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Areal Distribution and Geophysical Significance of Heat Generation in the Idaho Batholith and Adjacent Intrusions in Eastern Oregon and Western Montana

ABSTRACT

Gamma-ray spectrometry has been used to measure potassium (K), uranium (U), thorium (Th), heat generation (A), Th/U, and $(A - A_k)/\mathrm{K}$ (A_k = heat from potassium) for over 600 samples in the Idaho batholith. Values of heat generation are remarkably consistent within a given pluton, but vary markedly and predictably between plutons of different composition and(or) different levels of emplacement. Values of $(A - A_k)/\mathrm{K}$ are similar for suites of rocks that were emplaced at approximately the same depth during the same intrusive event, but are considerably different between suites belonging to different intrusive events emplaced at different depths. Thus, on the basis of their $(A - A_k)/\mathrm{K}$ ratio and various geologic parameters, the rocks of the Idaho batholith can be divided into four intrusive groups. Table 1 lists these groups with their characteristics, weighted according to areal abundances of the constituent plutons.

The remarkable uniformity of heat generation for a given igneous unit, even over large geographical areas, and the uniformity of $(A - A_k)/\mathrm{K}$ for rocks intruded during the same intrusive event suggest that these parameters are diagnostic properties of igneous rocks, and may be used by the geologist to map individual units, to correlate different rock types intruded during the same intrusive event, and to separate similar rock types intruded during different intrusive events.

INTRODUCTION

The amount of heat generated by radioactive disintegration of potassium, uranium, and thorium is related to heat flow by the equation (Birch and others, 1968)

$$Q = Q_0 + Ab \qquad (1)$$

where Q is surface heat flow (hfu = 10^{-6} cal/cm²-sec), A is surface heat generation (hgu = 10^{-13} cal/cm³-sec), and b and Q_0 are constant within a given heat-flow province (Roy and others, 1968).

Equation (1) is consistent with a wide variety of heat generation–depth relations, three of which are discussed by Lachenbruch (1970, 1971):

$$A(z) = A_0 \qquad 0 \leq z \leq b \qquad \text{constant source model} \qquad (2)$$

$$A(z) = A_0(1 - z/2b) \qquad 0 \leq z \leq 2b \qquad \text{linear model} \qquad (3)$$

$$A(z) = A_0 \exp(-z/b) \qquad 0 \leq b \qquad \text{exponential model.} \qquad (4)$$

Lachenbruch (1968) argues theoretically that the exponential model is required to reconcile

TABLE 1. INTRUSIVE GROUPS OF THE IDAHO BATHOLITH

	A (hgu)	$(A - A_k)/\mathrm{K}$	Approx. outcrop area (km²)
West border group	0.8	0.5	1,150
Main group	2.6	0.8	24,200
Intermediate group	3.6	1.3	2,500
Tertiary epizonal group	6.1	1.8	6,420
Unsampled area			7,900

Average Idaho batholith (K_2O = 3.2%, U = 1.9 ppm, Th = 9.1 ppm, A = 3.3 hgu, Th/U = 4.9)

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differential erosion with the linear relation between heat flow and heat generation (equation 1). Swanberg (1972) develops experimental evidence for a decrease in heat generation due to decreasing uranium and thorium with increasing depth of emplacement consistent with the exponential model, but, however, finds ambiguous evidence on the manner of variation of Ak (the heat contribution from potassium) with increasing depth. Because potassium usually contributes 20 percent or less to the total heat generation, the exponential model must apply to the bulk of the heat produced. So equation (4) can be written in the form (Swanberg, 1972)

$$A(z) = (A - Ak)_0 \exp(-z/b) + Ak(z) \quad (5)$$

or

$$(A - Ak)_z = (A - Ak)_0 \exp(-z/b) \,. \quad (6)$$

Another important result, on which the interpretation of much of the data in this paper is based, is that the ratio of the heat generation (less the contribution from potassium) to the potassium content of the rock is constant for rocks interpreted as having been intruded during the same intrusive event, so

$$\frac{(A - Ak)}{\mathrm{K}} = \beta \quad (7)$$

(see Figs. 1 through 4, Tables 2 through 6). Using this equation, diorite to granite of one intrusive group can be separated from rocks of similar composition but of a different group by their value of β. Now it appears that the area of study has been undergoing systematic uplift, with the representatives of each intrusive group being emplaced at about the same depth and the successively younger groups being emplaced at shallower depths. For the Idaho batholith, therefore, equation (7) can be written

$$\frac{(A - Ak)_z}{\mathrm{K}(z)} = \beta(z) \,. \quad (8)$$

If β is plotted as a function of depth of intrusive group (Fig. 5; see also Swanberg, 1972), then the data can be fitted by the equation

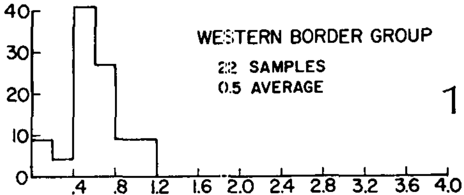
$$\beta(z) = \beta_0 \exp(-z/b) \quad (9)$$

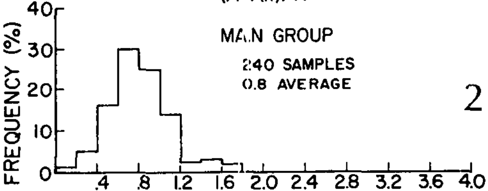
or

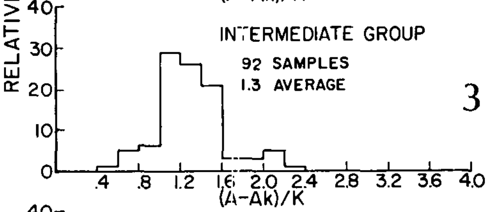
$$[(A - Ak)/\mathrm{K}]_z = [(A - Ak)/\mathrm{K}]_0 \exp(-z/b) \quad (10)$$

where b can have the same value as found for the Basin and Range province from heat-flow data (Roy and others, 1968). Equations (9) and (10) are derived from, and apply to, the *crust* and can be expected to apply to a single pluton only if one is willing to consider an extremely thick magma chamber. Thus the quantity $[(A - Ak)/\mathrm{K}]_0$ does not apply to the heat generation at the top of a given pluton, but rather to the ratio of heat generation (minus the contribution from potassium) to potassium in a pluton that crystallized under the shallowest of intrusive conditions.

It should be noted that equation (10) reduces to equation (6) for the case $\mathrm{K}(z) = \mathrm{K}_0$, the only condition under which both (6) and







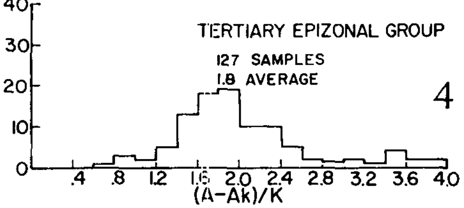


Figure 1. **Histogram of $(A - Ak)/\mathrm{K}$ values for individual samples of the west border group.**

Figure 2. **Histogram of $(A - Ak)/\mathrm{K}$ values for individual samples of the main group.**

Figure 3. **Histogram of $(A - Ak)/\mathrm{K}$ values for individual samples of the intermediate group.**

Figure 4. **Histogram of $(A - Ak)/\mathrm{K}$ values for individual samples of the Tertiary epizonal group.**

TABLE 2. SUMMARY OF DATA ON THE INTRUSIVE GROUPS OF THE IDAHO BATHOLITH

	West border[a]	Main[b]	Intermediate[c]	Tertiary epizonal[d]	Tts[e]	Average Idaho batholith[f]
K^+(%)	1.0	2.7	2.3	2.9	3.4	2.7 (3.2% K_2O)
U(ppm)	0.4	1.3	2.1	4.0	11.5	1.9
Th(ppm)	2.1	7.1	10.2	17.2	31.1	9.1
A(hgu)	0.8	2.6	3.6	6.1	13.2	3.3
Th/U	5.2	5.4	4.9	4.3	2.7	4.9
$(A - A_k)/K$	0.5	0.8	1.3	1.8	3.6	1.0
Average Pb-Alpha age (m.y.)[g]	105	108[h]	107	64[h]		
Average K-Ar age (m.y.)[i]	131	91[h,j]	66	44[h]		
z(km)[k]	14–22	9–15	6–10	0–6	0–6	
Chemical trend[l]	Trondhjemitic	Calc-Alkaline	Calc-Alkaline	Calc-Alkaline		
Outcrop area (km²)[m]	1,150	24,200	2,500	6,420	100	42,170 (about 16,000 mi²)
Samples	21	241	92	127	5	

[a] Data for constituent units given in Table 3.
[b] Data for constituent units given in Table 4.
[c] Data for constituent units given in Table 5.
[d] Data for constituent units given in Table 6.
[e] Values for the pluton (Tts) near Twin Springs, Idaho, the most radioactive pluton in the Idaho batholith.
[f] Weighted according to areal abundance of constituent plutons.
[g] Jaffe and others (1959).
[h] Does not include anomalous Tertiary dates for the quartz monzonite in the canyon of Lost Horse Creek (Kgqm).
[i] McDowell and Kulp (1969).
[j] Rb-Sr date on biotite (Reeve, 1971, written commun.).
[k] Approximate depth of emplacement (Swanberg, 1972).
[l] See Figure 9.
[m] 7,900 km² or 19% of the batholith not sampled.

(10) can be simultaneously valid. As both equations appear to be empirically true (Fig. 5; Swanberg, 1972), potassium must be constant over the depth range under consideration, a conclusion that is consistent with the potassium-depth relations of Swanberg (1972).

Once the validity and the limits of application of equations (9) and (10) have been established, they may be used to estimate the depth of emplacement for plutonic bodies, a technique that is somewhat more quantitative than the criteria described by Buddington (1959). Rewriting equations (9) and (10), we have

$$z = b \ln\left[\left(\frac{A - A_k}{K}\right)_0 \Big/ \left(\frac{A - A_k}{K}\right)_z\right] \qquad (11)$$

$$= b \ln \frac{\beta_0}{\beta_z}$$

where z is an estimate of emplacement depth for a plutonic body and $[(A - A_k)/K]_z$ is measured. If b is taken as 9.4 km, the value suggested for the Basin and Range province (Roy and others, 1968) and $[(A - A_k)/K]_0$ is taken as 3.6, the average value for the most radioactive pluton in the Idaho batholith (Tts, Table 2), then equation (11) adequately predicts the depth of emplacement for all plutons in the Idaho batholith for which depth estimates have been published or may be inferred from their geologic occurrence. Although the use of the value $[(A - A_k)/K]_0 = 3.6$ in equation (11) yields results consistent with geologic data in the Idaho batholith, there are, to date, no data on the areal distribution of $[(A - A_k)/K]_0$ within or between petrographic provinces; therefore, extreme care must be used in applying this value to other sequences of intrusive rock.

The application of equation (11) also depends on the assumption that potassium is an adequate index of magmatic evolution. The use of potassium rather than the lime-alkali (Peacock) index as suggested by Tilling and others (1970) is strictly pragmatic. Gamma-ray spectrometry allows immediate measurement of potassium, whereas the use of the lime-alkali index would require extensive chemical analysis.

Of great significance in the present study is the observed similarity of $(A - A_k)/K$ for units that were emplaced during the same intrusive event. Published materials on the Idaho

TABLE 3. SUMMARY OF K, U, Th, A, Th/U, $(A - Ak)/\mathrm{K}$ AND WEIGHTED AVERAGE VALUES FOR UNITS COMPRISING THE WEST BORDER GROUP

Map unit	JKpqd	Jkbqd	Jkcrc	Average[a]
Approx. outcrop area (km^2)	600	50	500	1,150
K (%K$^+$)				
Average	1.3	1.4	0.7	1.0
Range	0.9–1.5	1.1–1.7	0.1–0.9	
Literature[b]	1.06[c,d]	1.06[c]	0.6[c,e]	
U(ppm)				
Average	0.4	0.9	0.3	0.4
Range	0.0–0.9	0.3–1.3	0.0–0.6	
Literature[b]	1.0[f]	1.4[f]	0.8[f]	
Th(ppm)				
Average	2.6	2.9	1.4	2.1
Range	2.0–3.8	1.6–4.1	0.3–2.1	
A(hgu)				
Average[g]	1.0	1.4	0.5	0.8
Range	0.5–1.3	0.7–1.5	0.0–0.8	
Th/U[h]	6.5	3.2	4.7	5.2
$(A - Ak)/\mathrm{K}$				
Average[g]	0.5	0.8	0.5	0.5
Range	0.3–0.6	0.4–1.1	0.0–1.0	
Samples	6	4	11	21

[a] Weighted according to areal abundance of constituent units.

[b] Average of published values for each unit or equivalent units.

[c] Hietanen (1962).

[d] Larson and Schmidt (1958).

[e] Hietanen (1963a).

[f] Larson and Gottfried (1961).

[g] Average of individual samples.

[h] Calculated from average Th, U values and not from individual Th/U ratios.

batholith reveal reference to four different periods of intrusive activity (for example, Anderson, 1952). If the area including and surrounding the Idaho batholith has undergone general uplift and erosion since the onset of plutonic activity during the Jurassic, then the younger intrusive events would involve activity at increasingly shallower levels of the crust. Thus $(A - Ak)/\mathrm{K}$ ratios should be progressively higher for rocks of the younger, shallower intrusive events (equations 8 and 11). Analysis of $(A - Ak)/\mathrm{K}$ ratios for all plutons for which age dates or depth estimates are published, or may be inferred from their geologic occurrence, indicates almost without exception that plutons emplaced during younger, shallower intrusive events are enriched in $(A - Ak)/\mathrm{K}$ relative to plutons emplaced during older, deeper intrusive events. Thus, for rocks of the Idaho batholith, the $(A - Ak)/\mathrm{K}$ ratio may be used to correlate diverse rock types intruded during the same period of intrusive activity and may also be used to separate similar rock types involved in different intrusive episodes.

The present study interprets the Idaho batholith in terms of the $(A - Ak)/\mathrm{K}$ ratio, a technique that is consistent with geologic data for the Idaho batholith but remains to be tested as a general interpretive tool. The procedure followed is to measure $(A - Ak)/\mathrm{K}$ for all plutons for which age dates, depth estimates, or some other form of geologic control suggest emplacement during the same intrusive event. These values are then used to define a range of $(A - Ak)/\mathrm{K}$ as characteristic of each intrusive event. Remaining plutons are then assigned to an intrusive group on the basis of their $(A - Ak)/\mathrm{K}$ ratio and whatever geologic evidence is available. The assignment of plutons to the various groups does not knowingly contradict any published data or geologic interpretation for rocks of the Idaho batholith, unless the geologic data themselves are contradictory, in which case the $(A - Ak)/\mathrm{K}$ ratio may be used to favor one interpretation over another. In fact, much of the data on the Idaho batholith that previously was considered

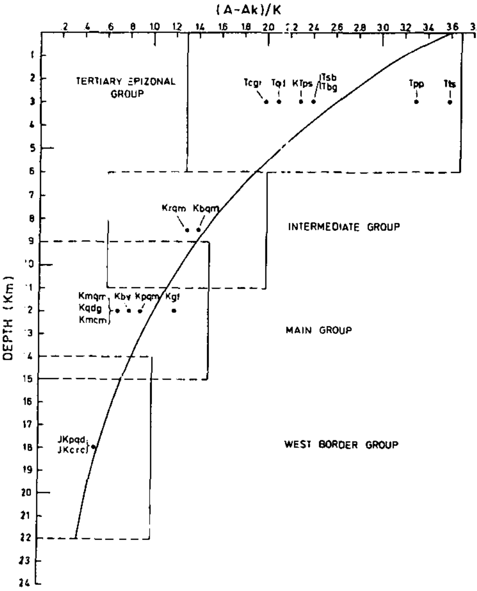


Figure 5. Plot of $(A - Ak)/\mathrm{K}$ versus depth for plutons of the four intrusive groups, showing the maximum measured range of $(A - Ak)/\mathrm{K}$, the maximum assumed range of emplacement depth (see Swanberg, 1972), and equation (11) using b = 9.4 km and $[(A - Ak)/\mathrm{K}]_0 = 3.6$. Average $(A - Ak)/\mathrm{K}$ values for the plutons arbitrarily plotted at mean depth.

anomalous, including the uranium values considered anomalous by Larson and Gottfried (1961) and the anomalous K-Ar age dates of McDowell and Kulp (1969), may be explained by the present scheme of subdivision.

In the following pages, the various units comprising the Idaho batholith are discussed, with special attention given to areas that exemplify the use of the $(A - Ak)/K$ ratio as a tool for geologic interpretation, and to areas where the geologic data are in contradiction. Units are defined according to previous geologic mapping where available and according to reconnaissance sampling in unmapped areas. The locations of the various units are shown in Figures 6 through 8. Table 2 summarizes the data upon which the present interpretations are based.

It should be noted in passing that the uniformity of heat generation and $(A - Ak)/K$ values is always greatest in plutons that have been clearly defined by detailed geologic mapping, where samples could be collected with confidence. It is likely that a significant amount of the scatter in the data (Figs. 1 through 4) results from samples collected from small plutons, contact areas, or other unrepresentative areas that were not recognized during rapid reconnaissance sampling.

WEST BORDER GROUP

Hietanen (1963a) mapped the intrusive rocks of the northwest corner of the batholith and noted that the chemical and lithologic properties of these intrusions suggest a separation into an older, synorogenic potassium-poor suite and a younger, post-orogenic potassium-rich suite. The west border group is taken here to include only the rocks of the potassium-poor suite. Major units include a large body (600 km^2) of quartz diorite near Pierce, Idaho (JKpqd), a smaller body of quartz diorite east of Bungalow Ranger Station (JKbqd), and the hornblendite, gabbro, tonalite, and quartz diorite in the canyon of the Clearwater River (JKcrc). The distribution of these units is shown in Figure 6.

The age, depth of emplacement, and chemical differentiation trend (Table 2; Fig. 9) all serve to distinguish the rocks of the west border group from the remainder of the

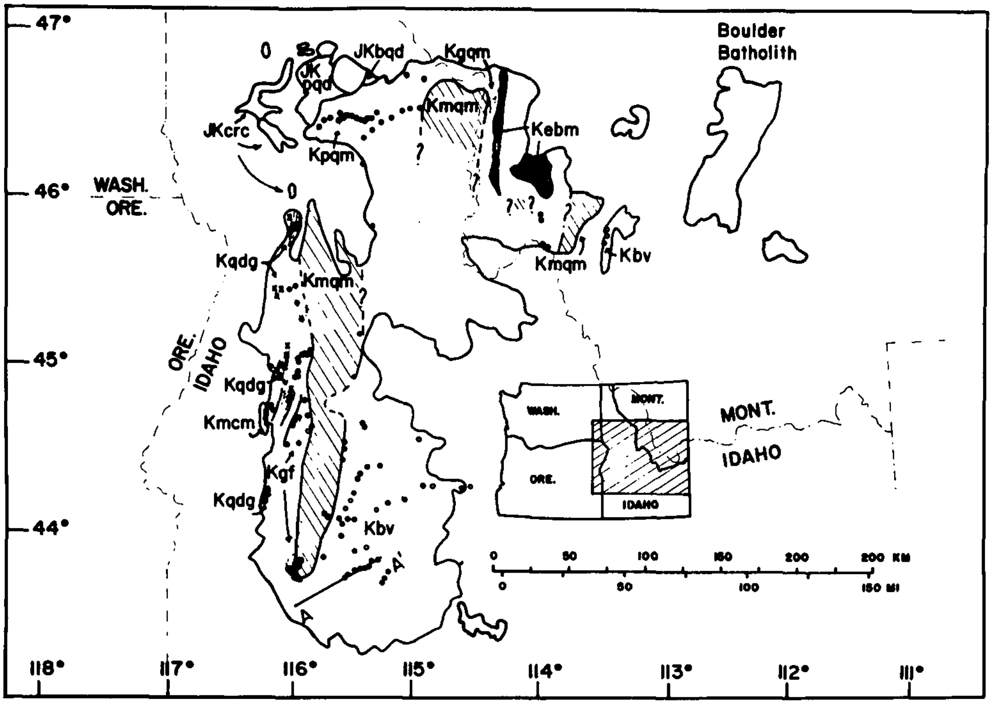


Figure 6. Index map showing the locations of the units of the west border group and the main group. Geology from Hietanen (1962), Langton (1935), Lindgren (1904), Ross and Forrester (1940), Ross and others (1955), Schmidt (1964), and the author (Kmqm). Sample locations are shown for Kbv (open circles east of Kmqm), Kgf and Kpqm (open circles west of Kmqm), Kqdg (x and shaded), and Kmcm (solid circles).

TABLE 4A. SUMMARY OF K, U, Th, A, Th/U, $(A - Ak)/K$, AND WEIGHTED AVERAGE VALUES FOR UNITS OF THE MAIN INTRUSIVE GROUP

Map unit	Kmcm	Kqdg	Kgf	Kpqm	Kmqm	Kbv	Kgqm	Kebm	Kgr	Average[a]
Approx. outcrop area (km^2)	100	1,000	1,200	1,500	8,700	10,000	700	1,000	. .	24,200
K(%K$^+$)										
Average	1.8	1.9	2.5	2.6	2.7	2.8	3.0	2.3	3.8	2.7
Range	0.9–2.5	1.0–2.9	1.1–3.6	1.2–3.9	1.6–4.7	1.9–4.4	2.5–3.6	2.5–3.1	3.1–5.1	
Literature[b]	0.9[c]	1.11[c]	2.79[c,d]	2.20[e]	3.56[c,d,f]	3.18[g]				
U(ppm)										
Average	0.5	0.6	1.6	1.4	1.3	1.5	0.6	1.1	1.5	1.3
Range	0.1–1.3	0.0–1.7	0.5–3.1	0.0–4.0	0.1–3.9	0.5–3.8	0.1–1.4	0.6–1.9	0.6–2.7	
Literature[b]		1.6[h]	1.9[h]		1.4[h]	2.2[h]				
Th(ppm)										
Average	5.1	5.3	11.0	8.8	6.7	7.1	6.0	6.3	4.8	7.1
Range	3.7–8.7	1.9–12.7	5.7–18.4	4.1–13.8	1.8–14.7	1.5–16.4	1.7–9.1	1.2–9.9	4.0–5.9	
A(hgu)										
Average[i]	1.6	1.7	3.4	2.9	2.5	2.8	2.1	2.4	2.7	2.6
Range	1.3–2.2	0.4–3.2	1.7–4.9	1.3–5.2	1.5–4.6	1.7–4.6	1.3–2.9	1.3–3.2	2.1–3.1	
Th/U[j]	10.2	8.8	6.9	6.8	5.2	4.7	10.0	5.7	3.2	5.4
$(A - Ak)/K$										
Average[i]	0.7	0.7	1.2	0.9	0.7	0.8	0.5	0.7	0.5	0.8
Range	0.5–1.2	0.0–1.6	0.7–1.7	0.6–1.5	0.3–1.3	0.2–1.2	0.2–0.9	0.3–1.0	0.3–0.8	
Samples	8	15	33	25	94	50	8	5	3	241

TABLE 4B. SUMMARY OF K, U, Th, A, Th/U, AND $(A - A_k)/\mathrm{K}$ FOR SUBDIVIDED UNITS OF THE MAIN INTRUSIVE GROUP

Map unit	Kgf	Kgf	Kgf	Kmqm	Kmqm	Kmqm	Kmqm	Kmqm	Kmqm	Kbv	Kbv	Kbv	Kbv	Kpqm
Comment	near Kmqm	near Klqd	near Schaefer Butte	near Warm Lake	southern unit	northern unit	near Lost Trail Pass	near Silver City	dike rocks	near Bear Valley	along Boise River	near Wisdom, Mont.	near Sula, Mont.	altered by intrusion of KTlt
$\mathrm{K}(\%\mathrm{K}^+)$														
Average	2.8	1.7	3.8	3.4	2.7	2.7	2.8	2.1	3.5	2.8	3.0	2.7	2.8	3.6
Literature[b]			3.1[d]	3.4[e]										
U(ppm)	1.5	1.5			1.3	1.4	1.2	0.7	2.7	1.4	1.8	1.5	1.2	2.8
Th(ppm)	9.4	9.4			6.4	7.6	7.0	7.0	4.1	7.0	6.9	8.0	7.6	16.4
A(hgu)	3.1	2.9			2.5	2.8	2.6	2.1	3.2	2.7	3.0	2.9	2.7	5.3
Th/U[j]	6.3	6.3			4.9	5.4	5.8	10.0	1.5	4.9	3.9	5.3	6.3	5.8
$(A - A_k)/\mathrm{K}$[i]	0.9	1.5			0.7	0.9	0.7	0.8	0.7	0.8	0.8	0.9	0.8	1.2
Samples	8	7	5	5	63	15	10	6	4	31	12	2	5	5

[a] Weighted according to areal abundance of constituent units.

[b] Average of published values for each unit or equivalent units.

[c] Schmidt (1964).

[d] Lindgren (1904).

[e] Hietanen (1963a).

[f] Larson and Schmidt (1958).

[g] Ross (1934).

[h] Larson and Gottfreid (1961).

[i] Average of individual samples.

[j] Calculated from average Th, U values and not from individual Th/U ratios.

TABLE 5. SUMMARY OF K, U, Th, A, Th/U, $(A - Ak)/K$ AND WEIGHTED AVERAGE VALUES FOR UNITS COMPRISING THE INTERMEDIATE INTRUSIVE GROUP

Map unit	Klqm	Kwqm	Kbqm	Klqd	Kcgn	Klgn
Approx. outcrop area (km²)	100	20	100	200	600	200
K(%K⁺)						
Average	2.6	2.6	3.4	2.3	1.9	2.1
Range	1.8–3.3	2.0–2.9	3.7	1.8–2.8	1.5–2.9	1.4–2.6
Literature[b]			3.4[c]	2.0[d]	2.5[e]	
U(ppm)						
Average	2.9	3.1	3.5	1.2	1.5	1.6
Range	1.6–4.4	2.0–4.7	3.3–3.7	0.5–1.6	0.3–2.7	1.0–2.5
Literature[b]	2.3[f]				2.0[f]	
Th(ppm)						
Average	10.0	12.1	15.1	11.5	9.2	9.1
Range	6.8–13.3	8.3–15.8	14.2–16.2	10.2–12.8	6.8–13.3	6.6–12.9
A(hgu)						
Average[g]	4.1	4.6	5.5	3.2	3.0	3.0
Range	2.9–4.7	3.1–6.3	5.1–6.0	2.8–3.8	1.9–4.7	2.1–3.7
Th/U[h]	3.4	3.9	4.3	9.6	6.1	5.7
$(A - Ak)/K$						
Average[g]	1.3	1.5	1.4	1.2	1.3	1.2
Range	1.1–1.4	1.3–1.9	1.3–1.4	1.0–1.3	0.4–2.0	0.7–2.2
Samples	4	5	3	6	15	7

Map unit	Ksgn	Kcqm	Keqm	Keqd	Krqm	Td	Average[a]
Approx. outcrop area (km²)	200	700	30	20	300	25	2,500
K(%K⁺)							
Average	1.9	2.4	2.8	1.4	3.5	1.3	2.3
Range	1.4–2.8	1.5–2.7	2.5–3.1		2.2–4.5		
Literature[b]							
U(ppm)							
Average	1.8	2.4	2.0	0.9	3.1	1.5	2.1
Range	0.8–2.9	1.2–3.6	1.1–2.8		0.8–5.6		
Literature[b]							
Th(ppm)							
Average	9.1	9.8	11.0	7.0	13.4	4.6	10.2
Range	3.0–15.4	7.5–15.0	10.2–11.8		8.7–16.3		
A(hgu)							
Average[g]	3.1	3.7	3.7	2.0	5.0	2.0	3.6
Range	1.6–4.8	2.1–5.1	3.2–4.0		3.3–6.7		
Th/U[h]	5.0	4.1	5.5	7.7	4.3	2.9	4.9
$(A - Ak)/K$							
Average[g]	1.4	1.3	1.1	1.2	1.3	1.3	1.3
Range	0.8–2.5	1.0–2.0	0.8–1.3		0.6–2.0		
Samples	9	18	3	1	20	1	92

[a] Weighted according to areal abundance of constituents.
[b] Average published values for each unit or equivalent units.
[c] Hietanen (1963a).
[d] Schmidt (1964).
[e] Lindgren (1904).
[f] Larson and Gottfried (1961).
[g] Average of individual samples.
[h] Calculated from average Th, U values and not from individual Th/U ratios.

batholith. This distinction is even more dramatically exhibited by the heat-generation data. As shown in Table 3, heat-generation values average 0.8 hgu (range, 0 to 1.5 hgu for individual samples; 0.5 to 1.4 for constituent plutons), and the $(A-Ak)/K$ ratios (Table 3; Fig. 1) average only 0.5 (range, 0 to 1.1 for individual samples; 0.5 to 0.8 for constituent plutons). Both averages are considerably lower than the values for the remainder of the batholith (Tables 4 through 6; Figs. 1 through 4), but are only slightly lower than the values for the intrusions of eastern Oregon (Table 7). Thus, Anderson's (1952) tentative correlation

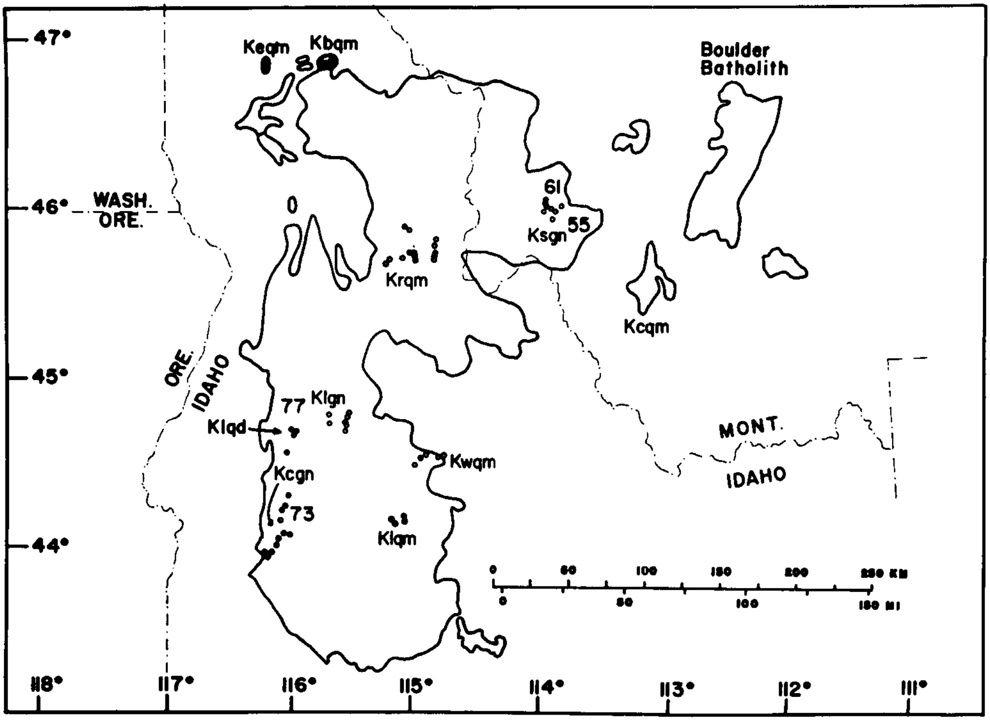


Figure 7. Index map showing sample locations for rocks included in the intermediate group. Geology from Hietanen (1962), Ross and Forrester (1940), and Ross and others (1955). Numbers indicate K-Ar age determinations of McDowell and Kulp (1969).

of the rocks of the west border group with the granitic rocks of Oregon and Washington does not appear inconsistent with the heat-generation data.

The Pb-alpha age date of 105 m.y. for the small body of quartz diorite east of Bungalow (Jaffe and others, 1959) is considerably younger than the 131-m.y. average of two hornblende and one biotite K-Ar age dates obtained for the rocks in the canyon of the Clearwater River (McDowell and Kulp, 1969), thus suggesting that the quartz diorite east of Bungalow should be included with rocks of the main group. However, the heat generation data for this unit (Table 3) show considerable scatter, possibly resulting from contact effects associated with the intrusion of the Bungalow granite (Tbg, Fig. 8), which may also have affected the age date. A definite statement for this unit cannot be made without additional data.

MAIN GROUP

The rocks intruded during the main intrusive event have an average $(A - Ak)/K$ ratio of 0.8 (range, 0 to 1.7 for individual samples; 0.5 to 0.9 for constituent plutons) as compared to 0.5, 1.3, and 1.8 for the west border, intermediate, and Tertiary epizonal groups, respectively (Figs. 1 through 4; Table 2). These rocks crop out over 24,000 km^2 in central Idaho and western Montana and, together with areas for which data are unavailable or inconclusive (7,900 km^2), constitute 75 percent of all rocks mapped as Idaho batholith (Ross and Forrester, 1940).

The rocks of the main group may be separated into seven large (5 to 50-km-wide), north-south-trending units (Fig. 6), each of which is fairly constant in physical appearance, chemical composition, and heat generation (Table 4b). For the most part, these units grade into one another in the east-west direction and may be traced or have equivalents over almost the entire north-south extent of the batholith.

The gradational nature of texture and composition between adjacent units of the main group (Lindgren, 1904; Schmidt, 1964) along with the consistency of their $(A - Ak)/K$ ratios (Table 4) and Pb-alpha age dates (Jaffe

TABLE 6. SUMMARY OF K, U, Th, A, Th/U, $(A - Ak)/K$ AND WEIGHTED AVERAGE VALUES FOR UNITS COMPRISING THE TERTIARY EPIZONAL INTRUSIVE GROUP

Map unit	Tcgr	Tsb	Tqd	Tpp	Tbg	KTae	Tts	KTaw[a]	KTlt
Approx. outcrop area (km^2)	800	500	350	20	400	3,000	100	1,000	500
K(%K$^+$)									
Average	3.3	3.3	1.8	3.3	3.7	2.6	3.4		3.7
Range	2.7–4.0	2.8–3.6	0.2–2.5	3.2–3.3	3.4–4.0	1.6–4.0	3.1–3.8		2.6–4.2
Literature[d]	4.9[e]				3.7[f]	3.2[g]			
U(ppm)									
Average	4.5	5.9	2.7	10.3	5.8	3.2	11.5		4.3
Range	2.7–6.9	3.5–7.5	0.6–3.9	9.2–11.4	4.3–7.9	1.3–5.1	10.1–12.9		2.5–5.6
Literature[d]		about 8[h]			5.0[i]	2.4[i]			5.5[i]
Th(ppm)									
Average	22.2	25.0	9.9	26.0	29.4	13.5	31.1		19.8
Range	12.9–44.3	9.5–36.0	2.3–17.8	25.2–26.7	19.2–44.6	8.9–27.2	25.2–34.1		13.6–25.7
A(hgu)									
Average[j]	7.3	8.7	3.9	11.6	9.5	4.9	13.2		6.9
Range	4.7–13.3	6.6–11.4	1.0–5.4	11.0–12.1	7.2–10.3	2.9–8.6	11.7–14.5		4.8–8.3
Th/U[k]	4.9	4.2	3.7	2.5	5.1	4.2	2.7		4.6
$(A - Ak)/K$									
Average[j]	2.0	2.4	2.1	3.3	2.4	1.7	3.6	1.5	1.7
Range	1.4–3.5	1.4–3.1	1.3–3.7	3.0–3.5	1.8–2.8	0.9–2.2	3.4–3.7		0.9–1.9
Samples	10	6	13	2	6	14	5	7	12

Map unit	KTlhs	KTcc	KTs	KTpc	KTsf	KTps[b]	Trgn	Average[c]
Approx. outcrop area (km^2)	300	100	200	..	..	100	150	6,420
K(%K$^+$)								
Average	3.5	3.8	3.7	3.2	2.1		1.8	2.9
Range	2.6–3.9	3.4–4.2	3.2–4.1	2.4–4.0	1.4–2.6	1.0–3.7	1.6–2.0	
Literature[d]								
U(ppm)								
Average	4.3	6.3	4.0	4.9	3.7		1.9	4.0
Range	2.3–6.1	5.9–6.7	2.0–5.7	4.2–5.9	2.9–4.3	1.9–6.3	1.7–2.1	
Literature[d]	3.4[i]	6.3[i]						
Th(ppm)								
Average	17.1	24.1	20.7	23.1	15.5		5.7	17.2
Range	9.4–20.0	23.0–25.8	7.8–36.7	15.7–35.4	9.0–18.4	4.7–26.5	4.3–6.5	
A(hgu)								
Average[j]	6.3	8.9	6.8	7.7	5.4		2.6	6.1
Range	3.8–8.4	8.5–9.1	3.7–8.9	6.7–10.1	3.8–6.3	2.4–9.2	2.1–2.8	
Th/U[k]	4.0	3.8	5.2	4.7	4.2		3.0	4.3
$(A - Ak)/K$								
Average[j]	1.6	2.1	1.7	2.2	2.5	2.1	1.2	1.8
Range	1.2–1.8	1.9–2.4	0.8–2.2	1.8–2.5	1.7–3.8	1.7–2.4	1.0–1.4	
Samples	10	3	13	4	5	6	3	127

[a] Omitted from averages, see text.

[b] Average values not calculated, as a wide range of rock types are included in this unit.

[c] Weighed according to areal abundance of constituent units.

[d] Average value of published values for each unit or equivalent units.

[e] Ross (1934).

[f] Hietanen (1963a).

[g] Lindgren (1904).

[h] Killsgaard (1970).

[i] Larson and Gottfried (1961).

[j] Average of individual samples.

[k] Calculated from average Th, U values and not from individual Th/U ratios.

and others, 1959) suggest that the rocks of the main group have been emplaced essentially as a unit, a hypothesis proposed by Ross (1936) for the batholith as a whole. Intrusions that postdate the Idaho batholith (Anderson, 1952; Hietanen, 1963a; Reid, 1963; Ross, 1934) have considerably higher $(A - Ak)/K$ ratios and are interpreted as belonging to separate intrusive events.

The following description of the main-group

TABLE 7. SUMMARY OF K, U, Th, A, Th/U, AND $(A - Ak)/\mathrm{K}$ FOR INTRUSIVES OF EASTERN OREGON

Unit	Wallowa[a] batholith	Cornucopia[a] stock	Grays Peak[b] stock	Anthony Lake[b] granodiorite
K(%K$^+$)	1.4	0.7	1.1	1.5
U(ppm)	1.8	0.3	0.1	1.0
Th(ppm)	5.0	1.2	2.5	4.0
A(hgu)[c]	2.3	0.6	0.8	1.6
Th/U[d]	2.7	3.3	13.5	3.8
$(A - Ak)/\mathrm{K}$[c]	1.3	0.6	0.4	0.9
Samples	6	4	3	5

[a] Krauskopf (1943) for geologic description.

[b] Taubeneck (1957) for geologic description.

[c] Average of individual samples.

[d] Calculated from average Th, U values and not from individual Th/U ratios.

units follows the terminology of Schmidt (1964) who conducted a reconnaissance petrographic profile across the west flank of the Idaho batholith.

Migmatite of McCall (Kmcm)

The westernmost unit described by Schmidt (1964) is the migmatite of McCall, a texturally variable unit of quartz dioritic composition whose zone of outcrop area varies in width from 3 to 11 km. Similar migmatites are observed farther north along the extreme west flank of the batholith and reach a maximum width of 14 km along the Selway River (Greenwood and Morrison, 1967). The distribution of these migmatites is shown in Figure 6. The values of $(A - Ak)/\mathrm{K}$ (Table 4) for the eight measured samples of this relatively minor unit are typical of the rocks intruded during the main intrusive event.

Quartz Diorite Gneiss of Donnelly (Kqdg)

Schmidt (1964) describes this 10-km-wide unit as a uniformly textured, medium-grained quartz diorite gneiss located between the migmatite of McCall to the west and the more leucocratic rocks to the east. Similar gneissic and directionless quartz diorite is common along the west flank of the batholith and includes the large body of tonalite that crops out from McCall north to the canyon of the Salmon River (Larson and Schmidt, 1958). The distribution of this quartz diorite is shown in Figure 6.

The radioelement concentration, heat generation, and $(A - Ak)/\mathrm{K}$ ratios for the 15 samples of quartz diorite included in this unit are given in Table 4. In general, this quartz diorite is low in uranium, thorium, and heat generation but still has $(A - Ak)/\mathrm{K}$ ratios typical of rocks intruded during the main intrusive event.

It is tempting to correlate the quartz diorite gneiss of Donnelly with the quartz diorite near Pierce (JKpqd) which is included with rocks of the west border group. However, the quartz diorite near Pierce is similar to many of the rocks in the canyon of the Clearwater River (Hietanen, 1963a) which have two hornblende and one biotite K-Ar age dates (McDowell and Kulp, 1969) averaging 131 m.y., whereas three Pb-alpha age dates on rocks included in the quartz diorite gneiss of Donnelly (Jaffe and others, 1959) average 105 m.y. A definite relation cannot be established without additional geologic data.

Leucocratic Quartz Diorite of Little Valley (Klqd)

This unit has been described by Schmidt (1964) as grading imperceptibly into the quartz diorite gneiss of Donnelly to the west and into the Gold Fork granodiorite (Kgf) to the east, both of which are included in the main group. Since rocks equivalent to all three units have similar Pb-alpha age dates (Jaffe and others, 1959), it might be assumed that the leucocratic quartz diorite of Little Valley was also intruded during the main event. However, recent data (McDowell and Kulp, 1969; Taubeneck, 1971) suggest that the leucocratic quartz diorite of Little Valley and its equivalent to the south, the Cascade granodiorite (Kcgn; Larson and Schmidt, 1958) are post main group units. The $(A - Ak)/\mathrm{K}$ ratio is used in tentative support of the latter hypothesis; the arguments are summarized below.

1. The $(A - Ak)/\mathrm{K}$ ratios for the 21 samples of the leucocratic quartz diorite of Little Valley and Cascade granodiorite are similar (Table 5) and are typical of the higher values of the units included in the intermediate group.
2. A K-Ar age date (biotite) of 73 m.y. has been obtained for the Cascade granodiorite (McDowell and Kulp, 1969).
3. A K-Ar age date (biotite) of 77 m.y. has been obtained for a tonalite (quartz diorite gneiss of Donnelly) near McCall. McDowell and Kulp (1969) suggest an episode of degassing during the Late Cretaceous or early Tertiary as a possible explanation for this anomalous date.

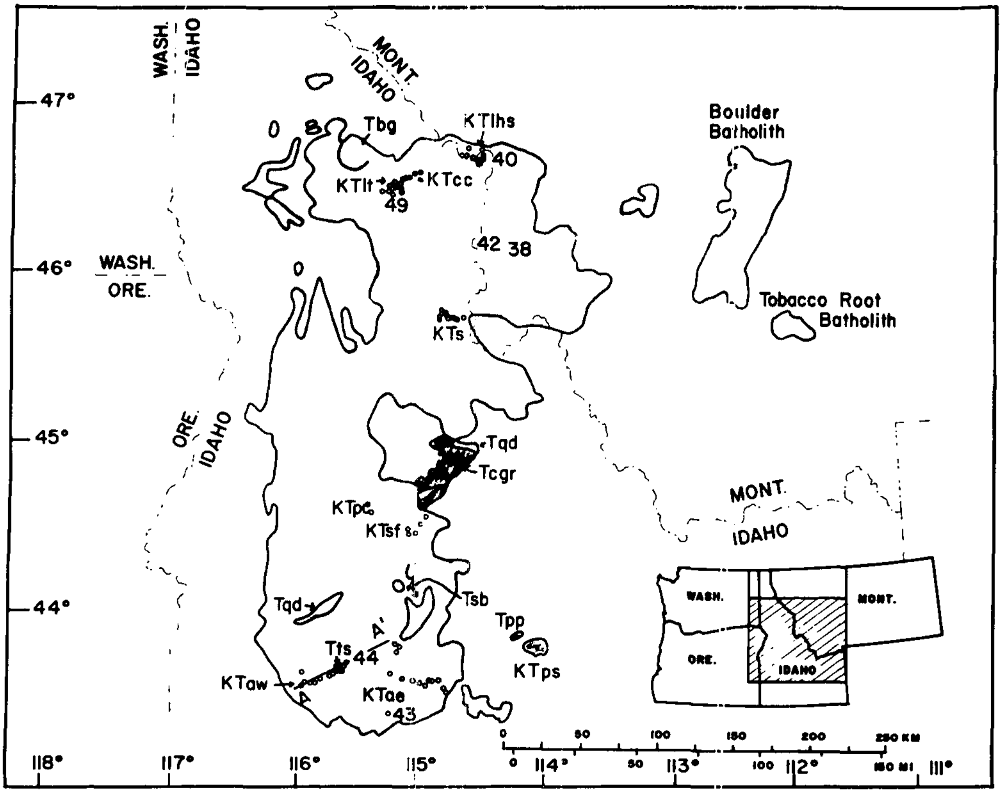


Figure 8. Index map showing the locations of the units included in the Tertiary epizonal group. Sample locations are designated by open circles (solid circles for Tts and KTcc) for units not mapped in detail. Geology from Hietanen (1962), Ross and Forrester (1940), and Ross and others (1955). Numbers indicate K-Ar age determinations of McDowell and Kulp (1969).

4. The leucocratic quartz diorite of Little Valley and the Cascade granodiorite are similar in lithology, radioelement concentration, and heat generation (Table 5) to the body of Cascade granodiorite (Klgn) cropping out north of Landmark, Idaho (Larson and Schmidt, 1958), which, on a regional scale, appears to crosscut the muscovite quartz monzonite of the main group (Figs. 6 and 7).

5. Each unit described by Schmidt (1964) may be traced or has equivalents over most of the north-south extent of the batholith, except the leucocratic quartz diorite of Little Valley which is observed only in the southern part of the batholith.

6. A post main group interpretation for the leucocratic quartz diorite of Little Valley provides a suitable explanation for the anomalous Rb-Sr age date and the anomalous $(A - Ak)/K$ ratios for adjacent rocks in the Gold Fork granodiorite (see following section).

7. Taubeneck (1971) presents field relations and modal data to suggest that the Cascade granodiorite intrudes the quartz diorite gneiss of Donnelly.

Gold Fork Granodiorite (Kgf)

The granodiorite of Gold Fork occupies a zone about 10 km wide between the quartz monzonite of Warm Lake and the more mafic rocks to the west (Schmidt, 1964). It includes medium-grained to porphyritic granodiorite and quartz monzonite and is distinguished from the muscovite quartz monzonite of Warm Lake by the absence of muscovite. Rocks in an equivalent position and of similar composition and texture in the northern portion of the batholith (Hietanen, 1963a; Greenwood and Morrison, 1967) are grouped as quartz monzonite near Pierce (Kpqm). The distribution of these units is shown in Figure 6.

Although the $(A - Ak)/K$ ratios for the quartz monzonites near Pierce are typical of the main group (Fig. 10a; Table 4), the Gold

Fork granodiorite has abnormally high ratios (Fig. 10b; Table 4). These anomalous ratios are thought to result from contact effects associated with later intrusion of the leucocratic quartz diorite of Little Valley for the following reasons:

1. The histogram (Fig. 10b) of $(A - Ak)/K$ for the Gold Fork granodiorite shows considerable scatter with the outcrops near the quartz monzonite of Warm Lake predominantly in the range 0.7 to 1.3 and the outcrops adjacent to the leucocratic quartz diorite of Little Valley predominantly in the range 1.4 to 1.9 (Table 4b).
2. Anomalous $(A - Ak)/K$ ratios are not observed in the quartz monzonite near Pierce (Kpqm) in the northern section of the batholith (Table 4) where rocks equivalent to the leucocratic quartz diorite of Little Valley are not present.
3. Contact effects for distances as great as 8 km are observed adjacent to the previously unmapped pluton (Tts) near Twin Springs, Idaho (Fig. 11).
4. An age date of 91 m.y. (Reeve, 1971, written commun.) has been obtained on biotite from a sample collected near the contact of the leucocratic quartz diorite of Little Valley. This value is intermediate between the 75-m.y. age suggested for the leucocratic quartz diorite of Little Valley and the 108-m.y. average for the main group (Jaffe and others, 1959).

Muscovite Quartz Monzonite of Warm Lake (Kmqm)

The muscovite quartz monzonite of Warm Lake is the largest single unit in the Idaho batholith and occupies almost 9,000 km^2 in the core of the batholith. It occurs in two large bodies, which may be separated by a major fault offsetting the entire batholith by as much as 150 km (Fig. 6). The southern body crops out continuously from as far south as the Boise Basin to north of the Salmon River. The northern body occupies the area from Nez Pierce Pass north to the Lochsa River (Lindgren, 1904). Smaller bodies of muscovite quartz monzonite are also observed on the east flank of the batholith near Lost Trail Pass (Fig. 6) and in the Silver City region south of the Snake River.

Heat-generation values for samples collected from all parts of this impressively large, continuous unit (Fig. 12a; Table 4b) do not vary significantly, suggesting that heat generation may be a diagnostic property of igneous bodies that may be useful as a geologic mapping tool, especially in areas where exposures are poor and standard field techniques are difficult to apply. As shown in Figure 12a, 82 percent of the measured samples have heat generation values between 1.8 and 3.2 hgu, a range that is one-tenth of the range for rocks of the batholith as a whole.

The variation of uranium, thorium, and $(A - Ak)/K$ within the muscovite quartz monzonite of Warm Lake is given in Figure 12 (b through d). The $(A - Ak)/K$ values are similar to values obtained from other units intruded during the main intrusive event.

Bear Valley Quartz Monzonite (Kbv)

The east flank of the Idaho batholith contains numerous rock types, none of which is as extensive or continuous as the units described above. In the Bear Valley area, the muscovite quartz monzonite of Warm Lake appears to grade into a fine-grained to porphyritic quartz monzonite lacking muscovite. This porphyritic quartz monzonite is the most frequently observed rock type on the east flank of the batholith and is here called the Bear Valley quartz monzonite. Samples locations are shown in Figure 6. Radioelement concentrations, heat-generation values, and approximate outcrop area for the Bear Valley quartz monzonite are given in Table 4. $(A - Ak)/K$ ratios (Fig. 13a; Table 4) are typical of the units intruded during the main intrusive event.

Throughout the present study, every at-

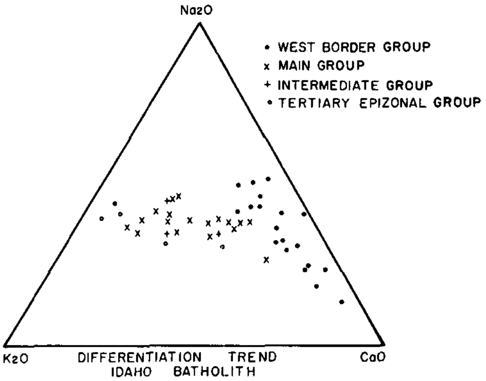


Figure 9. Ternary diagram for rocks of the Idaho batholith, grouped according to the four intrusive events. Data taken from Hamilton (1963), Hietanen (1962, 1963a), Larson and Schmidt (1958), Lindgren (1904), Ross (1934), Schmidt (1964), and Shenon and Ross (1936).

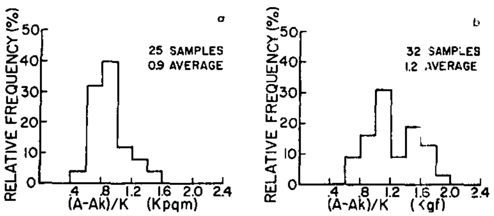


Figure 10. Histograms of $(A - Ak)/K$ values for (a) the quartz monzonites cropping out near Pierce, Idaho (Kpqm), and (b) the Gold Fork granodiorite (Kgf).

tempt has been made to adhere to existing geologic interpretations. In the case of the Bear Valley quartz monzonite, exceptions are made in two areas.

1. The segment of Atlanta granodiorite (Larson and Schmidt, 1958) that crops out along the middle fork of the Boise River between Twin Springs and Atlanta, Idaho, and the adjacent body of quartz monzonite (Larson and Schmidt, 1958) have $(A - Ak)/K$ ratios (Table 4b) and Pb-alpha age dates (Jaffe and others, 1959) that are typical of rocks emplaced during the main event, whereas the remaining rocks of the Atlanta granodiorite have $(A - Ak)/K$ ratios (Table 6) and K-Ar age dates (McDowell and Kulp, 1969) that are typical of rocks emplaced during the Tertiary epizonal event. Thus, in this paper the Atlanta granodiorite is subdivided into western, central, and eastern segments. The central segment and the adjacent body of quartz monzonite (Larson and Schmidt, 1958) are considered to be the southern extension of the Bear Valley quartz monzonite and are included in that unit in Figures 6, 11, and 13a and in the average values given in Table 4a. The western and eastern segments of the Atlanta granodiorite are discussed in the section on Tertiary epizonal intrusives.

2. Although only three samples from two outcrops have been measured for the large body of quartz monzonite cropping out east of Wisdom, Montana, this unit (Kbv, Fig. 6) is treated in detail because it occupies an interesting geographic position between the Idaho batholith and the Boulder batholith. Ross and others (1955) designate this unit "TKb," suggesting a close association with the Boulder batholith, even though the quartz monzonite is separated from the Idaho batholith only by the alluvium in the valley of the Big Hole River. However, the appearance of the core unit (Kmqm) of the Idaho batholith, cropping out on the east flank of the batholith (Fig. 6) just west of Wisdom, and the observation that the muscovite quartz monzonite grades into the Bear Valley quartz monzonite over much of the southern section of the batholith lead to the interesting speculation that the quartz monzonites east of Wisdom are Bear Valley equivalents and may grade into the muscovite quartz monzonite of the Idaho batholith, the relations being hidden beneath the alluvium in the Big Hole Valley. Lithology, radioelement concentration, and $(A - Ak)/K$ ratios for the three samples collected from this unit are similar to those of samples collected in the Bear Valley area (Table 4b), and the radioelement concentration and $(A - Ak)/K$ ratios are considerably lower than quartz monzonites of the Boulder batholith (Table 8; Tilling and Gottfried, 1969). So the lithologic dissimilarity between the quartz monzonites east of Wisdom and the Idaho batholith (Kmqm) cropping out immediately to the west does not necessarily indicate that these two units are unrelated, as they may be different units intruded during the same intrusive event.

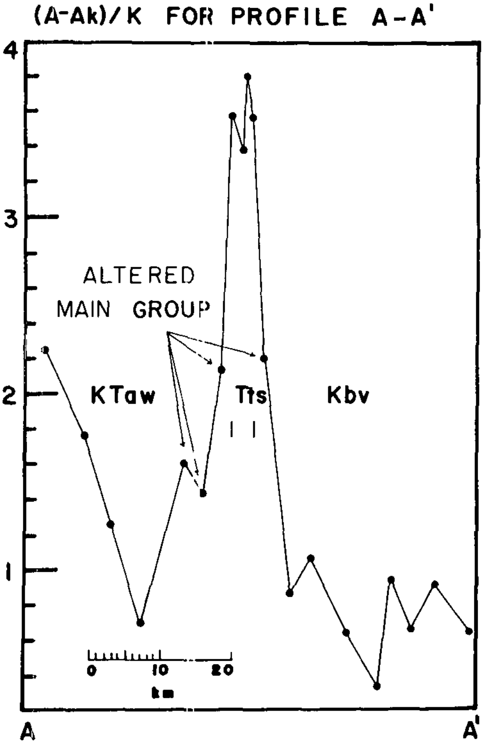


Figure 11. Plot of $(A - Ak)/K$ along the profile A-A′ showing the contact effects of the Twin Springs pluton on $(A - Ak)/K$ values in the country rock.

Quartz Monzonite Gneiss (Kgqm)—East Border Gneiss (Kebm)

East border rocks of the Idaho batholith are observed only in the Bitterroot Range in the northeast section of the batholith. In this area, an 8-km-wide zone of quartz monzonite gneiss grades into the muscovite quartz monzonite to the west and into the more strongly gneissose rocks to the east (Lindgren, 1904). There is considerable disagreement as to the origin of the east border units (Langton, 1935; Lindgren, 1904; Ross, 1952), and the age dates are Tertiary and not Cretaceous (Jaffe and others, 1959; McDowell and Kulp, 1969). The east border rocks are placed in the main group on the basis of their (*A* – *Ak*)/K ratios.

INTERMEDIATE GROUP

A number of plutons of the Idaho batholith have been described as intrusive into the main body of the Idaho batholith but, in turn, are intruded by rocks of the Tertiary epizonal group (Ross, 1934; Reid, 1963). These rocks have intermediate (*A* – *Ak*)/K ratios averaging 1.3 (range, 0.4 to 2.5 for individual samples; 1.1 to 1.5 for constituent plutons; Fig. 3; Table 5), intermediate age dates ranging from 55 to 77 m.y. (Table 2; McDowell and Kulp, 1969), and contact relations that suggest emplacement at intermediate depths (Buddington, 1959). It is not suggested that the units included in the intermediate group are genetically related or that they were emplaced during a separate period of plutonism which affected the batholith as a whole. In fact, the units may well represent late-stage activities of the main event or early activities associated with the Tertiary epizonal event. In each locality discussed, however, rocks included in the intermediate group are readily distinguished from rocks of the other groups by their (*A* – *Ak*)/K ratio and some form of geologic control. The following units have average (*A* – *Ak*)/K ratios ranging from 1.1 to 1.5 and are placed in the intermediate group on the basis of their (*A* – *Ak*)/K ratios and the given geologic criterion.

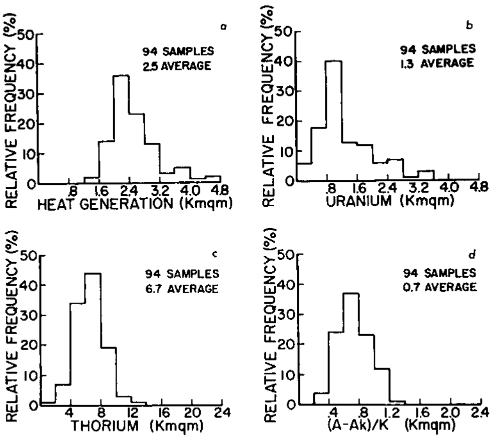


Figure 12. Histograms of (a) heat generation, (b) uranium, (c) thorium, and (d) (*A* – *Ak*)/K for samples of the muscovite quartz monzonite of Warm Lake (Kmqm).

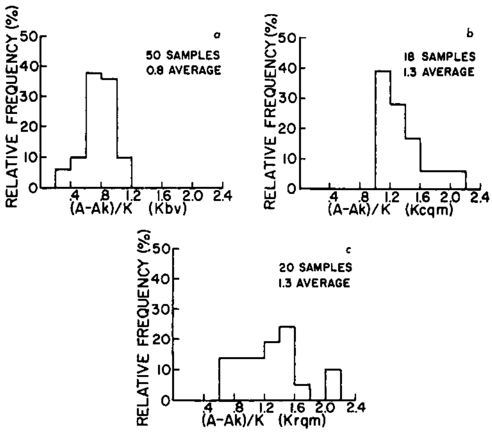


Figure 13. Histograms of (*A* – *Ak*)/K values for samples of (a) the Bear Valley quartz monzonite (Kbv), (b) the quartz monzonite cropping out near Coolidge, Montana (Kcqm), and (c) the quartz monzonite cropping out near Red River (Krqm).

Leucocratic Quartz Monzonite (Klqm)

The leucocratic quartz monzonite of the Sawtooth area is described by Reid (1963, p. 13) as intruding the Idaho batholith, but being intruded by the Tertiary Sawtooth batholith. Reid (1963) regards this unit as a late differentiate of the Idaho batholith.

White Quartz Monzonite (Kwqm)

The white quartz monzonite of the Casto quadrangle is shown by Ross (1934, p. 34) to be intermediate in age between rocks of the Idaho batholith and the Tertiary Casto granite. Ross (1934) regards this unit as a more silicic and potassic differentiate to the same magma that formed the main body of the batholith.

Beaver Creek Quartz Monzonite (Kbqm)

The Beaver Creek pluton is described by Hietanen (1963a) as being older than the

TABLE 8. SUMMARY OF K, U, Th, A, Th/U, AND $(A - A_k)$/K FOR THE BUTTE QUARTZ MONZONITE OF THE BOULDER BATHOLITH

	Average	1	2	3
K(%K$^+$)	3.3	3.4	3.6	3.4
U(ppm)	4.3	4.0	5.9	6.3
Th(ppm)	20.8	16.2	22.3	22.8
A(hgu)	7.0	6.02	8.28	8.56
Th/U	4.7	4.05	3.78	3.62
$(A - A_k)$/K	1.8			
Samples	11	14	6	19

Column
1. Tilling and Gottfried (1969), Butte quartz monzonite.
2. Tilling and Gottfried (1969), silicic Butte quartz monzonite.
3. Tilling and Gottfried (1969), drill hole (DDH-B-3) Butte quartz monzonite.

Bungalow granite but postdating all other units in the northwest corner of the batholith.

Leucocratic Quartz Diorite of Little Valley (Klqd)

This unit is similar in lithology, heat generation, and $(A - A_k)$/K to the bodies of Cascade granodiorite near Cascade, Idaho, and Landmark, Idaho (Larson and Schmidt, 1958). All three units are placed in the intermediate group for reasons discussed in the section on the main group.

Diorite near Horseshoe Bend (Td)

A characteristic pyroxene-hornblende-biotite diorite near Horseshoe Bend is described by Anderson (1952) as intruding the Idaho batholith while a similar diorite in the Hailey-Bellevue area is intruded by a quartz monzonite. On the basis of these field relations, the diorite at Horseshoe Bend is placed in the intermediate group, and the quartz monzonite in the Hailey-Bellevue area (section on Atlanta granodiorite-east) is placed in the Tertiary epizonal group. The only measured sample of this diorite (Table 5) has an $(A - A_k)$/K ratio typical of those units included in the intermediate group.

Granodiorite near Sleeping Child Creek, Montana (Ksgn)

Ross (1952, p. 150) notes the presence of numerous small intrusions in the Bitterroot Range which he considers to be intermediate in position and probably in age between the Idaho batholith to the west and the Boulder batholith to the east. Comprising the granodiorite near Sleeping Child Creek is a selection of samples collected from several small granodioritic to quartz monzonitic bodies occupying such a position, one of which was collected from a postbatholithic intrusion mapped by Langton (1935) as later quartz monzonite. The extent of post main group intrusive activity in this area is unknown, but it is probably extensive enough to account for the anomalous K-Ar age dates of 61 m.y. (biotite) and 55 m.y. (muscovite) that McDowell and Kulp (1969) obtained for a recrystallized Precambrian (Belt) gneiss and for the segment of muscovite quartz monzonite near Lost Trail Pass, respectively.

Quartz Monzonite near Coolidge, Montana (Kcqm)

The large mass (700 km^2) of quartz monzonite cropping out near Coolidge, Montana, occupies a position between the Idaho batholith and the Boulder batholith. The $(A - A_k)$/K ratios for the 18 samples of this unit are uniform (Fig. 13b) and characteristic of the plutons included in the intermediate group.

Stocks North of Elk River, Idaho (Keqm, Keqd)

Cropping out in the area just north of Elk River, Idaho, are small stocks of quartz monzonite (Keqm) and quartz diorite (Keqd) and several small bodies (Kgr) mapped as Cretaceous granite (Hietanen, 1963b). Although only seven samples were collected from these minor units, they are treated in detail because they are an example of how the $(A - A_k)$/K ratio may be used to supplement geologic field data. Analysis of the $(A - A_k)$/K ratios (Tables 4 and 5) suggests that the Cretaceous granite, described as strongly elongate parallel to the regional trend (Hietanen, 1963b), was emplaced at greater depth than the stocks of quartz monzonite and quartz diorite that are described as being elongate parallel to the regional trend but with discordant contact relations (Hietanen, 1963b). Hence, the Cretaceous granite is included in the main group, while the two stocks are included in the intermediate group. Although the relative ages of these units cannot be established by field relations alone (Hietanen, 1963b), the conclusion that the stocks of quartz diorite and quartz monzonite are younger than the Cretaceous granite is consistent with the structural interpretations of these units and with the intermediate age dates (67 m.y., 68 m.y.) McDowell (1966) obtained for a similar stock north of Moscow, Idaho.

Quartz Monzonite near Red River (Krqm)

This unit includes all quartz monzonite cropping out in the region between Elk City, Idaho, and the Selway River, an area dominated by small intrusions (Larson and Schmidt, 1958). The largest body of quartz monzonite in this area has a small zone of associated contact migmatites (Greenwood and Morrison, 1967), suggesting that this unit was emplaced at shallower depths than the rocks intruded during the main intrusive event (see Swanberg, 1972). Thus, all quartz monzonite in this area is included in the intermediate group. The histogram (Fig. 13c) of $(A - Ak)/K$ for the quartz monzonite suggests that all samples included in this unit may not be related. They are grouped together to avoid separating out small bodies on the basis of one sample.

TERTIARY EPIZONAL GROUP

Tertiary epizonal rocks have been described by Anderson (1952) in the Boise Basin and Hailey-Bellevue areas, by Dover (1969) in the Pioneer Mountains, by Reid (1963) in the Sawtooth area, by Ross (1934) in the Casto quadrangle, and by Hietanen (1969) in the Bungalow area. Regardless of rock type or location in the batholith, these Tertiary epizonal units are characterized by extremely high $(A - Ak)/K$ ratios (Fig. 4; Table 6) averaging 1.8 (range, 0.8 to 3.7 for individual samples; 1.6 to 3.6 for constituent plutons). Thus, all units having average $(A - Ak)/K$ ratios greater than 1.6 are included in the Tertiary epizonal group. Rocks of this group are sufficiently numerous along the borders of the batholith as to suggest widespread, possibly related plutonic activity during Tertiary time.

The following units have been confidently dated as Tertiary, exhibit properties typical of shallow intrusions (Buddington, 1959), and are used to define rocks with average $(A - Ak)/K$ ratios greater than 1.6 as characteristic of the Tertiary epizonal group:

1. Casto granite (Ross, 1934; Tcgr);
2. Sawtooth batholith (Reid, 1963; Tsb);
3. Pioneer Mountains pluton-postorogenic phase (Dover, 1969; Tpp);
4. Quartz diorites from the Casto quadrangle (Ross, 1934; Tqd);
5. Quartz diorites from the Boise Basin (Anderson, 1952; Tqd);
6. Bungalow granite (Hietanen, 1963a, 1969; Tbg).

Since the interpretation of the $(A - Ak)/K$ ratio for these units is consistent with their geologic interpretation, there is no need to discuss these units further, even though their combined outcrop area (2,400 km^2) constitutes a significant portion of the batholith. The remaining units having $(A - Ak)/K$ ratios exceeding 1.6 are placed in the Tertiary epizonal group on that basis and the geologic criterion discussed below.

Atlanta Granodiorite-East (Ktae)

As mentioned earlier, the Atlanta granodiorite of Larson and Schmidt (1958) is here subdivided into an eastern, western, and central segment. The eastern segment includes about 3,000 km^2 and occupies the entire southeast section of the Idaho batholith. It is by far the largest unit included in the Tertiary epizonal group and may be considered a batholith in itself, as suggested by Anderson (1952). The 14 samples of this unit were collected along a profile extending southeast from Atlanta, Idaho, and in the extreme southern part of the batholith (Fig. 8). The unsampled post-batholithic quartz monzonite, which can be traced from the Hailey-Bellevue area through the Hailey gold belt into the areas sampled in the southeast corner of the batholith (Anderson, 1952), is included in this unit, along with adjacent unsampled areas mapped by Larson and Schmidt (1958) as Atlanta granodiorite, and the Tertiary epizonal quartz monzonites near Rocky Bar (Anderson, 1943).

In addition to the $(A - Ak)/K$ data, there is considerable geologic evidence for including this unit with the Tertiary epizonal intrusives, including the field relations described by Anderson (1943, 1950, 1952), the K-Ar age dates of McDowell and Kulp (1969), and the lithologic dissimilarity between the rocks of this unit and rocks of the main intrusive group.

Twin Springs Pluton (Tts)

The most radioactive unit in the Idaho batholith is a previously unmapped 100 km^2 pluton cropping out near Twin Springs, Idaho. This pluton appears to intrude the central segment of the Atlanta granodiorite. Anomalous $(A - Ak)/K$ ratios in the granodiorite as far as 8 km from the contact may result from contact effects associated with the Twin Springs pluton (Fig. 11). The heat-generation and $(A - A_k)/K$ values for this pluton are the highest of any unit in the Idaho batholith and are used to constrain the limits of A_0 and $[(A - A_k)/K]_0$ in equations (4) and (11).

Atlanta Granodiorite-West (Ktaw)

The seven samples of this segment of the Atlanta granodiorite were collected along a profile from Twin Springs, west to Boise, Idaho. The unsampled area south and west of Twin Springs is also included in this unit, using the reconnaissance mapping of Larson and Schmidt (1958) as control. It is not suggested that the heat-generation and $(A - A_k)/K$ values for the samples measured for this unit apply to the unit as a whole. In fact, the data (see Fig. 11) suggest that the high $(A - A_k)/K$ ratios may be due to contact effects associated with the intrusion of the Twin Springs pluton to the east and some unmapped pluton to the west. The average $(A - A_k)/K$ ratio for this unit is given in Table 6 but is not interpreted or included in the average values.

Pioneer Mountains Pluton-Synorogenic Suite (KTps)

Although only six samples were collected from the suite of rocks comprising the areally small synorogenic suite of the Pioneer Mountains pluton, these rocks are treated in detail because they exemplify the use of the ratio $(A - A_k)/K$ as a geologic tool for correlation of diverse rock types belonging to the same intrusive event. The synorogenic suite of the Pioneer Mountains pluton is described by Dover (1969) as consisting of rocks varying in composition and texture from gneissic quartz diorite to directionless quartz monzonite. The subtle gradations among these rocks prompted Dover (1969) to conclude that they were emplaced during the same intrusive event. Analysis of the data in Table 6 and Figure 14 indicates that these diverse rock types, belonging to the same intrusive event and including rocks ranging in composition from pyroxenite (1.1 percent K) to quartz monzonite (3.7 percent K), are virtually indistinguishable on the basis of their $(A - A_k)/K$ ratio.

If equation (11) is applied to the synorogenic rocks of the Pioneer Mountains pluton, emplacement depths of about 3.8 to 6.6 km are obtained. Such depths seem to be consistent with interpretation of the observed lack of contact metamorphism and the observed cross-cutting structural relations (Dover, 1969, p. 37, 42).

Quartz Monzonite along the Lolo Trail (KTlt)

A distinctive body of medium-grained, pink quartz monzonite is exposed for 25 km along the Lolo Trail between Indian Postoffice and Castle Butte (Fig. 8). This body appears to intrude the quartz monzonite (Kpqm) of the main group and is apparently responsible for the anomalously high $(A - A_k)/K$ ratios for the rocks of the main group near the contact (Table 4b). These anomalous rocks extend nearly to the locality where McDowell and Kulp (1969) have obtained a Tertiary (49 m.y., biotite) K-Ar age date for the quartz monzonite near Pierce (Kpqm), suggesting that heat from this intrusion may have partially or totally reset the K-Ar clock. The age date of McDowell and Kulp (1969), the $(A - A_k)/K$ ratios (Table 6), and the anomalous main group rocks near the contact all suggest that this rather large unit is postbatholithic and should be included with the units intruded during the Tertiary epizonal event.

Quartz Monzonite near Lolo Hot Springs, Montana (KTlhs)

A body of grayish-pink, coarse quartz monzonite is exposed along the Idaho-Montana

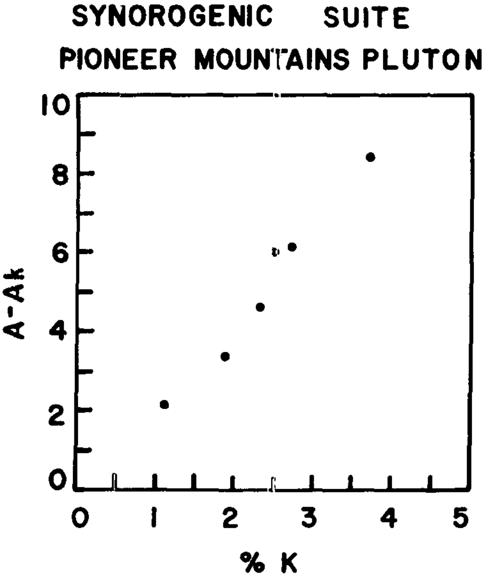


Figure 14. Plot of A-Ak versus K for rocks of the synorogenic suite of the Pioneer Mountains pluton.

border just south of Lolo Hot Springs, Montana (Fig. 8). The sharp contact of this unit with surrounding metasediments (Lindgren, 1904), the lithologic similarity of this unit to the nearby quartz monzonite along the Lolo Trail, and the 40-m.y.-age data from a nearby pegmatite (Hayden and Wehrenberg, 1960) suggest that this unit is properly grouped with rocks of the Tertiary epizonal group.

Microgranite near Cayuse Creek (KTcc)

A small body of miarolitic microgranite is exposed along the Lolo Trail near the headwaters of Cayuse Creek (Larson and Schmidt, 1958). The relation of this body to the remainder of the batholith is unknown except that the $(A - Ak)/K$ ratio (Table 6), miarolitic texture, and abundance of microperthite are typical of the rocks emplaced during the Tertiary epizonal event.

Microgranite near the Selway River (KTs)

Two bodies of light-gray, fine-grained microgranite are exposed along the Selway River near MacGrueder Ranger Station (Larson and Schmidt, 1958). The $(A - Ak)/K$ ratios for these bodies (Table 6) are typical of the rocks emplaced during the Tertiary epizonal event.

Small Bodies of Cascade Granodiorite (KTpc, KTsf)

In addition to the bodies of Cascade granodiorite exposed along the Payette River and north of Landmark, Larson and Schmidt (1958) describe several small bodies of Cascade granodiorite cropping out in the area north of Stanley, Idaho (Fig. 8). These small bodies are readily recognized by the presence of giant, pink phenocrysts (up to 25 cm long) of microcline microperthite. The $(A - Ak)/K$ ratios (Table 6) are extremely high and suggest emplacement at very shallow depths.

Roundtop Granodiorite (Trgn)

This 150-km^2 pluton is described briefly by Hietanen (1969) and dated at 41 m.y. (biotite) by Reid and Greenwood (1968). Only three samples were measured from this unit and their $(A - Ak)/K$ ratios show considerable scatter (Table 6). The average $(A - Ak)/K$ value is consistent with a postbatholith interpretation but is lower than the values from the other units included in the Tertiary epizonal group. The reason for this discrepancy cannot be determined without additional heat-generation data and age determinations.

CONCLUSIONS

The principal conclusions of this study can be grouped into two general areas: (1) the development of heat generation and the ratio $(A - Ak)/K$ as potentially valuable tools for geologic interpretation and (2) the interpretation of the Idaho batholith on the basis of these tools. Although the techniques described below are applicable to the Idaho batholith, they have yet to be established as general methods, and caution must be exercised in applying them to widely scattered and diverse geologic provinces.

Techniques

1. The uniformity of heat generation within a given pluton even over large geographical areas suggests that this parameter may be useful as a geologic mapping tool, particularly in areas where exposures are poor and standard field techniques difficult to apply.

2. If the quantity $(A - Ak)$ decreases exponentially with increasing depth for rocks of the same bulk composition (Swanberg, 1972) and increases linearly with increasing potassium content for rocks emplaced at about the same depth (Tables 1 through 5; Fig. 14), then the ratio $(A\ Ak)/K$ may be used (equation 11) to estimate emplacement depths for plutons of calc-alkaline magma series, provided that sufficient heat flow–heat generation data are available to evaluate the parameters b and $[(A - Ak)/K]_0$.

3. The observed uniformity of $(A - Ak)/K$ for rocks intruded during the same intrusive event suggests the use of this ratio as a general tool for determining the nature and extent of intrusive episodes and the relations between them. Thus, diverse rock types intruded during the same intrusive episode may be correlated, and, conversely, similar rock types of different intrusive episodes may be recognized.

Idaho Batholith

The $(A - Ak)/K$ ratio is used to present a multiple intrusion concept for the Idaho batholith in a scheme that adheres very closely to that proposed by Anderson (1952). The assignment of plutons to the various groups does not knowingly contradict any published data or geologic interpretation of the batholith unless the geologic data or interpretations of the data are themselves in contradiction. The general features of the four groups are given in Table 2 and described briefly below.

1. The west border group [average $(A - Ak)/K = 0.5$] consists of gabbro, quartz diorite, and tonalite that appear to be more closely associated with the Late Jurassic intrusive rocks of eastern Oregon than with the remainder of the Idaho batholith.

2. The main group [average $(A - Ak)/K = 0.8$] consists of seven units that are elongate in the north-south direction and that may grade into one another in the east-west direction. Most of these units may be traced or have equivalents over most of the north-south extent of the batholith, and together with areas for which data is unavailable or inconclusive, comprise 75 percent of the total outcrop area of the batholith. The largest single unit of the main group (and of the batholith as a whole) is the homogeneous muscovite quartz monzonite that occupies almost 9,000 km^2 in the core of the batholith. The apparent offset of this impressively large, continuous, easily recognized unit in the area north of the Salmon River (Fig. 6) suggests that the northern and southern parts of the batholith may be separated by a major fault, involving a strike-slip component that may be as great as 150 km. Unfortunately, the critical area for interpretation of such a fault lies in the Selway-Bitterroot wilderness area where no samples were collected and very little detailed geology has been published.

3. The plutons included in the intermediate group [average $(A - Ak)/K = 1.3$] may result from late-stage activities of the main intrusive event, early activities of the Tertiary epizonal event, or a separate intrusive event.

4. The Tertiary epizonal group [average $(A - Ak)/K = 1.8$] involves intrusive activity principally along the north, south, and east margins of the batholith. Rocks of this group are more extensive than previously recognized and are sufficiently numerous as to suggest extensive, possibly related intrusive activity during the Tertiary period.

Ross (1936) concludes that most of the rocks of the Idaho batholith came to place essentially as a unit. In making this statement, Ross (Ross and Forrester, 1940) excluded from the Idaho batholith all plutons that were known at that time to postdate the Idaho batholith. The excluded plutons were the Casto granite, the diorite and quartz diorite in the Casto quadrangle and the Boise Basin, and the diorite in the Horseshoe Bend area. If their definition of the Idaho batholith is retained, then the plutons of the west border group, the Tertiary epizonal group, and some of the plutons of the intermediate group should not be considered part of the Idaho batholith. Thus, the Idaho batholith would be synonymous with the main group described above and would involve about 20 percent less total outcrop than indicated by Ross and Forrester (1940). According to this definition, the heat-generation data would support the conclusion that the Idaho batholith came to place essentially as a unit. If, however, the Idaho batholith is defined to include all intrusions of central Idaho and western Montana (excluding the Boulder batholith and its satellites) with the subdivisions noted above, then the Idaho batholith would involve about 5 percent more outcrop area than suggested by Ross and Forrester (1940) and would be a temporally composite body.

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