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STRUCTURAL STATE OF THE K-FELDSPAR IN THE BUTLER HILL – BREADTRAY GRANITE, ST. FRANCOIS MOUNTAINS, SOUTHEASTERN MISSOURI

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ABSTRACT

Unit-cell refinements for twenty-eight samples of K-feldspar from the Butler Hill – Breadtray Granite, St. Francois Mountains, southeastern Missouri, reveal a very modest amount of variation in structural state within the presently exposed parts of this Proterozoic pluton. Values for the structural state parameter Z, each determined with an experimental uncertainty of $\pm$ 0.019, vary from 0.745 to 0.878, with a mean of 0.832 and a standard deviation of 0.029. Unlike the trend surface determined by Sides (1980) to model the major-element chemical variation within this pluton, the trend surface that best fits the structural state data is virtually horizontal. We interpret the discordance between these two trend surfaces, along with the limited total range of order shown by these samples, as evidence for a pervasive hydrothermal event that operated along a nearly horizontal surface at some time subsequent to any syn- or postemplacement tilting of the St. Francois Mountains complex.

Keywords: K-feldspar, microcline, structural state, granite, St. Francois Mountains, Missouri, Proterozoic, hydrothermal.

SOMMAIRE

Nous présentons les résultats de l'affinement de la maille élémentaire de vingt-huit échantillons de feldspath potassique du granite de Butler Hill – Breadtray, dans les montagnes St. François, dans le Sud-Est du Missouri. Le degré d'ordre varie très légèrement dans la partie de cette suite protérozoïque qui affleure. Le paramètre Z, auquel est associé une incertitude $\pm$ 0.019, varie de 0.745 à 0.878 (moyenne 0.832, écart type 0.029). La surface qui répond le mieux à cette variation dans le microcline a une attitude quasiment horizontale, en contraste avec celle qui décrit la zonation chimique du pluton, selon Sides (1980). Cette discordance entre les deux surfaces, et la variabilité limitée du degré d'ordre du microcline, font penser qu'un événement hydrothermal répandu a affecté le pluton le long de plans horizontaux, et donc après le basculement synchrone ou postérieur à la mise en place du complexe des montagnes St. François.

(Traduit par la Rédaction)

Mots-clés: feldspath potassique, microcline, degré d'ordre, granite, montagnes St. François, Missouri, protérozoïque, stade hydrothermal.

INTRODUCTION

The St. Francois Mountains of southeastern Missouri represent the best exposure of Precambrian basement in the midcontinent region of the United States. Over an area of nearly 1000 square kilometers, erosion has removed the Paleozoic cover and exposed a complex series of Proterozoic silicic volcanic and granitic plutonic rocks that are interpreted to be remnants of a series of collapsed calderas (Sides *et al.* 1981, Kisvarsanyi 1981, Kisvarsanyi *et al.* 1981).

The Butler Hill – Breadtray granite is the largest pluton exposed in the St. Francois Mountains complex (Fig. 1). This pluton is interpreted to have formed as a subvolcanic massif that crystallized beneath a cover of its own volcanic ejecta (Sides *et al.* 1981, Kisvarsanyi 1981, Kisvarsanyi *et al.* 1981). Pratt *et al.* (1979) mapped the Butler Hill – Breadtray granite as a single pluton with two

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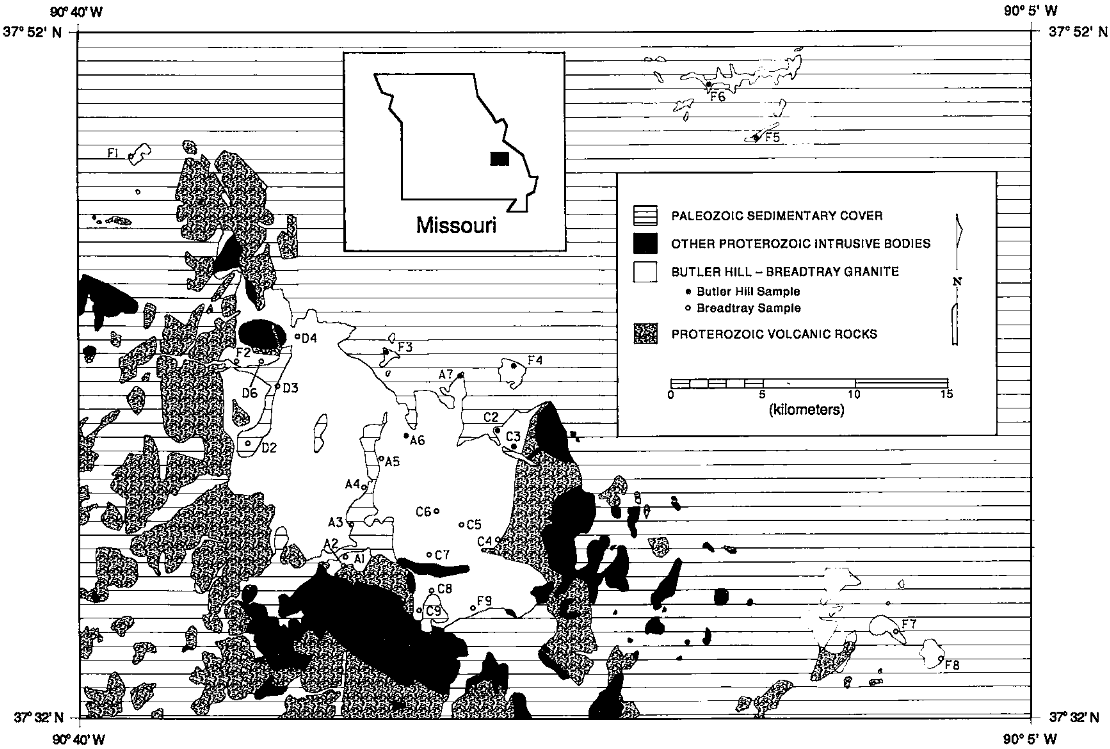

FIG. 1. Index map of the exposed Precambrian rocks in the St. Francois Mountains, southeastern Missouri, showing location of Butler Hill - Breadtray granite samples (after Pratt *et al.* 1979)

distinct facies separated by a gradational contact: the Butler Hill Facies constitutes the northeastern third of the exposure, whereas the Breadtray Facies constitutes the southwestern two-thirds. The Butler Hill Facies is generally medium- to coarse-grained, whereas the Breadtray Facies is distinctly finer-grained. Based on this textural variation, along with systematic variations in the modal mineralogy, the Butler Hill is generally interpreted to represent the main phase of the magma body, whereas the Breadtray is interpreted to be the roof facies (Sides 1980, Sides *et al.* 1981). Pratt *et al.* (1979) also mapped several small, isolated exposures of granite as parts of the Butler Hill - Breadtray pluton. The largest of these outlying exposures, sometimes referred to as the Hawn Park pluton, is located approximately 20 km northeast of the main exposure of the Butler Hill - Breadtray granite.

Field relationships among the various Proterozoic volcanic and plutonic units exposed in the St. Francois Mountains suggest that the entire complex is a roughly tabular sequence that has been tilted to the west-southwest and subsequently beveled by erosion (Bickford *et al.* 1977, Sides *et al.* 1981). Based on variation in the major-element bulk chemistry, Sides (1980) concluded that the Butler Hill - Breadtray granite has been tilted approximately 10° in the S68.3°W direction, exposing the structurally lowest and least differentiated part of the pluton to the northeast. From this chemical variation within the pluton, along with petrographic and field relationships with the surrounding volcanic units, Sides (1980) inferred that the Breadtray granite exposed along the southwestern intrusive contact may have crystallized beneath as little as 1 to 2 km of volcanic cover, whereas the northeastern exposures of the Butler Hill granite may represent depths of crystallization as great as 10 km.

The most abundant mineral throughout the Butler Hill - Breadtray granite is microperthitic K-feldspar. The factors that control the structural state of plutonic K-feldspar are numerous and varied (Martin 1974, Stewart & Wright 1974, Parsons & Brown 1984, Brown & Parsons 1989), and there does not yet seem to be a consensus as to which, if any, of these factors should be dominant in any particular pluton. Nevertheless, K-feldspar structural state has been shown to vary systematically in a number of plutonic bodies (Wright 1964, Tilling 1968, Parsons & Boyd 1971, Bychkov *et al.* 1977, Cherry & Trembath 1978, Jiránek 1982), and this variation has proved useful in deciphering the geometry and geological history of those plutons. If the model of Sides (1980) for the emplacement and subsequent exhumation of the Butler Hill – Breadtray granite is correct, one might expect a systematic variation in K-feldspar structural state from southwest to northeast across the presently exposed parts of this pluton. The purpose of this study was to determine whether any such variation could be detected by X-ray powder diffraction.

Experimental Procedure

We collected twenty-three samples from the main exposure of the Butler Hill – Breadtray granite (Fig. 1). Some samples were collected within a few meters of the intrusive contact, whereas others were collected several kilometers from the nearest outcrop of the overlying volcanic rocks. We also collected a total of five samples from the three major groups of outlying bodies mapped by Pratt *et al.* (1979) as being correlative with the Butler Hill – Breadtray granite. Care was taken in the field to avoid obvious dikes, veins, and other contamination, but the exposure in some areas was not sufficiently good to yield completely fresh samples.

All samples were slabbed, and any obvious weathering rinds or xenoliths were removed. These slabs were then crushed to −60 mesh, and the K-feldspar was concentrated by centrifuge in a fluid of density 2.595 (81.5% acetylene tetrabromide; 18.5% dimethyl formamide). The K-feldspar fraction produced by this separation was then ground to −325 mesh, and this powder was centrifuged three more times.

TABLE 1. MEASURED UNIT-CELL PARAMETERS FOR BUTLER HILL - BREADTRAY K-FELDSPAR

	Sample	Latitude†	Longitude‡	Elevation (meters)	*a*	*b* (Angstroms)	*c*	*α*	*β* (degrees)	*γ*
Main Exposure: Breadtray Facies	A1	36.733	30.200	265	8.5918	12.9744	7.2171	90.657	115.935	87.883
	A2	36.433	30.333	280	8.5853	12.9753	7.2189	90.614	115.900	87.954
	A3	37.750	29.800	235	8.5865	12.9631	7.2161	90.656	115.932	87.919
	A4	38.867	29.400	251	8.5953	12.9722	7.2191	90.608	115.985	87.986
	A5	39.567	28.800	271	8.5899	12.9743	7.2169	90.643	115.958	87.832
	C4	37.217	24.800	305	8.5848	12.9652	7.2154	90.664	115.899	87.866
	C5	37.650	26.133	326	8.5874	12.9682	7.2160	90.657	115.980	87.847
	C6	38.000	27.067	311	8.5857	12.9634	7.2165	90.663	115.960	87.835
	C7	36.850	27.067	271	8.5901	12.9721	7.2185	90.626	115.953	87.905
	C8	35.717	27.067	250	8.5957	12.9779	7.2160	90.500	115.971	88.141
	C9	35.150	27.600	247	8.5932	12.9698	7.2188	90.638	115.979	87.880
	D2	40.033	33.600	343	8.5916	12.9672	7.2176	90.656	115.976	87.836
	D3	41.750	32.600	347	8.5888	12.9645	7.2122	90.636	115.927	87.969
	D4	43.083	31.933	344	8.5913	12.9635	7.2149	90.671	115.974	87.933
	D6	42.400	33.133	341	8.5933	12.9689	7.2170	90.609	115.949	87.904
	F2	42.483	34.333	326	8.5844	12.9652	7.2172	90.423	116.012	88.243
	F9	35.367	25.250	262	8.5861	12.9651	7.2173	90.626	115.933	87.919
NW Outlier (Breadtray Facies?)	F1	48.467	37.917	311	8.5854	12.9709	7.2172	90.553	115.930	87.950
SE Outlier (Breadtray Facies?)	F7	34.517	10.000	248	8.5900	12.9670	7.2187	90.689	115.953	87.901
	F8	33.617	8.400	226	8.5917	12.9671	7.2191	90.702	115.960	87.888
Main Exposure: Butler Hill Facies	A6	40.217	27.800	300	8.5900	12.9737	7.2188	90.619	115.951	87.854
	A7	42.000	26.200	262	8.5838	12.9673	7.2159	90.627	115.929	87.947
	C2	40.433	24.667	256	8.5853	12.9725	7.2162	90.512	115.939	88.170
	C3	39.750	23.867	268	8.5911	12.9733	7.2179	90.540	115.942	88.079
	F3	42.783	28.750	256	8.5815	12.9714	7.2188	90.678	115.968	87.804
	F4	42.417	24.083	250	8.5921	12.9718	7.2192	90.582	115.973	87.932
NE Outlier (Butler Hill Facies?)	F5	48.900	15.083	230	8.5878	12.9725	7.2197	90.625	115.973	87.820
	F6	50.450	16.000	219	8.5796	12.9625	7.2181	90.604	116.017	87.867
Uncertainty¶					0.0023	0.0026	0.0015	0.030	0.020	0.030
Standard deviation					0.0040	0.0043	0.0017	0.063	0.028	0.108

† minutes north of 37°N, ‡ minutes west of 90°W,

¶ Each uncertainty listed is the average of the standard errors for that parameter from the 28 unit-cell refinements.

TABLE 2. CALCULATED STRUCTURAL PARAMETERS FOR BUTLER HILL - BREADTRAY K-FELDSPAR

	Sample	V (Angstroms^3)	α^* (degrees)	γ^*	t_1o†	t_1m†	N_{Or}‡	Z§
Main Exposure: Breadtray Facies	A1	722.99	90.299	92.035	0.916	0.018	1.02	0.813
	A2	722.92	90.311	91.976	0.904	0.040	1.01	0.850
	A3	721.85	90.282	91.995	0.919	0.037	0.98	0.819
	A4	723.10	90.305	91.944	0.901	0.052	1.02	0.849
	A5	722.64	90.340	92.098	0.927	0.006	1.01	0.817
	C4	721.93	90.298	92.050	0.926	0.020	0.99	0.804
	C5	721.87	90.318	92.075	0.928	0.014	0.98	0.817
	C6	721.63	90.317	92.085	0.939	0.019	0.98	0.832
	C7	722.76	90.323	92.025	0.918	0.031	1.01	0.846
	C8	723.29	90.349	91.824	0.848	0.071	1.03	0.785
	C9	722.75	90.323	92.047	0.928	0.029	1.01	0.852
	D2	722.35	90.325	92.088	0.938	0.018	1.00	0.837
	D3	721.78	90.280	91.949	0.892	0.034	0.98	0.745
	D4	721.90	90.261	91.973	0.911	0.036	0.98	0.795
	D6	722.72	90.342	92.034	0.917	0.030	1.01	0.817
	F2	721.54	90.387	91.748	0.844	0.114	0.97	0.847
	F9	722.04	90.316	92.010	0.920	0.039	0.99	0.838
NW Outlier (Breadtray Facies?)	F1	722.32	90.382	92.011	0.905	0.039	1.00	0.830
SE Outlier (Breadtray Facies?)	F7	722.49	90.255	91.999	0.927	0.037	1.00	0.855
	F8	722.63	90.247	92.007	0.931	0.035	1.01	0.860
Main Exposure: Butler Hill Facies	A6	722.86	90.357	92.086	0.929	0.018	1.01	0.849
	A7	721.87	90.301	91.978	0.906	0.038	0.98	0.815
	C2	722.35	90.321	91.786	0.849	0.084	1.00	0.810
	C3	722.99	90.334	91.874	0.874	0.068	1.02	0.829
	F3	721.89	90.315	92.112	0.944	0.009	0.98	0.870
	F4	722.86	90.360	92.017	0.915	0.041	1.01	0.857
NE Outlier (Butler Hill Facies?)	F5	722.54	90.366	92.120	0.942	0.015	1.00	0.873
	F6	720.89	90.368	92.078	0.938	0.033	0.95	0.878
Uncertainty¶		0.29	0.036	0.036	0.012	0.012	0.01	0.019
Standard deviation		0.57	0.036	0.095	0.028	0.024	0.02	0.029

† Kroll & Ribbe (1983) equations 10b and 11, ‡ Hovis (1986) equation 7, § Hovis (1986) equations 8 and 15,
¶ For each calculated parameter the experimental uncertainties from Table 1 were propagated through the defining equations according to the techniques discussed by Bevington (1969) and Meyer (1975).

X-ray powder-diffraction profiles (Cu*K*α radiation) were recorded from 10° to 60° 2θ at a scan rate of 0.56°/minute using a fully automated Rigaku DMax-1B diffractometer. These diffraction profiles showed little or no contamination by quartz or plagioclase. Two profiles were collected for each specimen, and the 2θ values for the corresponding diffraction maxima were averaged. In one profile for each sample, finely powdered silicon metal (United Mineral and Chemical Corporation, 99.99% purity; 4:1 sample-to-standard by weight) was used as an internal standard to check for any systematic error caused by sample misalignment. Preliminary indexing of each diffraction profile was based on the structure of maximum microcline. Unit-cell refinements were performed according to the procedure of Appleman & Evans (1973), as modified by Benoit (1987). An average of 43 diffraction peaks were used in each refinement.

RESULTS

Table 1 lists the results of our 28 K-feldspar unit-cell refinements; Table 2 lists structural parameters calculated from these data. The uncertainties listed in Table 1 are the average standard errors for the cell parameters generated in the unit-cell refinement regressions; the uncertainties listed in Table 2 were determined by propagating the experimental uncertainties from Table 1 through the defining equations for each of the calculated structural parameters. Each value in these tables is listed with one digit beyond the first uncertain digit, so that these data can be used in subsequent calculations without the introduction of round-off error (Bevington 1969, Lyon 1970). Also listed in Tables 1 and 2 are the standard deviations for our twenty-eight determinations of each parameter. The extent to which these standard deviations exceed the corresponding uncertainties is an indication of the extent to which our data contain "real" variation, *i.e.*, variation that is measurable beyond the limits of our analytical precision.

The method most commonly used to illustrate variations in structural state in alkali feldspar is to plot the cell parameters *b versus c* and α^* *versus* γ^* (Kroll & Ribbe 1983). These plots, in turn, can be used to determine the aluminum site occupancies t_1o and t_1m. Figures 2 and 3, respectively, show the

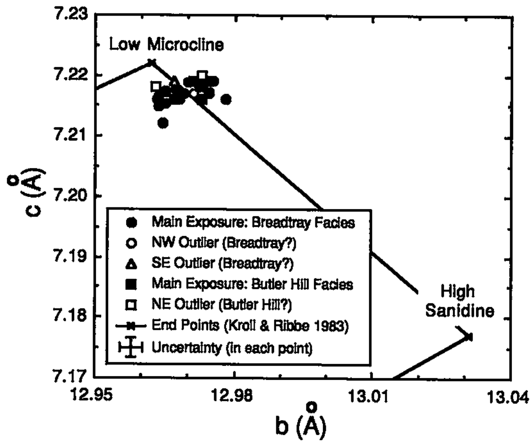

FIG. 2. Variation in structural state of K-feldspar in the Butler Hill - Breadtray granite as revealed by variation in the *b* and *c* cell parameters. The error bar included in the explanation indicates the experimental uncertainty in each data point.

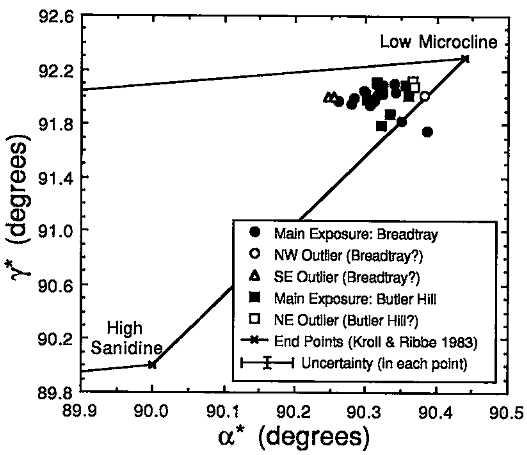

FIG. 3. Variation in structural state of K-feldspar in the Butler Hill - Breadtray granite as revealed by variation in the angles α^* and γ^* in reciprocal space. The error bar included in the explanation indicates the experimental uncertainty in each data point.

b–*c* and α^*–γ^* variation in our data relative to the cell parameters for the low ("maximum") microcline and high sanidine end-member structures (Kroll & Ribbe 1983). Compared to the total range of variation shown by natural K-feldspar, our Butler Hill - Breadtray samples form a relatively tight cluster near the maximum microcline end-point on each of these plots.

Thompson (1969, 1970) defined the structural state parameter Z ($\equiv t_1o + t_1m - t_2o - t_2m$), which varies from 0 for perfectly disordered feldspar structures to 1 for perfectly ordered structures. The advantage of combining all structural state information into a single parameter is obvious for studies such as ours: this parameter can be regressed, as a single dependent variable, against location parameters (latitude, longitude, and elevation) to determine the spatial variation of the degree of order of the K-feldspar within a particular body of rock.

Hovis (1986) derived a method for calculating the parameter Z directly from the results of a unit-cell refinement. Table 2 lists the Z values determined by this method for our twenty-eight samples, each with an uncertainty of $\pm$ 0.019. The Z values for our twenty-eight samples vary from 0.745 to 0.878, with a mean of 0.832 and a standard deviation of 0.029. For our twenty-three samples from the main plutonic body, Z varies from 0.745 to 0.870, with a mean of 0.826 and a standard deviation of 0.028. Because the standard deviation for each of these groups of Z values exceeds the uncertainty in the individual determinations of Z by a factor of approximately 1.5, we can conclude that at least a modest fraction of the variation in our data represents real variation among our samples.

Using trend-surface analysis (Davis 1986), Sides (1980) determined that the major-element chemical variation within the main exposure of the Butler Hill - Breadtray granite could best be modeled by a series of planar surfaces dipping 10°, S68.3°W. To see how our data on structural state of K-feldspar correlate with this chemical variation, we chose an arbitrary plane of this orientation and calculated the perpendicular distance from each of our sample sites to that plane. Figure 4A shows the variation of our Z values with perpendicular distance from (*i.e.*, "effective elevation" with respect to) the plane dipping 10°, S68.3°W through sample site F4. Figure 4A reveals a negative correlation (R = –0.503) between degree of order and effective elevation with respect to this plane, consistent with the interpretation of Sides that the chemical trend surface should be roughly parallel to the roof of the magma chamber and should therefore have been roughly horizontal at the time of crystallization. However, the correlation of

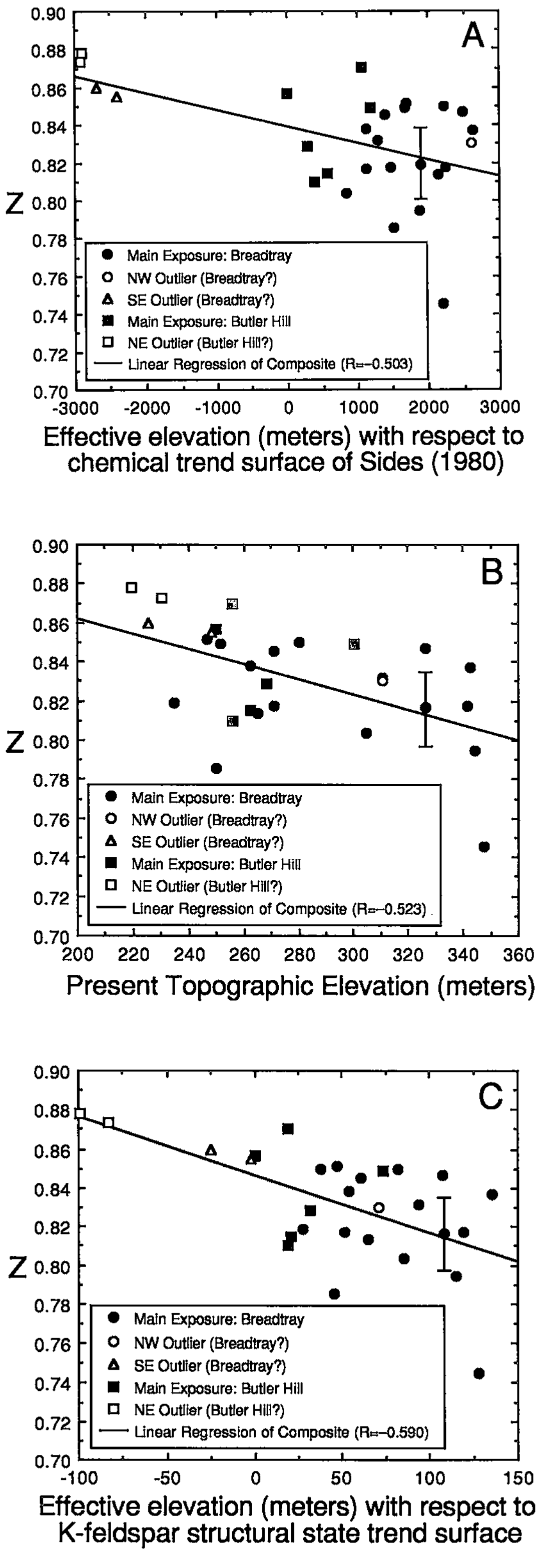

TABLE 3. CORRELATION COEFFICIENTS FOR K-FELDSPAR STRUCTURAL STATE PARAMETER *Z* VERSUS SURFACES OF VARIOUS ORIENTATIONS

Orientation of surface (dip angle, dip direction)	R for all 28 samples	R for the 23 samples from the main Butler Hill - Breadtray exposure
10°, S68.3°W†	−0.503	−0.141
Present sea level	−0.523	−0.363
0.21°, S36°W‡	−0.590	---
0.13°, S41°E§	---	−0.383

† Linear trend surface determined by Sides (1980) to model major-element chemical variation in Butler Hill - Breadtray granite.
‡ Determined by simultaneous linear regression of all 28 *Z* values versus latitude, longitude and elevation.
§ Determined by simultaneous linear regression of the *Z* values for the 23 samples from the main Butler Hill - Breadtray exposure.

degree of order with this chemical trend surface depends very strongly upon the structural state data from the northeastern and southeastern outliers. Without the data from these two isolated groups of outcrops, the variation of *Z* is essentially random (R = −0.141) with respect to this surface (Table 3).

Figure 4B shows the variation of the structural parameter *Z* with the present topographic elevation of our twenty-eight sample locations. Despite the significant amount of scatter in the data, the negative correlation (R = −0.523) between degree of structural order in the feldspar and present topographic elevation appears quite pronounced. Unlike the correlation with the chemical trend surface, the correlation with present elevation is not primarily caused by the data from the outlying outcrops. Rather, this correlation is still reasonably pronounced (R = −0.363) when only the twenty-three samples from the main Butler Hill – Breadtray exposure are considered.

We performed a simultaneous linear regression, *i.e.*, a first-order trend-surface analysis (Davis 1986), of the parameter *Z versus* latitude, longitude, and present topographic elevation for all

FIG. 4. The structural state parameter *Z* is plotted *versus* (A) effective elevation with respect to a surface dipping 10°, S68.3°W (arbitrarily anchored at sample site F4), as determined by Sides (1980) to best fit the major-element chemical variation within the main exposure of the Butler Hill - Breadtray granite; (B) present topographic elevation; and (C) effective elevation with respect to a surface dipping 0.21°, S36°W (also arbitrarily anchored at sample site F4), as determined by simultaneous linear regression of all twenty-eight of our structural state determinations *versus* latitude, longitude, and present topographic elevation. The error bar indicates the uncertainty determined by propagating the experimental uncertainties through the defining equations for each determination of *Z*: ±0.019.

twenty-eight of our samples. The resulting set of planar surfaces that best describe the variation in the K-feldspar structural data dip 0.21°, S36°W. Figure 4C shows the variation of *Z* with effective elevation with respect to (*i.e.*, perpendicular distance from) a surface of this orientation, once again arbitrarily anchored at sample site F4. This figure reveals a moderately strong negative correlation (R = –0.590) between K-feldspar structural order and elevation with respect to this surface. A corresponding analysis using only the twenty-three samples from the main Butler Hill – Breadtray exposure yields a trend surface that dips 0.13°, S41°E; the correlation coefficient for the variation of *Z* with elevation with respect to this surface is –0.383 (Table 3). (For a more thorough discussion of the technique used to determine these correlations, please refer to the Appendix.)

Discussion

If the model of Sides (1980) for the geometry and emplacement history of the Butler Hill – Breadtray pluton is correct, the depth of crystallization for our samples ranges from approximately 1 to 2 km in the southwest to approximately 10 km in the northeast. Regardless of what factors are the most important in controlling the structural state of K-feldspar in a large plutonic body, one would expect K-feldspar formed under such disparate conditions to show a significant amount of structural variation. However, the total range in degree of order shown by our samples is actually quite small. Furthermore, the trend surfaces that best fit our data on structural state coincide much more closely with the present-day erosion surface than with the trend surface that best fits the major-element chemical data of Sides (1980). Therefore, we must conclude either 1) that the tilted-batholith model is incorrect, or 2) that the structural state of the K-feldspar in the presently exposed parts of the Butler Hill – Breadtray granite reflects postcrystallization ordering in an event that operated along a nearly horizontal surface subsequent to any tilting that may have occurred. Independent petrographic and geochemical evidence strongly favors the latter interpretation.

The first detailed petrographic study of the rocks exposed in the St. Francois Mountains was published by Tolman & Robertson (1969). Sides (1978) studied the Butler Hill – Breadtray granite in detail, both geochemically and petrologically; a summary of his findings was published by Sides *et al.* (1981). Lowell (1976) reported petrographic details for the plutonic rocks exposed in Hawn State Park, the exposure that we, following Pratt *et al.* (1979), refer to as the northeastern outlier of the Butler Hill granite. All of these studies reported evidence of postcrystallization alteration, both in the feldspars and in the ferromagnesian minerals.

Sides *et al.* (1981) claimed that the extent of alteration increases from northeast to southwest across the Butler Hill – Breadtray pluton, but our petrographic examination of the samples used in this study does not support that conclusion. With the exception of the two samples from the northeastern outlier, which show only minor to moderate alteration, all our samples show evidence of pervasive alteration. Virtually all of the feldspar crystals, both K-feldspar and plagioclase, are extensively clouded by a fine-grained aggregate of kaolinite or sericite plus hematite. Many of the K-feldspar crystals show the "less regular" or "patchy" perthitic texture indicative of recrystallization or albitization (Hatch *et al.* 1972). The primary ferromagnesian minerals, mostly biotite with subordinate hornblende, are extensively altered to chlorite + epidote + opaque phase (magnetite?) + hematite ± titanite ± rutile. The pervasiveness of the secondary hematite accounts for the characteristic "brick red" color of this rock unit on outcrop.

Tolman & Robertson (1969) attributed the extensive alteration in the Butler Hill – Breadtray granite to deuteric processes operating immediately after crystallization, but recent geochemical data suggest that at least a significant fraction of the alteration may have been caused by a much more recent hydrothermal event. Rb–Sr dates for many rocks exposed in the St. Francois Mountains are significantly younger (1290–1380 Ma) than the corresponding U–Pb zircon dates (1460–1480 Ma) (Bickford & Mose 1975, Bickford *et al.* 1981). Bickford & Mose (1975) interpreted these anomalously young Rb–Sr dates to represent loss of Sr during a period of extensive hydrothermal alteration that occurred at some time subsequent to 1300 Ma. The oxygen and hydrogen isotope data of Wenner & Taylor (1976) also indicate a late Precambrian hydrothermal event in the St. Francois Mountains. Wenner (1988) concluded that this postcrystallization event affected rocks to a depth of at least 3 km.

It seems quite reasonable that K-feldspar could have become ordered significantly during a major hydrothermal event, and Abdel-Rahman & Martin (1987) have recently documented just such a hydrothermal ordering of the K-feldspar in a Proterozoic intrusive complex in southeastern Ontario. Therefore, we interpret the near-homogeneity of our data on structural state of the K-feldspar as further evidence for the pervasiveness of postcrystallization hydrothermal activity in the St. Francois Mountains complex. Why the ordering did not "proceed to completion" during the proposed event, to produce fully ordered "maximum" microcline (Z = 1.0), remains a mystery.

An interesting subsidiary conclusion from our data concerns the "closure temperature" for the K-feldspar ordering process, at least under hydrothermal conditions. Our calculated N_{Or} values ($\geq$0.97) indicate quite low values for the temperature of final equilibration of the alkali feldspar in the Butler Hill - Breadtray granite. For the entire range of reasonable pressures, this final equilibration temperature would be well below 300°C (Yund & Tullis 1983). This conclusion is supported by the oxygen isotope data of Wenner (1988), which suggest that the final temperature of re-equilibration of the alkali feldspar throughout much of the St. Francois Mountains complex is <250°C.

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APPENDIX: TECHNIQUE FOR DETERMINING CORRELATIONS BY TREND-SURFACE ANALYSIS

The correlation shown on Figure 4C was determined as follows: 1) We performed a linear (*i.e.*, first-order) regression of our experimentally determined values for the structural state parameter Z simultaneously as a function of latitude, longitude, and elevation for our twenty-eight samples. The resulting Z = f(lat, long, elev) equation is of the form referred to by Davis (1986) as a four-dimensional, first-degree trend surface and can be visualized as a series of parallel planes, each representing a specific value of Z. 2) We arbitrarily chose sample site F4 as the "origin" for this trend surface. Substituting the value of Z predicted by this regression for sample site F4 into the regression equation yields an equation of the form elev = f(lat, long). We then determined the spatial orientation of this planar surface through sample site F4 by solving a standard three-point problem. 3) To illustrate the variation of the structural state parameter Z with respect to the four-dimensional trend surface, we first calculated the perpendicular distance from each of our sample sites to the planar surface determined in step 2; the resulting distances can be visualized as the "effective elevation" of each sample site with respect to the trend surface, still referenced to sample site F4 as the arbitrarily chosen origin. We then plotted the experimentally determined values for the structural state parameter Z *versus* this effective elevation for each of our twenty-eight samples (Fig. 4C). 4) Finally, we performed a standard linear regression to illustrate the variation of Z with respect to this effective elevation. The straight line shown on Figure 4C and the correlation coefficient listed in Table 3 are the results of that linear regression.

We should emphasize that the purpose of the second regression (the linear regression of Z *versus* "effective elevation") was not to determine if these two variables are correlated; they are correlated by definition because the "effective elevation" was determined from the results of the first regression. Rather, this second regression was carried out simply to allow us to illustrate this pre-established correlation on a graph of the same type that was used to illustrate the correlation of Z *versus* present topographic elevation (Fig. 4B). In other words, the second regression is a means of projecting the correlation produced by the first regression onto a two-dimensional graph.