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Contributions to Mineralogy and Petrology

Two-Feldspar Geothermometry, Geobarometry in Mesozonal Granitic Intrusions: Three Examples from the Piedmont of Georgia

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Abstract. The equilibrium temperatures for coexisting plagioclase and potassium feldspar pairs have been calculated for various textural varieties of feldspar from 3 post-metamorphic granites from the Georgia Piedmont; the Danburg, Siloam, and Stone Mountain plutons. Assuming an intermediate structural state for the feldspars at time of equilibration, crystallization temperatures match those expected from experimental data for quartz monzonite magmas (650 to 780° C). The variations in solidus temperature, recorded in the feldspars, may be used to estimate relative differences in depth of intrusion. Sharp reversals in plagioclase compositional trends may be caused by isothermal decreases in confining pressure associated with upward migration through the crust. In fine grained and slowly cooled intrusions, albite tends to be lost from the alkali feldspar grains, and recrystallizes as separate unzoned grains of oligoclase, thus erasing the previous thermal history. Perthite exsolution and re-equilibration within the alkali feldspar grains appears to continue down to temperatures of 400° C or so, although the zoned plagioclase does not homogenize. The recrystallization associated with changes in structural state may facilitate exsolution within alkali feldspar grains.

Introduction

The distribution of $NaAlSi_3O_8$ between 2 coexisting feldspars has long been recognized as a potentially valuable geothermometric tool. Recently, Stormer (1975) has proposed a model based on feldspar thermodynamic data which considers the effects of pressure, as well as non-ideality in alkali feldspars, on $NaAlSi_3O_8$ distribution. The current report is an evaluation of the effectiveness of this geothermometer in mesozonal granitic rocks containing alkali feldspar perthites and plagioclase.

Three post-metamorphic granites of the Georgia Piedmont province, showing varying degrees of post-magmatic exsolution in the alkali feldspar phases, have been chosen for detailed study. These are the Danburg granite, located in northern Wilkes and Lincoln Counties (Hurst et al., 1966), the siloam granite from southern Green County (Humphrey and Radcliffe, 1971), and the Stone Mountain granite from eastern Dekalb County (Hermann, 1954). The Danburg and Siloam are coarse grained with perthitic alkali feldspar phenocrysts measuring up to several centimeters, while the Stone Mountain granite is a homogeneous, fine-grained unit.

$NaAlSi_3O_8$ Distribution Models and the Effects of Structural State

The $NaAlSi_3O_8$ distribution model derived by Stormer (1975) is based on thermodynamic parameters for high-sanidine. In the original paper, and in a subsequent application (Whitney and Stormer, 1976) lithologies discussed included volcanic and shallow intrusive units in which crystallization temperatures were mainly within the stability field of high-sanidine. In these cases, the following temperature equation derived by Stormer (1975) from sanidine-high albite solution data was applicable:

$$T(^\circ\mathrm{K}) = \frac{\{6326.7 - 9963.2\,X_{AF} + 943.3\,X_{AF}^2 + 2690.2\,X_{AF}^3 + (0.0925 - 0.1458\,X_{AF} + 0.014\,X_{AF}^2 + 0.0392\,X_{AF}^3)\,P_{(Kb)}\}}{\left\{-1.9872 \ln\left(\frac{X_{AF}}{X_{PF}}\right) + 4.6321 - 10.815\,X_{AF} + 7.7345\,X_{AF}^2 - 1.5512\,X_{AF}^3\right\}}. \tag{1}$$

X_{AF} is the mole fraction of $NaAlSi_3O_8$ in alkali feldspar; X_{PF} the mole fraction in coexisting plagioclase and P is pressure in kilobars.

In mesozonal granites, however, the crystallization temperatures are thought to be lower, and alkali feldspars of a lower temperature structural state (orthoclase) may crystallize in equilibrium with the melt. An expression exactly analogous to (1) has been developed for microcline-low albite solid solutions using the parameters of Bachinski and Mueller (1971) (Whitney and Stormer, in press):

$$T(^\circ\mathrm{K}) = \frac{\{7973.1 - 16910.6\,X_{AF} + 9901.9\,X_{AF}^2 + (0.11 - 0.22\,X_{AF} + 0.11\,X_{AF}^2)\,P_{(Kb)}\}}{\left\{-1.9872 \ln\left(\frac{X_{AF}}{X_{PF}}\right) + 4.6321 - 10.815\,X_{AF} + 7.7345\,X_{AF}^2 - 1.5512\,X_{AF}^3\right\}}. \tag{2}$$

Where the symbols are the same as in (1).

Unfortunately, there is insufficient thermodynamic data on intermediate structural states to formulate an equation analogous to (1) and (2) for orthoclase solid solutions. Presumably, temperatures for orthoclase bearing rocks would be intermediate between those calculated from the sanidine and microcline equations. If there is a continuous range of structural states between ordered and disordered feldspars (Stewart, 1974), there may be no single model possible for intermediate states. For the present discussion, we will average the results obtained from the sanidine and microcline models to obtain estimates of crystallization temperatures for feldspars of intermediate structural state which we believe equilibrated with each other in a melt, recognizing that errors of up to 20° C or so may be introduced by uncertainties in the exact degree of ordering and the appropriate thermodynamic parameters for such solutions.

Analytic Procedures

The plagioclase compositions were determined by chemical analysis for Na, K, and Ca using a MAC 400S electron microprobe employing 3 wavelength dispersive crystal spectrometers. In addition, in order to exclude the possibility of any other major component being present, X-ray spectra (1-10 KeV) were obtained with an energy dispersive system. Each analysis represents a minimum of three 20 second counts on different points in the sample. Analyzed natural feldspars were used as standards to minimize matrix effects, and all analyses were corrected using the procedure of Bence and Albee (1968) and the alpha factors of Albee and Ray (1970). Representative plagioclase analyses for all three plutons are presented in Table 1. Also listed are analyses of homogeneous, non-perthitic portions of the alkali feldspar which were determined in the same manner.

Microperthite in the cores of the alkali feldspar from the Stone Mountain granite was analyzed by defocusing the electron beam to give a broad beam, about 30 microns in diameter. Numerous spots were taken on a single core, and the average used to represent the entire core area. The resulting compositions are also summarized in Table 1.

The phenocrysts from the Danburg and Siloam plutons were too coarsely perthitic for microprobe analysis of the bulk composition. Single crystals could be selected which were nearly free of inclusions. These were carefully cut from the matrix, crushed, and traces of magnetite and biotite removed by magnetic separation. Where possible, half the crystal was thin sectioned for petrographic analysis. The concentrations of Na, K, and Ca were obtained by atomic absorption using a Perkin Elmer, model 303 unit, and employing the procedure for silicate analysis outlined by Medlin et al. (1969). Microscopic observation of the Siloam alkali feldspars suggested some variation in the bulk composition and the outer parts of several grains were removed and analyzed separately to test for possible zoning. Representative results of the atomic absorbtion analyses of the alkali feldspars are also summarized in Table 1.

Where sufficient sample was available, AA analyses for Si, Al, Fe, and Mg were also done, using the procedure outlined above, as a check on the composition of the feldspar concentrate. Representative results of these analyes are summarized in Table 2.

Tectonic Setting

All three plutons appear to post-date regional metamorphism with discordant contacts and no petrographic evidence of a penetrative fabric. These plutons belong to the 300 m.y. old series of Fullagar (1971). The Siloam has been dated at 270 m.y. (Jones and Walker, 1973) and the Stone Mountain intrusion at 290 m.y. (Whitney et al., 1976) by the rubidium-strontium isochron technique. Although no date for the Danburg has been published, preliminary rubidium-strontium data suggest an age of around 290 m.y. (Jones, Whitney, and Walker, unpublished data).

All three plutons would be classified as mesozonal granites according to the criteria of Buddington (1959). Buddington used the Stone Mountain and Lithonia gneiss association as an example of a rather deep seated mesozonal, transitional to catazonal, intrusion. A recent study (Whitney et al., 1976) has suggested a depth of intrusion of about 12 km, for the Stone Mountain granite ($P=3.5$ Kb). The actual depth of intrusion for the Danburg and Siloam plutons are less well known. The Danburg pluton has developed a significant contact aureole, but to date no andalusite or cordierite has been reported from this area. Mineral stability relationships and the general tectonic setting, suggest a depth of around 5 km ($P=1.5$–2 Kb). The Siloam pluton does not appear to have such a contact aureole, but it intrudes rather high grade metamorphic rocks. Mineral relationships within the Siloam, including some very late stage, partially primary or deuteric muscovite in its core, suggest that it might have been intruded at depth of 7 to 10 km ($P=2$–3 Kb) or more.

Table 1. Representative feldspar compositions based on partial chemical analyses

	Wt.% Ab	Wt.% Or	Wt.% An	Total	Mole % Ab
Danburg granite					
Plagioclase					
Rounded core	49.6	1.0	46.3	97.2	52.8
Inner zone	69.0	1.2	29.2	99.5	70.7
	71.8	1.2	26.3	99.3	73.5
Outer zone	79.8	1.7	19.8	101.3	79.3
Inner zone	70.2	0.7	30.9	101.8	70.2
	71.6	2.7	27.1	101.4	71.8
Outer zone	75.3	2.1	24.5	101.7	75.0
Rapakivi rim	75.5	1.5	23.5	100.5	76.2
outer edge	78.8	1.6	20.5	100.8	79.1
Small zoned grain	76.0	1.0	24.5	101.4	76.0
	80.8	0.4	20.2	101.4	80.6
Inclusions in alkali feldspar	67.8	0.7	30.0	98.5	70.1
	73.1	1.3	24.7	99.1	74.9
Alkali Feldspar					
K feldspar host of perthite	5.5	93.0	0.1	98.6	5.9
	7.3	92.0	0.2	99.5	7.7
	7.9	91.5	1.5	100.89	8.3
Exsolved albite	94.6	1.3	3.4	99.4	95.5
	98.2	0.9	2.9	102.0	96.4
Perthite phenocrysts[a] (atomic absorption)					
DG-1A	29.6	60.1	3.6	93.3	33.0
DG-3-1	29.7	62.7	3.0	92.5	33.4
DG-3-2	25.4	64.8	1.8	92.0	28.8
DG-11-1	27.6	65.1	2.5	95.3	30.2
DG-11-2	27.4	66.6	1.9	95.9	29.8
DG-21-1	26.1	60.7	2.8	92.1	30.2
Siloam granite					
Sample SG-1, Northern Part					
Plagioclase					
Inner zone	77.7	0.8	21.4	99.8	78.8
	76.7	1.3	22.1	100.1	77.7
	76.2	2.4	22.4	101.1	76.5
	74.4	1.7	22.5	98.6	76.6
Outer zone	70.1	1.8	25.5	97.5	73.1

Note: All analytic procedures are described in text. All analyses done by electron microprobe techniques except as noted

[a] The low totals for bulk analyses by atomic absorption are believed to result from small amounts of included quartz and alteration. The Mole % albite, however, is a value representing the ratio of feldspar components calculated from Na, K, and Ca, and is believed to be quite close to the actual composition of the unaltered feldspar

Table 1 (continued)

	Wt.% Ab	Wt.% Or	Wt.% An	Total	Mole % Ab
Alkali feldspar					
K feldspar host in perthite	5.9	94.2	0.1	100.2	6.3
Exsolved albite	97.8	1.0	2.6	101.4	96.6
Samples SG-1A and 1B, Northern Part					
Plagioclase					
Inner zone	81.3	0.4	20.1	101.8	80.8
	78.8	0.8	22.2	101.7	78.5
	75.3	0.8	25.8	101.9	75.0
	76.8	0.7	23.9	101.4	76.8
	81.5	0.4	19.9	101.9	81.0
Outer zone	74.6	0.4	26.7	101.7	74.5
Alkali feldspar					
K feldspar host in perthite	8.6	94.0	0.1	102.5	8.6
Exsolved albite	98.9	0.7	3.4	103.0	96.2
Sample SG-5, Southeastern Part					
Plagioclase					
Inner zone	75.8	0.6	24.9	101.3	75.9
	83.8	0.6	16.9	101.3	83.5
	76.2	0.7	23.8	100.7	76.7
	78.3	0.5	22.2	101.1	78.5
	78.8	0.5	21.5	100.8	79.2
	74.0	0.8	25.6	100.3	74.9
	76.8	1.1	22.7	100.5	77.4
	79.2	1.2	20.8	101.2	79.3
Outer zone	80.6	1.2	18.4	100.1	81.4
Perthite phenocrysts[a] (atomic absorption)					
SG-1 core	26.7	65.1	2.1	93.9	29.7
SG-1 rim	24.1	69.0	2.6	95.8	26.3
SG-1A	23.3	72.7	2.2	98.1	24.7
SG-1B-1	21.2	70.4	1.9	93.5	23.7
SG-1B-2	25.0	69.8	2.8	97.5	26.7
SG-1B-3	22.0	72.8	2.1	96.9	23.7
SG-5-1	20.6	77.0	1.4	99.0	21.8
SG-5-2	20.7	74.9	1.8	97.5	22.3
SG-5-3	20.1	73.6	1.7	95.4	22.0
Sample SG-2, Fine-grained Core					
Plagioclase					
Zoned grain	76.7	0.3	25.9	102.9	75.6
	82.8	0.4	18.9	102.1	82.0
Unzoned grain	82.9	0.4	17.9	101.2	82.7
Alkali feldspar					
Microcline	7.6	91.6	0.1	99.2	8.1

Table 1 (continued)

	Wt.% Ab	Wt.% Or	Wt.% An	Total	Mole % Ab
Stone mountain granite					
Plagioclase					
Core, zoned grain	83.0	0.1	16.4	99.6	84.2
	79.4	0.6	20.5	100.4	80.0
	80.1	0.6	19.2	99.8	81.2
Inner zone	77.1	0.7	22.6	100.4	77.8
	87.2	0.9	12.1	100.2	87.7
Edge	88.4	0.8	11.6	100.8	88.4
Unzoned grain	88.4	0.4	11.7	100.6	88.5
Alkali Feldspar					
Homogeneous microcline	5.5	92.4	0.1	98.0	6.0
	3.9	95.4	0.0	99.4	4.2
Perthitic cores (Wide beam)					
Average 5 grains	24.2	75.0	2.7	101.9	24.8
Average 3 grains	29.8	68.4	2.5	100.7	30.8
Average 3 grains	29.8	68.4	2.5	100.7	30.8
Average 5 grains	23.0	75.8	1.8	100.6	24.0

The Danburg Granite

Petrography

The Danburg granite is a coarse-grained, porphyritic quartz monzonite, composed of large (up to 2 cm) euhedral alkali feldspar phenocrysts, commonly showing an overgrowth of plagioclase in a rapakivi texture, set in a matrix of medium to coarse grained, euhedral plagioclase, anhedral quartz, and euhedral biotite, with minor sphene and rare hornblende, largely reacted to biotite.

The plagioclase forms euhedral, medium to coarse grained (2 to 5 mm, some up to 1 cm) crystals with few inclusions and very little alteration. Zoned crystals commonly contain a rounded core of calcic andesine to sodic labradorite, surrounded by normally zoned calcic oligoclase with most grains showing only one period of continuous normal zoning.

The alkali feldspars are large, homogeneous microcline perthites. Most are euhedral, columnar crystals with well formed {010} {001} faces and prismatic terminations. Carlsbad contact and interpenetration twins are exceedingly common. This morphology is most commonly associated with crystallization as orthoclase, and it is therefore believed that the alkali feldspar equilibrated with the melt in an intermediate structural state.

The distribution of perthitic albite lamellae is very homogenous and albite is not being lost from the phenocrysts. The alkali feldspar phenocrysts also contain inclusions of plagioclase ranging in composition from calcic to intermediate oligoclase.

Some phenocrysts are surrounded with rapakivi rims formed, in part, of optically continuous plagioclase growing on the alkali feldspar. The composition of these rims is the same as that

Table 2. Chemical analyses of alkali feldspar phenocrysts

	Danburg granite								Siloam granite					
	DG-1A		DG-3-3		DG-11-4		DG-21-2		SG-1B2		SG-5-2		SG-2D2	
SiO_2	63.74		65.29		64.83		65.53		64.10		64.89		64.03	
Al_2O_3	18.96		19.19		18.59		18.37		18.72		18.52		19.84	
Fe_2O_3*	0.30		0.25		0.24		0.21		0.19		0.19		–	
MgO	0.04		0.02		0.02		0.02		0.02		0.03		0.02	
CaO	0.87		0.44		0.43		0.59		0.57		0.39		0.53	
Na_2O	3.44		3.83		3.70		3.57		3.38		2.79		2.85	
K_2O	10.31		11.98		11.29		10.90		11.94		12.04		11.68	
Total	97.66		100.00		99.10		99.19		98.93		98.84		98.85	
Number of ions on the basis of 8 (0)														
Si	2.960		2.957		2.980		3.000		2.963		2.991		2.945	
Al	1.038	4.009	1.024	3.989	1.007	3.995	0.991	3.998	1.020	3.99	1.006	4.004	1.075	4.020
Fe	0.011		0.008		0.008		0.007		0.007		0.007		–	
Mg	0.003		0.001		0.001		0.001		0.001		0.002		0.001	
Ca	0.043	0.967	0.021	1.050	0.021	1.014	0.029	0.983	0.028	1.036	0.019	0.978	0.026	0.966
Na	0.310		0.336		0.330		0.317		0.303		0.249		0.254	
K	0.611		0.692		0.662		0.636		0.704		0.708		0.685	
Mole % Albite	32.1		32.0		32.5		32.2		29.2		25.5		26.3	

R. Smith, analyst

found in small zoned grains, of intermediate oligoclase. The relatively calcic composition of the rims, suggests that these rims formed during magmatic crystallization and not as subsolidus exsolution of the perthite.

Chemical Analyses of Feldspars

Analyses of the various textural varieties of plagioclase have been summarized (Table 1). The continuous normal zoning observed for the majority of plagioclase spans the range Ab_{70} to Ab_{80} (mole fraction) or as more commonly noted An_{30} to An_{20} (wt.%). (Since albite distribution is being studied we will give plagioclase compositions as mole percent Ab). There is a distinct break in composition between the resorbed cores (Ab_{53}) and the surrounding zone (Ab_{70}). The albite lamellae are also distinct in composition (Ab_{95}) from the rest of the plagioclase as previously noted.

The alkali feldspar analyses (Table 1 and 2) give a consistent value of around Ab_{32} (mole %), although some small amount of variation is noted in the partial analyses. Any zoning which might have existed before exsolution has apparently been obliterated by that process. However, study of the composition

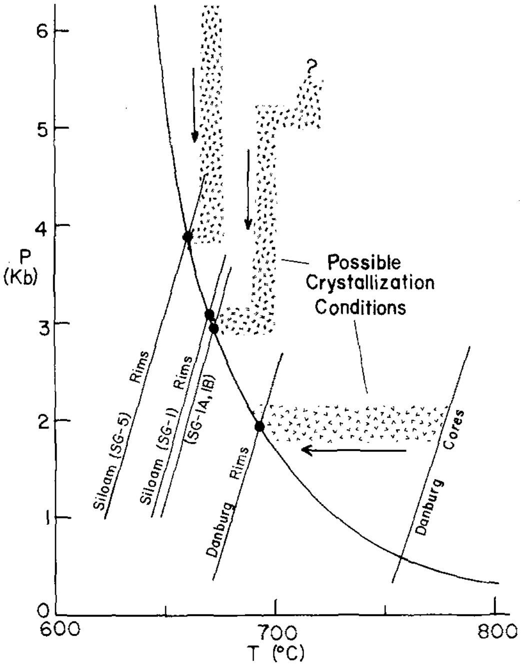

Fig. 1. Possible pressure and temperature conditions of crystallization for portions of the Danburg and Siloam feldspars. Solidus curve is that for quartz monzonite composition of Whitney, 1975

of alkali feldspars crystallizing from synthetic quartz monzonite melts (Whitney, 1975, Fig. 2) has shown that the composition of the alkali feldspar in equilibrium with plagioclase would not change much in the temperature interval of 700 to 800° C or so.

Temperature of Crystallization

The composition of the final feldspars to crystallize from the melt (plagioclase Ab_{80}; alkali feldspar Ab_{32}) defines possible pressure and temperature conditions along Curve A, Figure 1 (average of the sanidine and microcline distribution models as previously discussed). The intersection of this line with the solidus for granitic materials should indicate the pressure on the magma during crystallization. The intersection point for the Danburg is at 2 Kb, which agrees with pressures inferred from other data as discussed above. This coincidence does not prove that the confining pressure was 2 Kb, but suggests that the temperature calculated from the feldspars is consistent with such a confining pressure. No variation is seen in samples from various parts of the Danburg pluton, therefore, two kilobars is considered a reasonable overall pressure for crystallization of the Danburg feldspars. Figure 2 presents the feldspar data compared with isothermal curves for $NaAlSi_3O_8$ distribution at a pressure of 2 Kilobars.

Crystallization temperatures obtained from the zoned plagioclase and alkali feldspar, assuming the same intermediate structural state of the alkali feldspar,

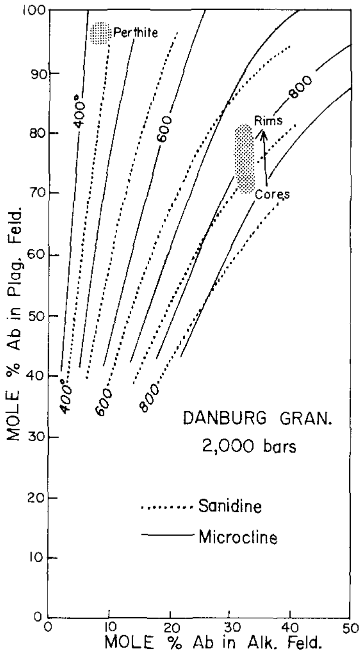

Fig. 2. Possible equilibration temperatures for the Danburg feldspars at 2 kilobars confining pressure. Distribution curves are from Stormer, 1975 (Sanidine), and Whitney and Stormer, in press (Microcline)

Table 3. Temperature of crystallization Danburg granite, 2 KB

	$X_{ab,AF}$	$X_{ab,PF}$	T(°C)		
			Sanidine	Microcline	Average
Large grains					
Inner zones	0.32	0.70	713	840	776
Outer zones	0.32	0.79	649	764	706
Rapakivi rims					
Inner zones	0.32	0.76	669	787	728
Outer zones	0.32	0.81	637	749	693
Exsolved perthite	0.07	0.95	–	411	–

range from 780° C to 690° C. Table 3 summarizes the temperatures calculated using both models and their average, assuming that the composition of the alkali feldspar remained nearly the same throughout.

The temperature calculated from the exsolved phases of the perthites, using the microcline solid solution model, are quite low, around 400° C. Thus, it would appear that equilibration in the perthite continued down to approximately that temperature, even though the values calculated are uncertain due to the inaccuracy of the method in this range.

The Siloam Granite

Petrography

Petrographically, the Siloam is similar to the Danburg, except that the alkali feldspar phenocrysts are larger (up to 5 cm) and show a strong flow foliation. The rest of the matrix is non-foliated and there are no indications of pervasive post-intrusion metamorphism. The center part of the body is an equigranular, medium grained lithology which looks nearly identical to the groundmass in the rest of the body. It may be a late stage of the Siloam which was separated from the phenocrysts by filter-pressing near the end of crystallization. Sericitization of the plagioclase is more common than in the Danburg. Near the core of the body some coarse grained muscovite is found. The muscovite appears to be hydrothermally replacing feldspar, and it is doubtful that any of it is a primary magmatic phase.

Samples from the southeastern portion of the body showed more coarse grained muscovite. If it were a primary magmatic phase in this area it would suggest somewhat greater pressures.

The plagioclase forms euhedral, medium to coarse grained crystals with few inclusions and sporadic alteration. Large crystals are complexly zoned intermediate oligoclase. Most samples show at least one major reversed zone, superimposed on an overall normal zonation. Some samples show as many as 4 to 6 reversed zones in the larger crystals. Within samples from a single outcrop, all large grains appear to have a similar pattern of zoning with individual reversals in compositions being recognizable from grain to grain. The process responsible for reversal in plagioclase compositional zoning thus appears to have affected a large portion of the magma simultaneously.

The plagioclase from the equigranular core of the body is less zoned with only one major normal zonation trend apparent.

The alkali feldspar is concentrated in large, homogeneous, microcline perthite phenocrysts, up to 5 cm long. Most are columnar crystals, as in the Danburg, commonly containing Carlsbad twins. They also may have equilibrated with the melt while in an intermediate structural state.

The distribution of albite lamellae is fairly uniform, although in some samples there appears to be a slight decrease in the concentration near the outer margin.

In one sample (SG-1, northern part of body) in which the plagioclase showed 1 major reversal in anorthite content, the alkali feldspar also showed 1 distinct period of resorption, with a rounded outline accentuated by biotite inclusions surrounded by a euhedral mantle.

The equigranular center of the body contains few large perthitic phenocrysts, with most of the alkali feldspar being small, non-perthitic microcline crystals. These samples also contain unzoned plagioclase with quite low anorthite contents. Here it appears that albite may have been lost from the smaller feldspar grains during exsolution and recrystallized as small, unzoned plagioclase grains.

Chemical Analysis of Feldspars

Analyses of plagioclase have been summarized in Table 1. Most of the plagioclase falls within the composition range Ab_{73} to Ab_{80} (mole %). The reversals in composition are often large enough to make the rims less sodic than the cores. Such reversals occur as a sharp break in composition followed by normal zoning of sodium content increasing outward. Exsolved lamellae from the perthite are distinctly different, being about Ab_{97}.

The alkali feldspars (Table 1 and 2) show more variation in composition from sample to sample than observed in the Danburg. Since the plagioclase and alkali feldspar compositions from different parts of the body seem to vary in composition, each sample locality has been treated separately in geothermometric interpretation.

Temperature of Crystallization

The temperature-pressure conditions have been calculated for the outer zones of coexisting feldspars from each sample. The small differences in alkali feldspar composition within individual grains had little effect. The results are portrayed graphically on Figure 1 for the various samples.

The temperature curve calculated for late stage crystallization intersects the granite solidus at higher pressures than for the Danburg Granite. This pattern is consistent with the proposition that the Siloam may have been intruded at a deeper depth than the Danburg. The intersection pressure is also reasonable in light of the tectonic setting. The systematic variation in both alkali feldspar and plagioclase compositions observed between sample SG-5 from the southern part of the body and the other samples from farther north suggests a higher pressure of final crystallization for the southern sample. Although the absolute pressures may not be significant, this relative difference may be real. Although regional uplift models have not been developed for this area, our data suggests that the southern part of the body was intruded at a greater depth and the body has since been tilted by subsequent uplift and erosion. Such a deformational pattern would be consistent with uplift patterns determined from regional isotopic studies further north (R.D. Dallmeyer, In Press).

The strong reversals in plagioclase composition cannot be explained by simple isobaric crystallization. A possible explanation, consistent with the described petrographic data and thermodynamic model of Stormer (1975), is that a sudden decrease in confining pressure could account for the observed shift. In fact, if it is assumed that a pressure drop (rise in the crust) is responsible, the magnitude required may be estimated by assuming that the temperature remains constant during the process. The zoning in the plagioclase can then be used, along with the compositions of the alkali feldspar, to determine how far the magma would have to rise to duplicate the observed zoning. Such paths have been constructed for SG-1 and SG-5 (Fig. 1) using the outer zones of the large crystals. To duplicate all the reversals shown in these samples, an initital pressure of around 10 kilobars would be required, with upward migration occurring in steps. Corresponding magmatic temperatures would be in excess of 750° C. The final pressure drop would have to be on the order of 2 kilobars or so. Thus, the reversals in zoning could be explained by periodic decreases in confining pressure as the magma moves up in the crust from depths near the base of the crust of depths of 7 to 10 km.

The temperatures calculated from the exsolved phases of the perthite are again low, around 400° C. The microcline from the fine-grained core of the body is quite pure, and temperatures calculated are all low. Unzoned plagioclase which may be a recrystallization product, is also present. The recrystallization accompanying slow cooling has apparently destroyed the original alkali feldspar composition.

Stone Mountain Granite

Petrography

The Stone Mountain granite has been previously described in detail (Whitney et al., 1976; Hermann, 1954).

This pluton is quite different from the other two bodies. It is a fine grained, homogeneous, hypidiomorphic-granular, peraluminous, leuco-quartz monzonite. Petrographically, it is composed of about equal amounts of oligoclase, microcline, and quartz with minor muscovite and biotite. The majority of the alkali feldspar appears to have undergone complete exsolution of its albite component, forming a homogeneous, potassium-rich microcline. Some perthitic cores are found, composed of patches of albite in untwinned microcline. Much of the plagioclase is unzoned sodic oligoclase. A few zoned crystals are encountered, with euhedral growth zones clearly shown. Most of the feldspar probably underwent considerable recrystallization during the slow cooling of the body. Only the cores of the feldspar show promise of representing magmatic phases.

Chemical Analysis of the Feldspars

The chemical analyses of the feldspars are summarized in Table 1. The homogeneous plagioclase is all about Ab_{90} to Ab_{88}. The inner zones of larger grains vary systematically with the cores of normally zoned grains reaching albite contents as low as Ab_{76}.

Temperature of Crystallization

The cores of zoned plagioclase and perthite alkali feldspar yield reasonable magmatic temperatures. Values of 650 to 700° C are obtained assuming an intermediate structural state and a pressure of around 5 Kb for confining pressure during equilibration of these cores as suggested by Whitney et al. (1976) (Fig. 3). Since albite may have been lost from the alkali feldspars, these values represent minimum estimates.

The homogeneous plagioclase and microcline yield very low equilibration temperatures regardless of pressure. These feldspars yield temperatures in the range of $\sim$400° C using microcline parameters (Fig. 3). The majority of the feldspar has thus recrystallized with subsolidus inter-crystalline exchange during cooling, destroying the initital composition of the alkali feldspar and forming new, unzoned plagioclase.

Conclusions

Even the relatively crude model of abite distribution now available allows some interpretation of the crystallization history of feldspars in mesozonal granitic rocks. Comparison of temperatures from late crystallizing feldspars with experimental solidus curves gives an indication of intrusion depth. In some granite bodies such as the Siloam, the pattern of feldspar zoning can be interpreted in terms of a more complicated P, T path of ascent through the crust.

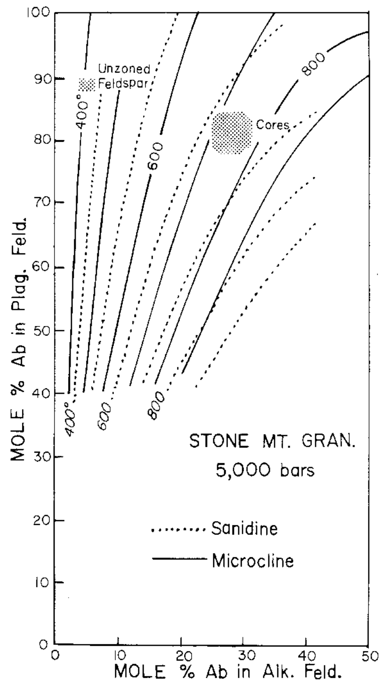

Fig. 3. Possible equilibration temperatures for the Stone Mountain feldspars at 5 kilobars confining pressure. Distribution curves are from Stormer, 1975 (Sanidine), and Whitney and Stormer, in press, (Microcline)

Feldspar temperatures for coarse grained porphyritic granites such as the Siloam and Danburg appear to be consistent and meaningful. Fine grained rocks such as the Stone Mt. and portions of the Siloam show much more intercrystalline exchange down to relatively low temperatures. Such feldspar temperatures have little meaning for interpretation of magmatic processes.

Equilibration between the 2 phases in perthitic intergrowths appears to take place down to about 400° C even though the accompanying zoned plagioclases do not show any evidence of homogenization. The exsolution process in alkali feldspar may be substantially aided by recrystallization accompanying the transition to microcline. Therefore, temperatures obtained from perthitic phases should be nearly the same in all specimens.

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References

Albee, A.L., Ray, L.: Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates. Anal. Chem. **42**, 1408–1414 (1970)

Bachinski, S.W., Muller, G.: Experimental determination of the microcline-low albite solvus. J. Petrol. **12**, 329–356 (1971)

Bence, A.E., Albee, A.L.: Empirical correction factors for the electron microanalyis of silicates and oxides. J. Geol. **76**, 382–403 (1968)

Buddington, A.F.: Granite emplacement with special emphasis on North America. Geol. Soc. Am. Bull. **70**, 671–748 (1959)

Dallmeyer, R.D.: $^{40}Ar/^{39}Ar$ incremental-release ages of hornblende and biotite across the Georgia Inner Piedmont: Their bearing on Late Paleozoic-early Mesozoic tectonothermal history. (In press)

Fullagar, P.D.: Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians. Geol. Soc. Am. Bull. **82**, 2845–2862 (1971)

Hermann, L.A.: Geology of the Stone Mountain-Lithonia district, Georgia. Georgia Geol. Survey Bull. **61**, 139 p. (1954)

Humphrey, R.C., Radcliffe, D.: Geology, petrology and mineral resources of the crystalline rocks of Green and Hancock Counties. Geor. Dept. Mines, Mining, and Geology, Open-File Rept., 55p. (1971)

Hurst, V.J., Crawford, T.J., Sandy, J.: Mineral resources of the central Savannah River area, Vol. 1, Technical Assistance Project, U.S. Dept. of Commerce, 467 p. (1966)

Jones, L.M., Walker, R.L.: Rb-Sr whole-rock age of the Siloam granite, Georgia: A Permian intrusive in the southern Appalachians. Geol. Soc. Am. Bull. **84**, 3653–3658 (1973)

Medlin, J.H., Suhr, N.H., Bodkin, J.B.: Atomic absorption analysis of silicate rock and mineral samples. Atomic Absorption Newsletter **3**, 25–29 (1969)

Stewart, D.B.: Optic axial angle and extinction angles of alkali feldspars related by cell parameters to Al/Si order and composition. In: (W.S. MacKenzie and J. Zussman, eds.), The Feldspars, pp. 145–161 (1974)

Stormer, J.C., Jr.: A practical two-feldspar geothermometer. Am. Mineralogist **60**, 667–674 (1975)

Whitney, J.A.: The effects of pressure, temperature and X_{H_2O} on phase assemblage in four synthetic rock compositions. J. Geol. **83**, 1–32 (1975)

Whitney, J.A., Jones, L.M., Walker, R.L.: Age and origin of the Stone Mountain granite, Lithonia district, Georgia. Geol. Soc. Bull. **87**, 1067–1077 (1976)

Whitney, J.A., Stormer, J.C., Jr.: Geothermometry and geobarometry in epizonal granitic intrusions: a comparison of iron-titanium oxides and coexisting feldspars. Am. Mineralogist **61**, 751–761 (1976)

Whitney, J.A., Stormer, J.C., Jr.: The distribution of $NaAlSi_3O_8$ between coexisting microcline and plagioclase and its effect on geothermometric calculations. Am. Mineralogist (in press)

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