THESIS

FELDSPAR GEOTHERMOMETRY OF THE HELL CANYON PLUTON, BOULDER BATHOLITH, MONTANA

By

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ABSTRACT

FELDSPAR GEOTHERMOMETRY OF THE HELL CANYON PLUTON, BOULDER BATHOLITH, MONTANA

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The Hell Canyon Pluton, located at the southeastern corner of the Boulder Batholith, contains alkali feldspars with structural states intermediate between orthoclase and maximum microcline as indicated by (060) vs ($\bar{2}04$) plots (Wright 1968). No structural state variation exists throughout the entire pluton, suggesting the lack of a fluid phase below 400 ^{o}C (Parsons 1978). Temperatures calculated using coexisting two feldspar geothermometry (Whitney and Stormer 1976, 1977, and Stormer 1975) average around 550 ^{o}C for groundmass feldspars, 600 ^{o}C for alkali feldspar phenocrysts and 320 ^{o}C for the exsolved albite phase. If equilibrium is assumed, zoned plagioclase give a continuous post crystallization cooling history of 675 to 550 ^{o}C. This may be related to a hydrothermal event in which reequilibration of the alkali feldspars may have occurred. If it is assumed that the minimum solidus temperature for a rock of this composition is near 700 ^{o}C, and that the plagioclase have not been affected by hydrothermal solutions, then a crystallization range of 900-700 ^{o}C is indicated.

ACKNOWLEDGEMENTS

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INTRODUCTION

The purpose of this study is to obtain structural state, composition, and temperature data on the feldspars from the Hell Canyon Pluton of the Boulder Batholith in order to determine its emplacement and crystallization history. The Hell Canyon Pluton was selected for this study because it is believed to be one of the latest plutons to be intruded into the batholith and should represent a relatively simple cooling history without secondary reheating (Robinson et al. 1968; Tilling et al. 1968). The Boulder Batholith was selected as an ideal area to study due to its shallow emplacement, thus making possible an accurate estimate of the depth during emplacement and crystallization. It is also an area of excellent outcrops for sampling purposes.

Two feldspar geothermometry was first proposed by Barth (1934), and over the past years many improvements and refinements have been suggested to increase the accuracy and reliability of this method (Stormer 1975; Whitney and Stormer 1977).

Two temperatures are calculated from the known thermodynamic constants of microcline and sanadine (Whitney and Stormer 1977, p. 52). For Microcline

$$T(^{o}K) = \frac{(7973.1 - 16910.6X_{AF} + 9901.9X_{AF} + (0.11 - 0.22X_{AF} + 0.11X_{AF})P(Kb)}{(-1.9872\ \mathrm{Ln}\ \frac{X_{AF}}{X_{PF}} + 6.48 - 21.52X_{AF} + 23.72X_{AF} - 8.62X_{AF})}$$

where X_{AF} is the mole percent albite in the alkali feldspar, X_{PF} is the mole percent albite in the coexisting plagioclase, and P(Kb) is the estimated pressure in kiobars at the time of crystallization. The sanadine equation will result in slightly lower temperatures compared to the above microcline equation. Because all the Hell Canyon samples possess structural states intermediate between microcline and orthoclase, the single microcline temperature equation was used. It must be kept in mind that the actual temperatures of the samples may be lower than indicated by as much as 30 to 40 ^{o}C. Although the absolute temperatures may be somewhat lower, the relative temperatures between samples should not be affected.

Bohen and Essene (1977) discuss the relationship between two feldspar geothermometry and iron-titanium geothermometry. They show that the Fe-Ti oxides continually equilibrate throughout the crystallization history so that the last phase represents that produced at the final crystallization temperature. However, the two feldspar method yields a range of temperatures from the initial to the final temperature of crystallization. This is indicated by the continuous change in composition of the plagioclase feldspar, and assumes continual equilibrium between the plagioclase and the coexisting alkali feldspar.

GENERAL DESCRIPTION OF THE BOULDER BATHOLITH

The Boulder Batholith is located in southwestern Montana (Figure 1). It is a composite igneous intrusion of over a dozen individual plutons exposed over an area of 6000 to 7000 square kilometers, with the main part of the batholith exposed as an elongate 50 x 100 kilometer body (Klepper et al. 1971). Estimated depths range from 5 kilometers (Hamilton and Meyers 1974) to over 15 kilometers (Klepper et al. 1971). The age of emplacement is believed to have occurred over a time span from 78 to 68 million years ago during Late Cretaceous time (Robinson et al. 1968).

The history of the Boulder Batholith has been described by Robinson et al. (1968). The following is a summary of their work.

The relationship between volcanism, plutonism, thrusting and folding is a complex one. Approximately 85 million years ago significant volcanism began which climaxed 79-77 million years ago with the formation of at least 2 kilometers of volcanic rock, resulting in the Elkhorn Mountain Volcanics. All age determinations were made from K-Ar data from biotite and hornblende samples. By 73 million years ago major volcanism had ceased. During the time of maximum volcanism,

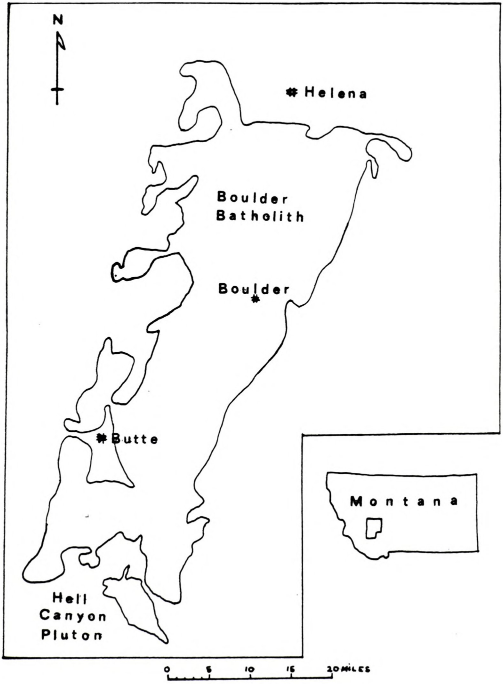


Figure 1. Location of the Hell Canyon Pluton with respect to the Boulder Batholith.

around 78 million years ago, plutonism is believed to have originated in this area and continued for 6 million years when the major bulk of the batholith had been emplaced below and within the volcanic cover. By 68 million years ago the entire batholith had been emplaced. In general, volcanism and folding preceded batholith emplacement, although at times it is evident that all three events took place simultaneously implying a synorogenic nature of the Boulder Batholith.

The composition of the Boulder Batholith is predominantly quartz monzonite and granodiorite. Other less abundant lithologies include mafic syenogabbros and syenodiorites, alaskite, aplite and granite. The intrusive sequence is believed to be in the order of increasing silica content from the older mafic intrusions to the younger leucocratic plutons. The Butte Quartz Monzonite is the largest pluton of the batholith and makes up at least 75 percent of the batholith.

Hell Canyon Pluton

The Hell Canyon Pluton (Figure 1) is located at the southwestern tip of the Boulder Batholith and is in contact with Precambrian metamorphic rock to the south, east and west, and with prevolcanic sedimentary rock to the north. It is believed to be one of the last magmatic intrusions to occur in the Boulder Batholith based on K-Ar age dating (Robinson et al. 1968). Although there are no exposed contacts between this pluton and the rest of the batholith, it is considered to be part of the batholith from evidence derived from radiometric age dating and isotope ratios (Doe et al. 1968), composition and mineralogy (Tilling et al. 1968; Tilling 1973, 1974), and proximity to the other plutons. The pluton is tear drop in shape, elongated in a northwest-southeast direction with the maximum width located at the northwest edge, approximately 7 kilometers wide, and the smallest width located at the southeast edge. The maximum length of the pluton is approximately 17 kilometers. Elevation of the pluton generally increases in a northwest direction with the southeast region at an elevation of about 4800 feet above sea level and the northwest region at an elevation of about 9600 feet above sea level. Access to the pluton is possible from a road that enters at its southeast corner and circles its interior.

Samples were collected along this road as well as from traverses along a number of streams within the pluton (Figure 2).

The Hell Canyon Pluton is a homogeneous, porphyritic quartz monzonite of hypidiomorphic-granular texture (Mathews et al. 1977). The bulk of the groundmass is composed of oligoclase (40%), orthoclase (25%), quartz (20%), and biotite (nearly 7%). The remaining minerals include hornblende, sphene, magnetite, apatite and pyroxene. Secondary minerals include chlorite, muscovite and sericite.

The plagioclase feldspar grains are most often euhedral with equidimensional to elongate shapes and sizes ranging from 0.1 to 10 millimeters in length. Most exhibit normal or

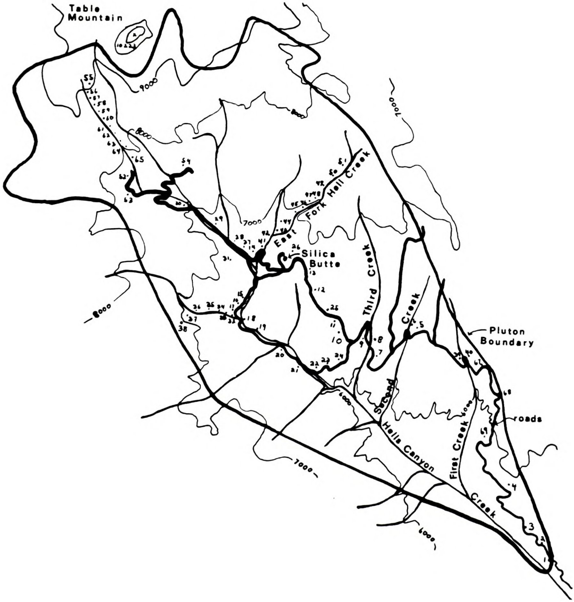


Figure 2. Sampling pattern for the Hell Canyon Pluton.

oscillatory zoning with a composition range of 30 to 35 percent anorthite at the grain boundaries to at least 57 percent anorthite within the cores (Figure 3). Albite rims which range from 0.001 to 0.2 mm thick are common. Composition of the albite rim edge was similar to that of the exsolved albite blebs in the alkali feldspar, averaging 95 percent albite. Although some grains are unaltered, most have small to large completely sericitized areas, especially within the zoned cores. A few grains are completely sericitized often only showing a thin unaltered albite rim. Inclusions consist of smaller plagioclase grains, sphene, biotite and chlorite. The contacts with adjacent plagioclase grains or alkali feldspar grains are occasionally irregular or corroded, indicating a disequilibrium.

The orthoclase grains occur as both phenocrysts and within the groundmass. The largest phenocryst observed was 33 x 37 x 25 mm although grains up to 30 x 60 mm are described by Mathews et al. (1977). The groundmass orthoclase range in size from 0.2 to 15 mm in diameter and are generally equidimensional and irregular in shape, although some smaller euhedral and sunhedral grains were observed. Some orthoclase is quite clean; most are partially to highly altered to sericite. Inclusions of quartz, plagioclase, biotite, albite, amphibole, chlorite, magnetite, pyroxene and sphene are quite common. Exsolved perthitic albite shows up as irregular blebs, parrallel linear blebs, small to large round, square or

Figure 3. Photomicrographs of Zoned Plagioclase.
A, B, C. Thick Compositional Zones with Thick Discontinuous Albite Rims. D, E, F. Thin Delicate Compositional Zonation and thin Albite Rims.

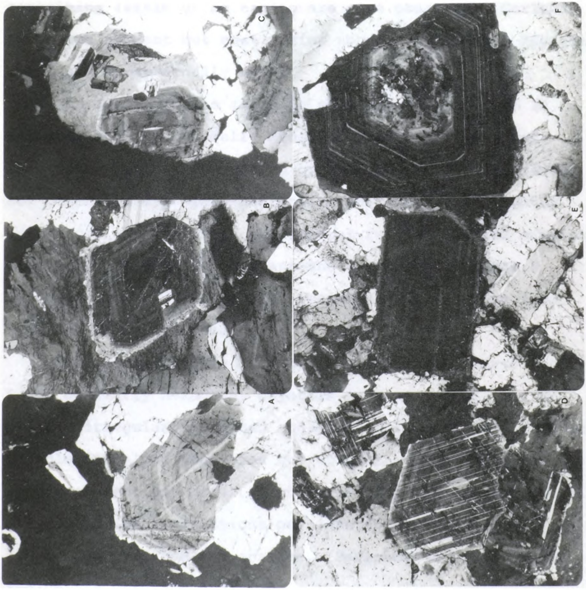


Figure 3.

rectangular blebs, and combinations of two or three different types (Figure 4). The irregular blebs generally show no preferential orientation, whereas the linear blebs are aligned along crystallographic axes. Orthoclase grains containing little or no albite are also observed. Carlsbad twins are present but most grains appear untwinned. Microcline twins are exceptionally rare.

The quartz grains range in size from 0.1 to 8 mm in diameter and are generally equidimensional and anhedral. They often contain inclusions of all other minerals present but otherwise are clean and unaltered. Sharp to slightly undulatory extinction is the general rule. In a few samples taken along the pluton contact the quartz grains show a mylonitic texture with quartz grains ranging in size from 0.01 to 0.2 mm in diameter.

The biotite grains are found as relatively large (up to 5 mm) perfectly hexagonal crystals in hand sample, and as smaller irregular elongated grains in thin section. Alterations to chlorite along fractures and at grain edges are almost always present and occur as thin chlorite veins to completely altered grains. Inclusions occur as opaques, chlorite, plagioclase, zircon and apatite. Radioactive halos around inclusions were not observed.

The remaining minerals make up about 8 percent of the total volume of the samples. Hornblende and sphene are more abundant than the other remaining minerals. Apatite and zircon are most often observed as inclusions within the biotite.

Figure 4. Photomicrograph of Exsolved Alkali Feldspar. A. Incoherent Albite Exsolution. D, E, F. Predominantly Coherent Albite Exsolution. B, C. Both Coherent and Incoherent Albite Exsolution Present.

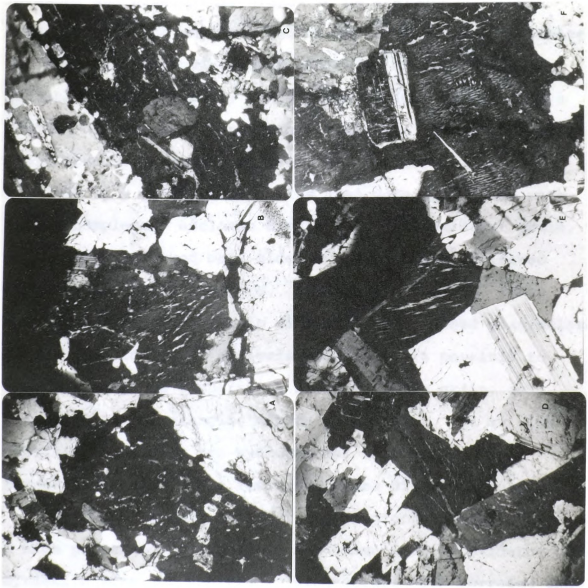


Figure 4.

ANALYTICAL METHODS

Grain Selection

A few requirements had to be met in choosing the alkali feldspar and plagioclase grains to be analysed. Alkali feldspar with the smallest amount and size of exsolve albite was most desirable since this indicates an optically and probably compositionally homogeneous grain. Grains with a minimum of inclusions and alterations were also chosen to avoid possible related compositional variations.

The only plagioclase grains used were those that were either completely enclosed within an alkali feldspar grain, or at least bordered on 3 sides by one. Clean unaltered plagioclase grains are rare. Grains with straight sharp boundaries and thin albitic rims were used. Zoned plagioclase grains were ideal for analysis because it is possible to obtain a complete temperature history of the grain, as indicated by the changing albite composition. It is also possible to predict pre-hydrothermal compositions and temperatures based on a few assumptions discussed later.

Grains of alkali feldspar and plagioclase that contained a high percentage of sericite and those showing evidence of myrmekite were not analysed. Plagioclase with corroded and embayed grain boundaries were avoided as well as those grains containing thick albitic rims.

Procedure

Two different analyses were run on the Hell Canyon Pluton samples. The first was the X-ray diffraction method of Wright (1968), which involved separating out the alkali feldspar by heavy liquids. Powdered alkali feldspar samples were analysed by X-ray diffraction to obtain d-spacings of the (060), ($\bar{2}04$) and ($\bar{2}01$) crystallographic planes. The values were then graphically related to structural state and composition.

About 15 grams of each sample were ground in a ceramic mortar and pestal and the powdered material was separated using a stack of graduated seives. The powder that remained between the 250 micron and 105 micron seives was saved while the finer material was discarded and the coarser material reground. Eventually approximately 10 grams of 105 to 250 micron sized material were collected from each sample.

In order to separate out the alkali feldspar from the other minerals it was necessary to use a Bromoform solution diluted by Dimethylforaminide. The Dimethylforaminide was added to the Bromoform until samples of quartz and albite sank while samples of orthoclase slowly floated to the surface. At this point the density of the heavy liquid was approximately 2.60. The seived samples were put into separatory funnels in small quantities and the Bromoform solution was added and agitated. After 5 minutes of settling the heavy minerals were removed. The lighter orthoclase was then washed out of the funnels with methanol, filtered, dried and placed into labeled vials. Small quantities of the orthoclase and heavies were observed under a petrographic microscope to make sure the separation was complete.

A small amount of an internal standard was added to the orthoclase samples and the combination was ground to a fine powder. CaF_2 and $KBrO_3$ were used as the internal standards for the orthoclase (060)-($\bar{2}04$) and ($\bar{2}01$) peaks respectively. Each powdered sample was packed into a 1 x 1 x 0.05 mm well which had been etched into a glass slide using concentrated HF acid. The slide and sample was then introduced into an X-ray diffractometer using Cu Kα radiation in a General Electric XRD-6 diffraction goniometer. High voltage potential was set at 50 KV and 20 milliamperes. A 0.1° slit was used along with a 3° MR collimnator and a HR receiving collimnator. The goniometer was run at a rate of 0.2° per minute for maximum peak resolution. The goniometer was run forward and backward between 19° and 23° 2θ for the ($\bar{2}01$) peak and between 40° and 52° 2θ for the (060) and ($\bar{2}04$) peaks, and the two values obtained for each peak were averaged together. The 2θ values of the (060), ($\bar{2}04$) and ($\bar{2}01$) peaks were determined by reference to the internal standard peaks (Figure 5a, 5b).

This procedure was repeated for each orthoclase sample, first in its natural exsolved state, and then after the orthoclase had been homogenized by heating to 1050°C for 24 hours. Homogenization was done to obtain the ($\bar{2}01$) peak which represents the homogeneous composition, before

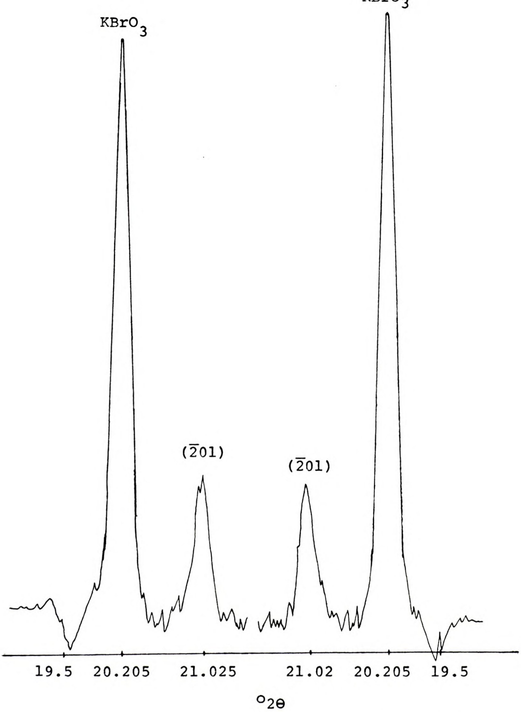
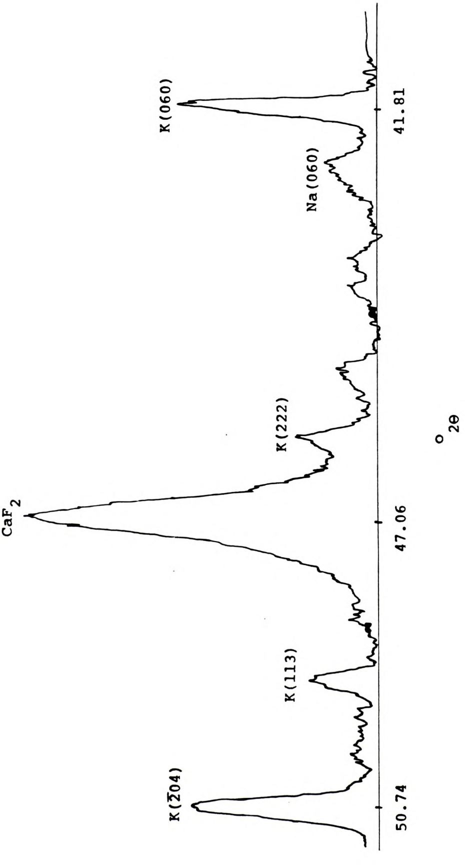


Figure 5a. Forward and Reverse Peaks for ($\bar{2}01$) and $KBrO_3$ Internal Standard for an Average Sample.

Figure 5b. Average X-ray plot of CaF_2 Internal Standard and (060)-($\bar{2}04$) Peaks.


K(060)
41.81
Na(060)
K(222)
°2θ
CaF$_2$
47.06
K(113)
K($\bar{2}$04)
50.74

exsolution of the albite.

The (060), $(\bar{2}04)$ and $(\bar{2}01)$ $^{\circ}2\theta$ values for each sample (Figure 6) are plotted on a (060) vs $(\bar{2}04)$ graph (Table 1) to obtain structural states of the samples (Wright and Stewart 1968).

The second part of the study required the use of a microprobe and polished thin sections of the Hell Canyon samples. The thin sections were analysed for Ca, Na and K using an ARL EMX microprobe set at 15 KV and 0.1 microampere beam current. LiF detector crystals were used to measure Ca $K\alpha$ and K $K\alpha$ and an RAP crystal was used to measure Na $K\alpha$. A point beam of approximately 0.5 microns was used in the analysis of plagioclase, exsolved albite and inhomogeneous orthoclase while a 50 micron defocused beam was used to measure homogeneous (orthoclase plus exsolved albite) compositions.

Samples of 90.7% orthoclase, 100% albite and 95.75% anorthite were used as standards, and background counts were recorded for these standards and a few samples. Six 12 second counts were recorded for each area analysed per grain. Between 3 and 6 areas per grain were analysed and between 2 to 6 grains per sample were used. Twenty-five different samples from the Hell Canyon Pluton were analysed for plagioclase, orthoclase and exsolved albite.

Analysis with the 50 micron defocused beam on homogeneous orthoclase gave consistently reproducible values. When the

Table 1. (060), (204) and (201) °2θ Cu Kα X-ray Peaks and Corresponding Orthoclase Compositions in Weight Percent Orthoclase.

Sample	(060)	($\bar{2}$04)	($\bar{2}$01) Inhomo-geneous	($\bar{2}$01) Homogeneous	Percent Or Inhomo-geneous	Percent Or Homogeneous
8-1	41.74	50.71	21.01	21.10	92.5	82.0
8-2	41.81	50.73	21.03	21.06	90.5	86.5
8-3	41.82	50.79	21.00	21.08	93.5	85.0
8-4	41.80	50.74	21.03	21.07	90.0	86.0
8-5	41.82	50.75	21.03	21.09	90.5	83.3
8-6	41.81	50.69	21.03	21.12	90.5	80.0
8-7	41.81	50.74	21.01	21.10	92.0	81.5
8-8	41.79	50.75	21.03	21.10	90.3	82.0
69-1	41.75	50.70	21.01	21.07	93.0	85.5
69-2	41.77	50.71	21.02	21.10	91.5	82.0
69-3	41.74	50.71	21.03	21.08	90.5	85.0
69-4	41.74	50.70	21.01	21.12	93.0	80.0
69-5	41.76	50.72	21.02	21.08	91.0	85.0
69-6	41.74	50.70	21.02	21.08	91.0	85.0
69-7	41.77	50.75	21.02	21.11	91.0	80.5
69-8	41.76	50.73	21.03	21.09	90.5	83.0
2	41.81	50.76	-	-	-	-
3	41.79	50.73	-	-	-	-
15	41.75	50.71	21.01	21.06	93.0	87.0
35	41.77	50.72	21.02	21.06	91.0	86.5
38	41.77	50.74	21.02	21.07	91.0	85.5
41	41.77	50.73	21.01	21.06	93.0	87.0
44	41.77	50.72	21.02	21.05	91.5	87.5
48	41.77	50.75	-	-	-	-
51	41.76	50.72	21.03	21.07	90.5	85.5
68	41.79	50.74	21.02	21.08	91.5	84.0

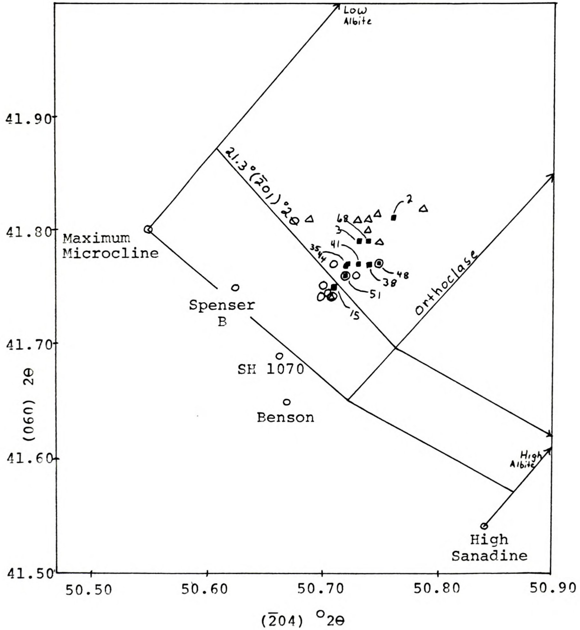


Figure 6. Plot of the (060) vs ($\bar{2}04$) 2Θ Cu Kα Peaks, (Wright 1968).

△ Samples obtained from single outcrop, area 8

○ Samples obtained from single outcrop, area 69

■ Samples collected along SW-NE traverse across pluton.

point beam was used a greater range of values were obtained due to the inhomogeneity of the orthoclase on a microscopic scale.

It was possible to avoid the albite rims surrounding the plagioclase because they were generally large enough to be delineated on the CRT which produced a magnified image of the analysed grain, generally at 2000X. It was possible to get a general picture of the Na and Ca distribution by setting the CRT to show X-ray intensities for Na and Ca. Thus the noticably high Na rims were easily defined and avoided.

Grains were analysed for orthoclase, orthoclase plus albite, and plagioclase compositions. The data was then compared with the X-ray values and used to make temperature determinations.

Microprobe data were corrected using methods and correction factors of Bence and Albee (1968) and Albee and Ray (1970).

RESULTS

From the graphs derived by Wright (1968.p. 92), (060) and ($\bar{2}$04) peaks are converted into structural state values (Figure 6). Structural state information was obtained within two different outcrops, samples 8-1 to 8-8 and 69-1 to 69-8, and across the entire pluton, samples 2, 3, 15, 35, 41, 44, 48, 51 and 68. Structural states from this study are considered anomolous due to the difference in the ($\bar{2}$01) values between that indicated on the (060) vs ($\bar{2}$04) plot and the actual measured values. A difference of over 0.2° 2θ is noted which exceeds the 0.1° 2θ acceptible difference of Wright and Stewart (1968). Although these values are considered anomolous, there is a definite consistency in the structural states of all the samples.

From Table 1 and Figure 6 it is noted that there is virtually no structural state variability between the two single outcrops and the northeast-southwest traverse across the pluton. All samples analysed fall between the Spenser B and SH 1070 samples of Wright (1968, fig 3). The structural state in this region is about 1/3 of the way between orthoclase and microcline, being closer to the structural state of orthoclase.

In order to determine temperature of crystallization from the microprobe feldspar compositions it is necessary to estimate the depth and thus pressure conditions existing at the time of crystallization. It is believed that the Boulder Batholith is a relatively shallowly emplaced intrusion, thus an estimate of 2 kilobars pressure corresponding to a depth of about 5 kilometers is used (Balk 1937; Buddington 1959). The pressure however does not greatly effect the temperature calculations when allowed to vary between wide limits in the microcline equation.

Temperature calculated from the microprobe data (Table 2) is plotted against distance to the edge of the pluton (Figure 7). Temperature vs elevation is also plotted to determine any vertical variations (Figure 8).

Figure 7 shows a marked correlation between temperature and position within the pluton. A correlation coefficient of -0.74 was calculated with a linear equation of best fit calculated as $y = -10.3x + 565.4$. Temperatures of 554 to 579 $^{\circ}$C are recorded at and near the pluton's edge while temperatures of 520 to 550 $^{\circ}$C are recorded at and near the center of the pluton. Standard deviations for a couple of samples were on the order of 550 $\pm$ 15 $^{\circ}$C.

Plots of temperature vs elevation (Figure 8) and temperature of exsolved albite vs distance to the edge of the pluton (Table 3, Figure 9) are also made. Neither plot shows any indication of any relationship between temperature and

Table 2. Microprobe Compositions and Temperatures.

X_{AF} = Mole Fraction of Albite in Orthoclase
X_{PF} = Mole Fraction of Albite in Plagioclase
5P and 15P are analyses of Phenocrysts

Sample	X_{AF}	X_{PF} (edge of grain)	Temp. ^{o}C (edge)	X_{PF} (center of grain)	Temp. ^{o}C (center)	Distance to edge of pluton (Km)
1	.1471	.6781	561.8	.6263	581.3	0.00
2	.1400	.6695	554.4	-	-	0.10
3	.1416	.6703	556.5	.4340	673.9	0.45
4	.1592	.6794	578.8	.6046	610.4	0.30
5	.1382	.6702	551.5	-	-	0.95
5P	.1674	.6694	594.8	-	-	0.95
8	.1685	.6948	555.0	-	-	2.00
10	.1341	.7116	532.0	.5663	580.7	2.60
15	.1485	.6926	558.7	.5285	629.7	1.80
15P	.1815	.6777	611.9	-	-	1.80
18	.1422	.6950	540.1	.4447	667.8	1.50
26	.1262	.7115	520.1	.5302	587.5	2.70
37	.1495	.6879	561.7	.5214	635.4	0.50
38	.1411	.6766	553.5	-	-	0.30
40	.1519	.6808	567.7	.5148	643.7	0.25
44	.1470	.7121	549.9	-	-	2.65
50	.1478	.6842	560.6	.4760	659.1	1.05
67	.1470	.6704	564.4	.6287	580.4	0.10
68	.1483	.6746	564.8	-	-	0.00
69	.1476	.6815	561.3	-	-	0.55

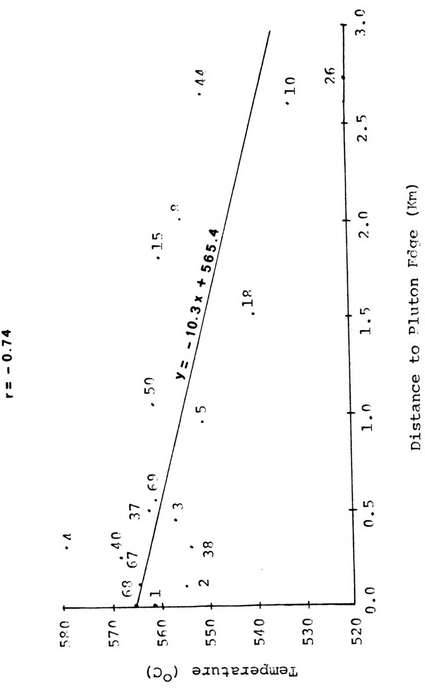


Figure 7. Plot of Temperature of Crystallization vs position within the Pluton.

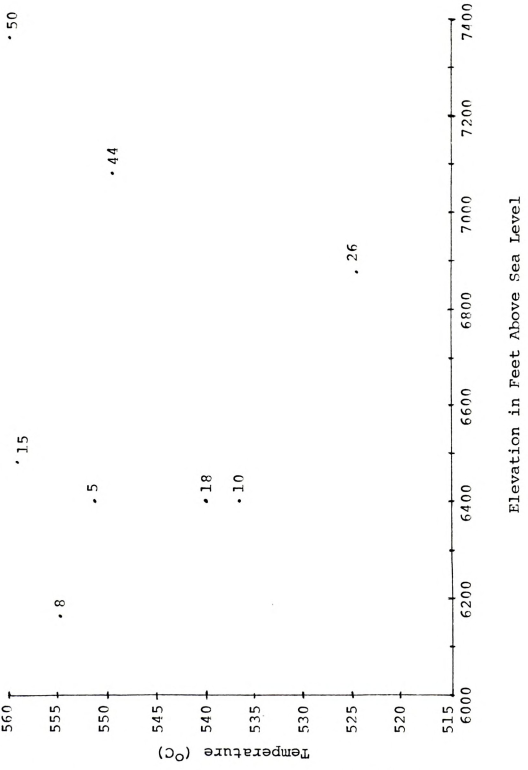


Figure 8. Temperature of Feldspar Crystallization vs Elevation.

Table 3. Composition and Temperature of Exsolved Alkali Feldspar. X_{AF} = Mole Fraction of Albite in Orthoclase. X_{PF} = Mole Fraction of Albite in Coexisting Exsolved Albite.

Sample	X_{AF}	X_{PF}	Temperature °C
1	.0400	.9782	336.0
3	.0322	.9671	318.8
4	.0281	.9577	308.7
8	.0357	.9706	327.1
15	.0282	.9488	309.8
37	.0342	.9645	324.0
38	.0344	.9628	324.7
40	.0303	.9674	313.8
43	.0278	.9654	307.1
44	.0388	.9658	334.7
67	.0250	.9690	298.5
68	.0325	.9669	319.6

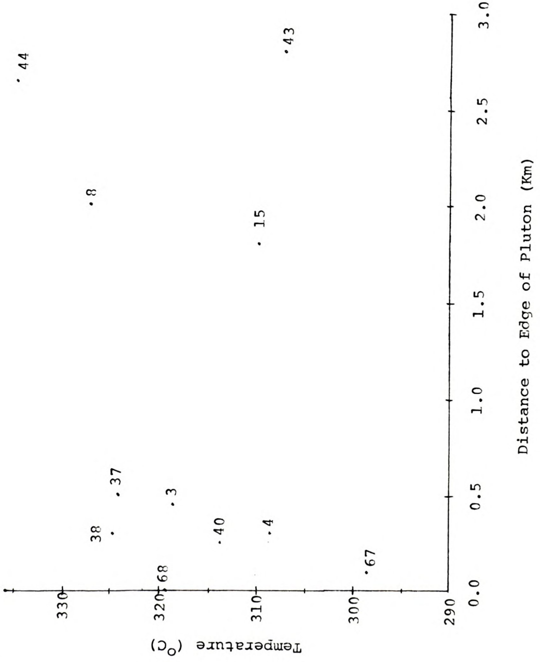


Figure 9. Exsolution Temperatures of Alkali Feldspars vs Position within the Pluton.

elevation or temperature of exsolution and position within the pluton. Temperatures of exsolution occur in a range from 298 to 336 ^{o}C.

The following feldspar compositions were obtained from the microprobe data (Table 4). Homogenized orthoclase (e.g. composition of orthoclase plus exsolved albite within a 50 micron area) range from 84 to 88 percent Or with an average near 86 percent. Nonhomogenized orthoclase)e.g. composition of orthoclase between albite blebs) is in the range 90 to 96 percent Or. Plagioclase compositions range from 30 to 35 percent anorthite at the grain edge to at least 57 percent anorthite at the center of a few highly zoned grains. Exsolved albite is generally from 93 to 97 percent albite. Homogenized orthoclase, determined from X-ray diffraction analysis ranges in composition from 83 to 88 percent orthoclase with an average near 85 percent. Nonhomogenized values range from 90 to 93 percent orthoclase.

Table 4. Orthoclase Compositions from X-ray and Microprobe Analysis as Weight Percent Orthoclase.

Sample	Homogeneous X-ray	Homogeneous Microprobe	Inhomogeneous X-ray	Inhomogeneous Microprobe
8	83.3	87.2	92.0	95.5
15	87.0	85.0	93.0	91.8
38	85.5	86.2	91.0	91.7
44	87.5	85.6	-	-
50	85.5	88.0	90.5	95.0
68	84.0	85.0	-	-
69	83.3	85.2	91.5	95.3
Radar Creek Sample				
2	76.0	76.3	96.0	96.5
26	81.0	79.3	95.0	92.8
30	86.0	85.5	-	-
41	88.0	87.0	95.0	93.8
43	86.5	86.6	-	-
44	86.0	84.2	-	-
45	88.0	86.5	-	-
48	85.0	86.1	-	-
49	84.0	84.8	-	-
53	86.0	88.6	-	-
54	85.0	87.0	-	-

DISCUSSION

The purpose of this study is to determine the composition and structural state variations within the Hell Canyon Pluton, which could be used to explain the cooling and crystallization history of the Hell Canyon Pluton. Although there appears to be a slight decrease in temperature as one approaches the center of the pluton, there is no indication of a sharp increase in crystallization temperature at the pluton's contact, due to the rapid cooling in this region, where one was expected.

Two possible explanations can be suggested to explain the homogeneity of the Hell Canyon Pluton. (1) It is possible that there are no measurable variations in the cooling rate of the pluton between the edges and its center, or (2) a secondary or hydrothermal event caused a re-equilibration of the pluton to a similar structural state and temperature.

In that the pluton intrudes both Precambrian gneiss and sedimentary rock, it may be assumed that a chilled border would have occurred at the pluton-country rock contact. As it turns out, there are fine-grained quartz monzonite outcrops at or near the expected contact, samples 1 and 68, although no precise contact was ever located.

However when analysed for composition, temperature and structural state, these samples are similar to the rest of the pluton. This indicates that if there were initial variations at the contacts, they may have been completely obliterated by later processes. A solid state reequilibration of the entire pluton is indicated by the relatively low temperatures of around 550 °C obtained throughout the pluton.

From past studies, crystallization temperatures for many different compositions and areas have been determined using both natural and artificial starting materials. For granitic compositions, solidus temperatures range from 970 °C under dry conditions to 640 °C at 4 kilobars water pressure and saturated conditions (Tuttle and Bowen 1958). Raguin (1965) determined a solidus range from 900 °C under dry conditions to 600 °C at pressures containing 7% water. Weill and Kudo (1968) show the initial melting temperature of the alkali feldspar-plagioclase-quartz system to occur between 680 and 755 °C at 2 kilobars pressure. Piwinskii (1967a, 1968, 1968a) and Piwinskii and Wyllie (1968b) conducted research at 2 kilobars pressure and 15 weight percent water, and show a solidus of quartz monzonite between 680-690 °C, a "granite" solidus at 670-680 °C and a granodiorite solidus at 705 °C.

Marmo (1968) states that under hydrothermal conditions and slow cooling, microcline can exist between 500 and 525 °C.

Above 525 °C or under rapid cooling conditions, orthoclase is the stable phase. Similarly Goldsmith and Laves (1954) show that under hydrothermal conditions sanadine will invert to microcline and presumably orthoclase, as an intermediate state, between 500 and 525 °C, independent of pressure in the range 0.4 to 30 kilobars. They also suggest that the transformation may occur at lower temperatures given enough time.

In summary, during magmatic cooling, feldspar crystallization takes place above 600 °C and may be as high as 900 °C under dry low pressure conditions. On the other hand under hydrothermal conditions, feldspar equilibrium reactions can occur at temperatures as low as 500 °C and possibly lower given enough time.

This hydrothermal range of temperatures, 500 to 600 °C is very similar to those obtained in this study and indicates that the low temperatures of the Hell Canyon Pluton samples may be due to a hydrothermal reequilibration of the feldspars.

Experimental solvus temperatures generally start between 650 to 700 °C and can extend down to at least 350 °C at 15 kilobars water pressure (Yoder et al. 1957; Goldsmith and Newton 1974). Work done by Martin (1974) shows a solvus temperature of 540 °C for an $Or_{85}Ab_{15}$ composition. Smith (1974) shows a 500 °C solvus temperature for $Or_{85}Ab_{15}$ at low pressures (near 0) and a 300 °C solvus for $Or_{97}Ab_{03}$.

Parsons (1978) may provide a key to the stability of orthoclase within the Hell Canyon Pluton by using exsolution lamellae to predict the availability of hydrous solutions below 400 ^{o}C. He states that below 400 ^{o}C, which is near the upper stability range of maximum microcline, orthoclase will remain stable if there are no fluids available to "facilitate the process of domain coarsening" which is intrumental in the conversion of orthoclase to microcline. Low temperature (≤400 ^{o}C) fluids are indicated by a change from coherent or crystallographically oriented exsolved albite lamellae to a noncoherent or nonoriented pattern. Most of the exsolved albite in the Hell Canyon Pluton is in the form of coherent exsolution although incoherent albite is also present to a much lesser degree (Figure 4). This indicates the hydrothermal solutions once present above 500 ^{o}C, no longer existed below 400 ^{o}C. This allowed the orthoclase to remain as the dominant structural state.

The exsolution composition and temperatures calculated in this study follow closely the expected results as indicated by the solvus curves of Martin (1974) and Smith (1974) under non-hydrothermal conditions and alkali feldspar compositions of $Or_{85}Ab_{15}$ and $Or_{97}Ab_{03}$. This may also indicate the lack of hydrothermal solutions during the time of alkali feldspar exsolution, between 300 and 500 ^{o}C.

It is possible to predict a simple cooling history using zoned plagioclase grains. The plagioclase grains show normal and oscillatory zoning with a maximum core composition of 43 percent albite and an unrimmed edge composition of 67 percent albite. Thus the initial temperature of crystallization began around 674 ^{o}C and continued to cool until a minimum temperature of 556 ^{o}C was attained, when reaction between plagioclase and coexisting orthoclase ceased. In order for these temperatures to be reliable it must be assumed that there was a continual equilibration at all times between the plagioclase and the orthoclase.

As was stated earlier in the paper, the low temperatures of near 550 ^{o}C indicate the possibility of a solid state hydrothermal reequilibration of the alkali feldspars. If the final alkali feldspar crystallization temperature is assumed to be 700 ^{o}C, which is the water saturated solidus temperature of a granitic melt, it may be possible to predict the crystallization temperature before hydrothermal equilibration occurred. Figure 10 shows the measured mole fraction of sample 3 at points A and A' with the alkali feldspar containing a constant .1416 mole percent albite and a plagioclase composition ranging from .6703 mole percent albite at point A' to . 4340 mole percent albite at point A. If it is assumed that the plagioclase composition was not affected by the hydrothermal solutions and only the alkali feldspar compostion changed, point A' can be projected to the right (constant plagioclase composition) until the 700 ^{o}C curve is reached at point B'. This is the predicted temperature of crystallization of an alkali

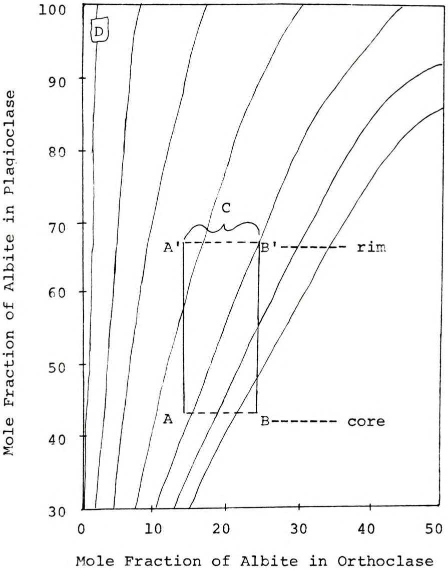


Figure 10. Mole Fraction of Albite in Plagioclase vs Alkali Feldspar. A, A' = Initial and Final Plagioclase Composition and Temperature of Sample 3. B, B' = Initial and Final Composition and Temperature before Hydrothermal Event. C = Mole Fraction of Albite lost from Alkali Feldspar due to Hydrothermal Event. D = Exsolved Albite Compositions.

feldspar of granitic composition at the solidus (Piwinskii 1967a, 1968, 1968a). The initial temperature of crystallization is now point B, near 900°C, corresponding to the plagioclase core composition of .4340 mole percent albite. This 900 to 700°C pre-hydrothermal temperature range of crystallization is close to what is indicated by Tuttle and Bowen (1958), Raguin (1965) and Piwinskii (1968).

The assumption that the solidus temperature of a granitic melt is near 700°C is based on data collected by Piwinskii (1967a, 1968, 1968a) and Piwinskii and Wyllie (1968b). It must be remembered that these are experimental values and may not exactly represent the real system. The assumption that the alkali feldspars were influenced by the hydrothermal solutions but not the plagioclase feldspars is based on petrographic evidence and Aluminum and Silicon bond energies. Because of the Ca-Al and Na-Si charge linkage it is not possible to change the Ca/Na ratio of plagioclase (e.g. composition) without breaking Al-O and Si-O chemical bonds. Bond breaking requires much more energy than is needed for the substitution or exchange of K^+ and Na^+ ions in the alkali feldspars. Thus from an energy point of view alkali feldspars are more susceptible to compositional changes than are plagioclase feldspars.

The plagioclase feldspars are often strongly zoned (Figure 3) and any change in composition after crystallization would destroy this compositional zonation. Therefore it is reasonable to assume that the alkali feldspars did indeed change composition while the plagioclase feldspars remained unchanged.

Figure 10 can be used to predict the amount of albite that was lost from the alkali feldspars during the influence of the hydrothermal solutions. A' is the calculated mole fraction of albite in the alkali feldspar after the influence of the hydrothermal solutions, and B' is the assumed composition before the hydrothermal solution. Therefore the difference, line C, is the amount of albite that was lost, corresponding to about 10 mole percent. This albite was either lost to the system or more likely may have gone into forming the albite rims around the plagioclase or into the albite inclusions that are present in the alkali feldspars. The plagioclase albitic rims were determined to have the same composition as the exsolved albite, near 95 percent albite.

Before the hydrothermal solution occurred the plagioclase and alkali feldspars were most likely in equilibrium. However, during the hydrothermal event the alkali feldspars began to reequilibrate by losing albite while the plagioclase feldspars remained unchanged. The result is an obvious disequilibrium between the orthoclase and the coexisting plagioclase, casting serious doubt on the application of the two feldspar geothermometric temperatures to the Hell Canyon samples.

CONCLUSION

The structural state of the alkali feldspars is near orthoclase and very consistent throughout the Hell Canyon Pluton. The stability of orthoclase as the dominant structural state indicates the absence of fluids once the pluton had cooled below 400 ^{o}C. Apparent crystallization temperatures based on coexisting feldspars are lower than expected and range from 520 to 580 ^{o}C, with phenocryst temperatures averaging 600 ^{o}C, and may indicate that the alkali feldspars have equilibrated with hydrothermal solutions. Exsolution temperatures are in the range 300 to 340 ^{o}C. Temperature variations across the pluton show a significant statistical difference between the edge and center of the pluton, with the edge temperatures being near 565 ^{o}C and the center being near 535 ^{o}C. Temperature vs elevation shows no general relationship, nor does albite exsolution temperature vs position within the pluton.

Although feldspar crystallization temperatures of 650 to 700 ^{o}C are expected for water saturated granitic or quartz monzonitic melts under magmatic cooling conditions, lower temperatures of 500 to 550 ^{o}C are possible if the post crystallization feldspars are subjected to hydrothermal solutions near the end of their cooling history.

Hydrothermal solutions existed in this area at one time as indicated by the Butte Porphyry Copper deposit and the gold-silver-lead mineral veins in and around the Hell Canyon Pluton. Because of the relative disorder of the alkali feldspars, hydrothermal solutions may not have been present below 400 ^{o}C based on the coherent solvus of Parsons (1978). Exsolution of albite began near 500 ^{o}C at a composition of $Or_{85}Ab_{15}$ and continued down to temperatures of about 300 ^{o}C and $Or_{97}Ab_{03}$ compositions. Because of the coherent perthites, it is likely that the hydrothermal solutions did not exist at the beginning of albite exsolution, near 500 ^{o}C.

Based on the assumption of continuous equilibrium between the plagioclase and the coexisting alkali feldspar, zoned plagioclase grains give indication of a simple cooling history with temperature of crystallization beginning near 675 ^{o}C and ending near 555 ^{o}C with a continuous change in temperature. However, if it is assumed that the solidus of a granitic melt is 700 ^{o}C and that plagioclase is not involved in the hydrothermal reequilibration process, a pre-hydrothermal feldspar crystallization temperature range from 900 to 700 ^{o}C occurred in the Hell Canyon Pluton. This corresponds to a plagioclase composition variation of 43.40% albite to 67.03% albite and an initial alkali feldspar composition of about 24% albite. Hydrothermal solutions were then responsible for lowering the alkali feldspar composition to the present 14.16% albite.

BIBLIOGRAPHY

BIBLIOGRAPHY

Albee, A. L., and L. Ray, 1970, Correction Factors for Electron-Probe Microanalysis of Silicates, Oxides, Carbonates, Phosphates, and Sulfates: Analytical Chemistry, vol. 42, no. 12, p. 1408.

Balk, Robert, 1937, Structural Behavior of Igneous Rocks: Geological Society of America Memoir 5.

Barth, T. F. W., 1934, Polymorphic Phenomena and Crystal Structure: American Journal of Science, vol. 5, p. 273.

Barth, T. F. W., 1969, Feldspars, John Wiley and Sons Inc., Great Britain, 261 pages.

Bence, A. E., and A. L. Albee, 1968, Empirical Correction Factors for the Electron Microanalysis of Silicates and Oxides: Journal of Geology, vol. 76, pp. 382-403.

Bohlen, S. R., and E. J. Essene, 1977, Feldspar and Oxide Thermometry of Granulites in the Adirondack Highlands: Contributions to Mineralogy and Petrology, vol. 62, pp. 153-169.

Buddington, A. F., 1959, Granite Emplacement with Special Reference to North America: Geological Society of America Bulletin, vol 70, pp. 671-747.

Buddington, A. F., and D. H. Lindsley, 1964, Iron-Titanium Oxide Minerals and Synthetic Equivalents: Journal of Petrology, vol. 5, pp. 310-357.

Carmichael, Ian Stuart Edward, 1963, The Crystallization of Feldspar in Volcanic Acid Liquids: Quarterly Journal of Geological Society of London, vol. 119, pp. 95-131.

Doe, B. R., R. I. Tilling, C. E. Hedge, and M. R. Klepper, 1968, Lead and Strontium Isotope Studies of the Boulder Batholith, Southwestern Montana: Economic Geology, vol. 63, pp. 884-906.

Franco, R. R., and J. F. Schairer, 1951, Liquidus Temperatures in Mixtures of the Feldspars of Soda, Potash, and Lime: Journal of Geology, vol 59, pp. 259-267.

Goldsmith, J. R., and F. Laves, 1954, The Microcline-Sanadine Stability Relation: Geochimica et Cosmochimica Acta, vol. 5, p. 1.

Goldsmith, J. R., and R. C. Newton, 1974, An Experimental Determination of the Alkali Feldspar Solvus: in The Feldspars, Manchester University Press, Crane, Russak and Co. Inc., New York, pp. 337-359, 717 pages.

Hamilton, Warren, and W. B. Myers, 1974, Nature of the Boulder Batholith of Montana: Geological Society of America Bulletin, vol. 85, pp. 365-378.

James, R. S., and D. L. Hamilton, 1969, Phase Relations in the System $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-SiO_2 at one Kilobar Vapor Pressure: Contributions to Mineralogy and Petrology, vol. 21, pp. 111-141.

Klepper, M. R., G. D. Robinson and H. W. Smedes, 1971, On the Nature of the Boulder Batholith: Geological Society of America Bulletin, vol. 82, pp. 1563-1580.

Laves, Fritz, 1952, Phase Relations of the Alkali Feldspars. I. Introductory Remarks: Journal of Geology, vol.60, pp. 436-450.

Laves, Fritz, 1952, Phase Relations of the Alkali Feldspars. II. The Stable and Psuedo-Stable Phase Relations in the Alkali Feldspar System: Journal of Geology, vol. 60, pp. 549-574.

Lowell, J. D., and J. M. Guilbert, 1970, Lateral and Vertical Alteration-Mineralization Zoning in Porphyry Copper Deposits: Economic Geology, vol. 65, pp. 373-408.

Marmo, Vladi, 1958, Orthoclase and Microcline Granites: American Journal of Science, vol. 256, pp. 360-364.

Marmo, Vladi, 1962, On Granites: Bulletin of the Commission Geological Survey of Finland, vol. 201, p. 1.

Marmo, Vladi, 1968, The Origin of Granites, A Hydrothermal Model: Lithos, vol. 1, pp. 58-69.

Marmo, Vladi, 1971, Granite Petrology and the Granite Problem, Elsevier Publishing Co., New York, 244 pages.

Martin, R. F., 1974, Controls of Ordering and Subsolidus Phase Relations in Alkali Feldspars: in The Feldspars, Crane, Rossak and Co., Inc., New York, pp. 313-336, 717 pages.

Mathews, Geoffrey W., Linda K. McClain, and William M. Johanns, 1977, Petrogenetic Aspects of the Hell Canyon Pluton and its Relation to the Boulder Batholith, Southwestern Montana: Northwest Geology, vol. 6-2 pp. 77-84.

McDowell, Douglas S., 1978, Little Chief Granite Porphyry: Feldspar Crystallization History: Geological Society of America Bulletin, vol. 89, pp. 33-49.

Orville, Philip M., 1963, Alkali Ion Exchange between Vapor and Feldspar Phases: American Journal of Science, vol. 261, March, pp. 201-237.

Parsons, Ian, 1978, Feldspars and Fluids in Cooling Plutons: Mineralogical Magazine, vol. 42, no. 321, pp. 1-17.

Piwinskii, A. J., 1967a, The Attainment of Equilibrium in Hydrothermal Experiments with "Granitic" Rocks: Earth and Planetary Science Letters, vol. 2, pp. 161-162.

Piwinskii, A. J., 1968, Studies of Batholithic Feldspars: Sierra Nevada California: Contributions to Mineralogy and Petrology, vol. 17, pp. 204-223.

Piwinskii, A. J., 1968, Experimental Studies of Igneous Rock Series, Central Sierra Nevada Batholith, California: Journal of Geology, vol. 76, no. 5, pp. 548-570.

Piwinskii, A. J., 1968a, Experimental Studies of Igneous Rock Series: "Felsic" Bodies from the Wallowa Batholith, Oregon: Geological Society of America Special Paper no. 101, pp. 166-167.

Piwinskii, A. J., and P. J. Wyllie, 1968b, Experimental Studies of Igneous Rock Series: A Zoned Pluton in the Wallowa Batholith, Oregon: Journal of Geology, vol. 76, no. 2, March, pp. 205-234.

Powell, Marjorie, and Roger Powell, 1977, Plagioclase-Alkali-Feldspar Geothermometry Revisited: Mineralogical Magazine, June, vol. 41, pp. 253-256.

Powell, Marforie, and Roger Powell, 1977, Geothermometry and Oxygen Barometry using Coexisting Iron-Titanium Oxides: a Reappraisal: Mineralogical Magazine, June, vol. 41, pp. 257-263.

Raguin, E., 1965, Geology of Granites, Interscience Publishers, New York, 314 Pages.

Robertson, Forbes, 1962, Crystallization Sequence of Minerals Leading to Formation of Ore Deposits in Quartz Monzonitic Rocks in the Northwestern Part of the Boulder Batholith, Montana: Geological Society of America Bulletin, vol. 73, October, pp. 1257-1276.

Robinson, G. D., M. R. Klepper, and J. D. Obradovich, 1968, Overlapping Plutonism, Volcanism, and Tectonism in the Boulder Batholith Region, Western Montana, in Studies of Volcanology: Geological Society of America Memoir 116, pp. 557-576.

Simonen, A., 1961, Feldspar-Equilibrium Temperature of some Finnish Rocks: Bulletin of the Commission Geological Survey of Finland, vol. 196, p. 367.

Smith, J. V., 1974, Feldspar Minerals. I. Crystal Structure and Physical Properties, Spinger-Verlag, New York 627 pages.

Smith, J. V., 1974, Feldspar Minerals. II. Chemical and Textural Properties, Spinger-Verlag, New York, 690 pages.

Stewart, D. B., and E. H. Roseboom, Jr., 1962, Lower Temperature Terminations of the Three-Phase Region Plagioclase-Alkali Feldspar-Liquid: Journal of Petrology, vol. 3, part 2, pp. 280-315.

Stormer, John C., 1975, A Practical Two-Feldspar Geothermometer: American Mineralogist, vol. 60, pp. 667-674.

Suttner, Lee J., and Abhijit Basu, 1977, Structural State of Detrital Alkali Feldspars: Sedimentology, vol. 24, pp. 63-74.

Tilling, Robert I., 1968, Zonal Distribution of Variations in Structural State of Alkali Feldspars within the Radar Creek Pluton, Boulder Batholith, Montana: Journal of Petrology, vol. 9, pp. 331-357.

Tilling, Robert I., 1973, Boulder Batholith, Montana: A Product of Two Contemporaneous but Chemically Distinct Magma Series: Geological Society of America Bulletin, vol. 84, December, pp. 3879-3900.

Tilling, Robert I., 1974, Composition and Time Relations of Plutonic and Associated Volcanic Rocks, Boulder Batholith Region, Montana: Geological Society of America Bulletin, vol. 85, pp. 1925-1930.

Tilling, Robert I., M. R. Klepper and J. D. Obradovich, 1968, K-Ar Ages and Time Span of Emplacement of the Boulder Batholith, Montana: American Journal of Sc ience, vol. 266, October, pp. 671-689.

Tuttle, O. F., and N. L. Bowen, 1958, Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O: Geological Society of America Memoir 74, November, 153 pages.

Weill, D. F., and A. H. Kudo. 1968, Initial Melting in Alkali Feldspar-Plagioclase-Quartz Systems: Geological Magazine, vol. 105, no. 4, pp. 325-337.

Whitney, James A., and J. C. Stormer Jr., 1976, Geothermometry and Geobarometry in Epizonal Granite Intrusions: a Comparison of Iron-Titanium Oxides and Coexisting Feldspars: American Mineralogist, vol. 61, pp. 751-761.

Whitney, James A., and J. C. Stormer, 1977, Two Feldspar Geothermometry, Geobarometry in Mesozonal Granitic Intrusions: Three Examples from the Piedmont of Georgia: Contributions to Mineralogy and Petrology, vol. 63, pp. 51-64.

Whitney, James A., and J. C. Stormer Jr., 1977, The Distribution of $NaAlSi_3O_8$ between Coexisting Microcline and Plagioclase and its Effect on Geothermometric Calculations: American Mineralogist, vol. 62, pp. 687-691.

Woodbury, Jerry L., and Thomas A. Vogel, 1970, A Rapid, Economical Method for Polishing Thin Sections for Microprobe and Petrographic Analyses: American Mineralogist, vol. 55, pp. 2095-2102.

Wright, Thomas L., 1968, X-ray and Optical Study of Alkali Feldspars: II. An X-ray Method for Determining the Composition and Structural State from Measurements of 2θ Values for Three Reflections: American Mineralogist, vol. 53, pp. 88-104.

Wright, Thomas L., and David B. Stewart, 1968, X-ray and Optical Study of Alkali Feldspar: I. Determination of Composition and Structural State from Refined Unit-Cell Parameters and 2V: American Mineralogist, vol. 53, pp. 38-87.

Yoder, H. S., D. B. Stewart, and J. R. Smith, 1957, Ab-Or-An-H_2O at 5000 Bars: Geological Society of America Bulletin, vol. 68, part 2, p. 1815.