textures and structures in the pegmatite body give no indication of

a second injection; note that several textural differences exist in the GAB and such textural evidence for a second injection may have been overlooked. Perhaps multiple injections in pegmatite bodies are a common but unrecognized phenomena.

FINAL COMMENT

A large amount of interrelated data has been presented here. E.E. Foord unfortunately cannot and the writer does not plan to utilize this information further; this data may then be used and developed by anyone interested. Most of the samples were used up during the course of analysis, and the present location of thin sections and blocks from which they were cut is unknown as they were in E.E. Foord's possession at the time of his death. W.D. Kleck has the crushed rock from which the garnet grains were taken for grain mounts. These samples weigh >30 grams, and only a few garnet grains have been removed; splits from these samples are available to anyone interested in further research.

REFERENCES CITED

Ague, J.J. and Brandon, M.T. (1992) Tilt and northward offset of Cordilleran batholiths resolved using igneous barometry. Nature, 360, 146–149.

Baldwin, J.R. and von Knorring, O. (1983) Compositional range of Mn-garnet in zoned granitic pegmatites. Canadian Mineralogist, 21, 683–688.

Deer, W.A., Howie, R.A., and Zussman, J. (1992) An Introduction to Rock-Forming Minerals, 2ⁿᵈ edition, 696 p. Longman Scientific & Technical, Essex, England.

Foord, E.E., Spaulding, L.B. Jr., Mason, R.A., and Martin, R.F. (1989) Mineralogy and paragenesis of the Little Three mine pegmatites, Ramona district, San Diego County, California. The Mineralogical Record, 20, 101–127.

Harrison, T.N. (1988) Magmatic garnets in the Cairngorm granite, Scotland. Mineralogical Magazine, 52, 659–667.

Jahns, R.H. (1955) The study of pegmatites. In Economic Geology, Fiftieth Anniversary Volume, 1025–1130.

Jahns, R.H. and Tuttle, O.F. (1963) Layered pegmatite-aplite intrusives. Mineralogical Society of America, Special Paper 1, 78–92.

Jahns, R.H. and Wright, L.A.(1951) Gem- and lithium-bearing pegmatites of the Pala District, San Diego County, California. 72 p, California Division of Mines Report 7-A.

Kleck, W.D. (1994) The Ashley Block—a pegmatite in section, Hiriart Mt., Pala Pegmatite District, San Diego Co., CA. Geological Society of America, Abstracts with Programs, 26, 63.

——(1996) Crystal settling in pegmatite magma. Geological Association of Canada—Mineralogical Association of Canada Annual Meeting, 1996, Program with Abstracts, 21, A50.

Leake, B.E. (1976) Zoned garnets from the Galway Granite and it's aplite. Earth and Planetary Science Letters, 3, 311–316.

Lichte, F.F., Golightly, D.W., and Lamothe, P.J. (1987) Inductively coupled plasma-atomic emission spectrometry. In P.A. Baedecker, Ed., Methods for geochemical analysis. U. S. Geological Survey Bulletin 17770, B1-B15.

Linnen, R.L. and Williams-Jones, A.E. (1993) Mineralogical constraints on magmatic and hydrothermal Sn-W-Ta-Nb mineralization at the Nong Sua aplite-pegmatite, Thailand. European Journal of Mineralogy, 5, 721–736.

London, D., Morgan, G.B., and Wolf, M.B. (1996) Boron in granitic rock and their contact aureoles. In Mineralogical Society of America Reviews in Mineralogy, 33, 299–385.

Macleod, G. (1992) Zoned manganiferous garnets of magmatic origin from the Southern Uplands of Scotland. Mineralogical Magazine, 56, 115–116.

Manning, D.A.C. (1983) Chemical variation in garnets from aplites and pegmatites, peninsular Thailand. Mineralogical Magazine, 47, 353–358.

Miller, C.F. and Stoddard, E.F. (1981) The role of manganese in the paragenesis of

magmatic garnet: an example from the Old Woman-Piute Range, California. Journal of Geology, 89, 233–246.

Orville, P.M. (1960) Petrology of several pegmatites in the Keystone District, Black Hills, South Dakota. Bulletin of the Geological Society of America, 71, 1467–1490.

Simpson, D.R. (1965) Geology of the central part of the Ramona pegmatite district, San Diego County, California. California Division of Mines and Geology Special Report 86, 3–23.

Taggart, J.E. Jr., Lindsay, J.R., Scott, B.A., Vivit, D.V., Bartel, A.J., and Stewart, K.C. (1987) Analysis of geologic materials by wavelength-dispersive X-ray fluorescence spectrometry. In P.A. Baedecker, Ed., Methods for geochemical analysis. U.S. Geological Survey Bulletin 1770, E1-E19.

Webber, K.L., Falster, A.U., Simmons, W.B., and Foord, E.E. (1997) The role of diffusion-controlled oscillatory nucleation in the formation of line rock in pegmatite-aplite dikes. Journal of Petrology, 38, 1777–1791.

Whitworth, M.P. (1992) Petrogenetic implications of garnets associated with lithium pegmatites from SE Ireland. Mineralogical Magazine, 56, 75–83.