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ORIGIN OF PEGMATITIC GRANITE SEGREGATIONS, WILLOW CREEK, BLACK HILLS, SOUTH DAKOTA

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ABSTRACT

Evaluation of melting of high-grade metagreywackes within the Precambrian core of the Black Hills, South Dakota, may be useful in understanding the generation of peraluminous granites in the region (*i.e.*, Harney Peak Granite and associated pegmatites). In the Willow Creek area, muscovite dehydration coincides with the occurrence of small granitic pods and sills that have been interpreted as representing anatectic melts derived by partial melting of quartz - feldspar - biotite - muscovite - sillimanite schists. The granitic pods are zoned from a potassium feldspar + quartz core to an albite + quartz rim. Abundances of major elements, many of the trace elements, and oxygen and neodymium isotopes are consistent with a model involving the derivation of granitic segregations from the local schist. The displacement of the granite compositions from the Or-Ab-Qtz-H_2O granite minimum toward the K-feldspar apex, the high Ba and Sr contents, a depleted *REE* pattern and a positive Eu anomaly suggest that these granitic segregations do not represent pristine minimum melts. Trace-element modeling using mineral-melt and mineral-fluid distribution coefficients suggests that the granite segregations represent the crystallization and accumulation of a K-feldspar-enriched component derived from a minimum melt or a fluid phase.

Keywords: peraluminous granite, melting, trace elements, isotopes, Black Hills, South Dakota, pegmatitic segregations.

SOMMAIRE

Une évaluation des processus de fusion des métagrauwackes du socle précambrien des Black Hills (Dakota du Sud) pourrait être utile pour comprendre la genèse des granites hyperalumineux de la région (par exemple, le granite de Harney Peak et les pegmatites associées). Dans la région de Willow Creek, la déshydratation de la muscovite coïncide avec la formation de petites lentilles et de sills de granite; ce granite aurait cristallisé à partir de bains fondus anatectiques, dérivés par fusion partielle de schistes à quartz + feldspath + biotite + muscovite + sillimanite. Les lentilles sont zonées, d'un centre à feldspath potassique + quartz à une bordure à albite + quartz. L'abondance des éléments majeurs, de plusieurs éléments en traces et des isotopes d'oxygène et de néodyme concorde avec une dérivation des ségrégations granitiques *in situ*. Le déplacement de la composition du granite du minimum dans le système Or - Ab - Qtz - H_2O vers le pôle Or, les concentrations élevées en Ba et Sr, l'appauvrissement relatif en terres rares et une anomalie positive en europium font penser que la composition de ces ségrégations granitiques ne correspond plus à celle du bain fondu primaire. Des modèles fondés sur les coefficients de partage des éléments en traces entre minéral et bain fondu et entre phases minérale et fluide montrent que les ségrégations pourraient résulter de la cristallisation et l'accumulation d'un constituant enrichi en feldspath potassique dérivé d'un bain fondu de composition "minimum" ou d'une phase fluide.

Mots-clés: granite peralumineux, bain fondu, éléments traces, isotopes, Black Hills, Dakota du Sud, ségrégations pegmatitiques.

INTRODUCTION

Pegmatitic granite segregations are commonly associated with many regionally metamorphosed terranes (*e.g.*, White 1966, Mehnert 1968, Ginsburg *et al.* 1979, Weber *et al.* 1985). The first appearance of many of the pegmatite segregations coincides with muscovite dehydration reactions in the surrounding aluminous country-rocks. The pegmatitic segregations in these regionally metamorphosed terranes show a wide range of relationships, from a gradational association with leucosome stringers of migmatites to an apparent lack of spatial and genetic relation with the migmatites. Ginsburg *et al.* (1979) suggested that migmatitic terranes associated with granulite-facies metamorphism contain only barren, ceramic, or allanite- and monazite-bearing pegmatites and that both the pegmatites and migmatites were derived during the regional metamorphism.

Numerous hypotheses have been put forward to explain the derivation of granite segregations in regionally metamorphosed terranes. Suggested origins include: (1) injection of granitic magma from an adjacent igneous intrusive body (*e.g.*, Sederholm 1923, Grout 1948, Page 1968); (2) *in situ* partial melting and subsequent segregation during regional metamorphism (*e.g.*, Eskola 1933, Von Platen 1965, Thompson & Norton 1968); (3) crystallization from an aqueous fluid (*e.g.*, Sederholm 1926, Leveson & Seyfert 1969); and (4) metamorphic differentiation and segregation (*e.g.*, Greenly 1923, Hughes 1970). The complexity of melt – residuum – fluid interaction during migmatization has been documented by Weber *et al.* (1985). The present study was undertaken to evaluate the genetic relationship of pegmatitic segregations in high-grade metamorphosed rocks in the Willow Creek area, Black Hills, South Dakota (Fig. 1), to the associated schists and regional metamorphism. Evaluation of melting of high-grade metagreywackes and modification of these melts should be useful in understanding the generation of peraluminous granites characteristic of the Harney Peak Granite.

Geological Setting

The Black Hills, in southwestern South Dakota, consist of a Precambrian core of a complex dome formed during the Laramide uplift (~60 Ma). The Precambrian in the southern Black Hills is dominated by metamorphosed early Proterozoic sediments, and the Harney Peak Granite and spatially associated pegmatites. The metamorphic rocks are predominantly schists whose protoliths were greywackes and shale. Less abundant rock-types include carbonate-facies banded iron-formations, metagabbro and metabasalt, quartzite, and very minor amounts of marble (Page *et al.* 1953, Redden & Norton 1975, Redden, unpubl. data). The sequence of deformation in the southern Black Hills, as interpreted by Redden (1968) in the Berne Quadrangle, consists of three major stages: 1) formation of early major structures (large isoclinal folds) and associated minor structures (*e.g.*, minor folds, axial-plane foliation); 2) later shear-deformation; and 3) a final doming related to the emplacement of the Harney Peak Granite and pegmatite masses (dated at 1703 Ma: Riley 1970). The main body of the Harney Peak Granite forms a structural dome and consists of many hundreds if not thousands of sills, both large and small, and some discordant bulbous masses and dykes. Structural evidence indicates that most of the larger masses of granite were forcefully emplaced from below and did not develop by *in situ* melting (Redden *et al.* 1982). Based upon experimentally determined phase-relationships, Huang & Wyllie (1981) concluded that the Harney Peak Granite may be a product of partial fusion of pelitic rocks at depths of between 20 and 40 km.

The Precambrian rocks of the southern Black Hills are predominantly in the staurolite and sillimanite–muscovite zones (low sillimanite) of metamorphism, but a small area on the southern flank of the Harney Peak Granite (Fig. 1) is in the sillimanite – potassium feldspar zone (high sillimanite) (Redden & Norton 1975). Redden *et al.* (1982) estimated conditions of metamorphism in the high sillimanite zone to be 640°C and 3.0 to 4.0 kbars. Between the low sillimanite and high sillimanite isograds, muscovite is eliminated from mineral assemblages by dehydration reactions. The disappearance of muscovite has been recognized in many regionally metamorphosed terranes (Heald 1950, Evans & Guidotti 1966, Lundgren 1966, Tracy 1978). Although Tracy (1978), Thompson & Algor (1977), and Thompson & Tracy (1979) have shown that the dehydration of muscovite in pelitic rocks is complex, the textural relationships observed in the schist in the Willow Creek area indicate that the muscovite breakdown reaction may be approximated by the reaction:

muscovite + plagioclase + quartz =
sillimanite + K-feldspar + vapor.

In this area, quartz – feldspar – biotite – sillimanite schists that are above the low sillimanite isograd are associated with many small, coarse-grained granitic pods, sills and dykes. Some of these develop in prominent boudinage structures, but others transect the schist.

Analytical Techniques

Modal data for the schist were collected by optical point-count, with a grid spacing of 150 μm on standard polished thin sections. Modal analyses of the granites were done on stained slabs. Modal data for the fine-grained portions of the slabs were collected by optical point-counting techniques and incorporated into the slab mode.

Analyses of the schist were done on 0.5 to 1 kg of homogenized whole-rock powder. Complete granitic segregations (sills and pods up to 15 kg) were collected from the Willow Creek area, crushed and homogenized for analysis. Major, minor and trace-element contents were obtained by energy-dispersion X-ray fluorescence and atomic absorption – inductively coupled plasma spectroscopy (AA/ICP). Several splits of the same rock powder were analyzed to monitor sample homogeneity. The data from the sample splits are reproducible to 0.5 – 4% for major and minor elements and 1 – 7% for trace elements. The FeO/Fe_2O_3 ratio was determined by a $KMnO_4$ titration technique (Goldich 1984), mineral compositions by AA/ICP (microcline) and electron microprobe (plagioclase), and *REE* abundances by isotope-dilution mass spectrometry. All *REE* data are reproducible to 1–2%.

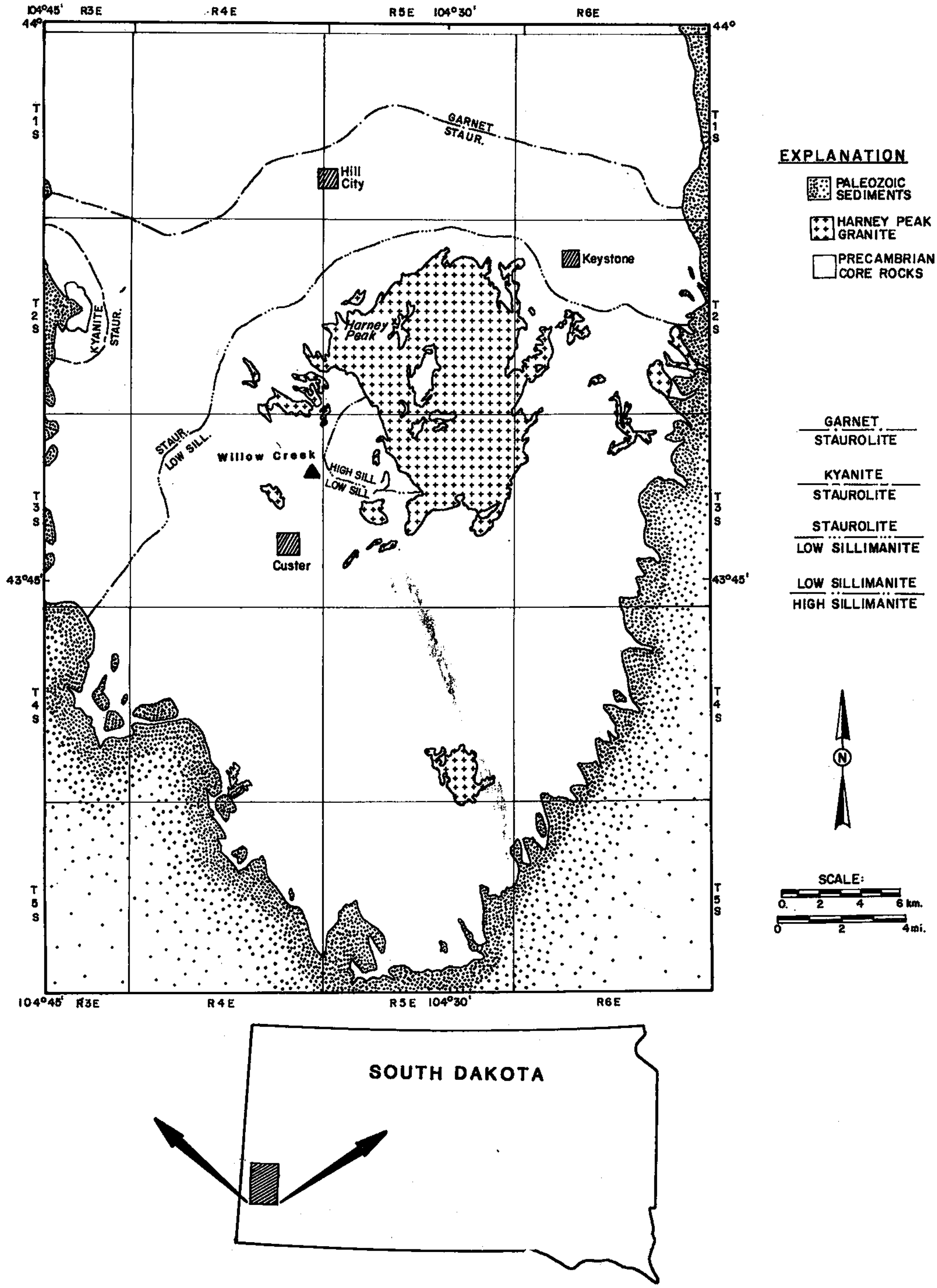

FIG. 1. Geological map of the Precambrian core of the southern Black Hills, showing the distribution of the Harney Peak Granite, metamorphic isograds, and location of the Willow Creek site (after Redden *et al.* 1982).

TABLE 1. TYPICAL MODES FOR SCHIST AND GRANITE AT THE WILLOW CREEK SITE

	Schist						Granite						
	WC1	WC2	WC3a	WC3b	WC4	WC5	WC9-1	WC9-2	WC9-3	WC9-4	WC9-5	WC9-6	WC9-7
Quartz	35.3	40.1	46.6	44.0	50.6	55.8	27.4	30.3	31.3	28.1	28.4	30.3	28.6
Plagioclase	13.6	17.3	14.4	13.4	11.9	9.5	24.4	23.8	24.4	26.2	28.9	27.4	28.6
K-Feldspar	7.8	2.9	4.1	0.6	0.6	2.9	47.6	45.2	43.8	44.4	42.2	40.1	41.4
Biotite	28.1	26.0	22.2	31.7	21.0	20.1	0.0	0.0	0.2	0.0	0.0	0.1	Tr
Muscovite	0.6	2.5	4.9	1.2	8.2	8.4	0.3	0.5	0.1	1.0	0.3	2.1	1.2
Sillimanite	12.5	10.0	6.4	7.2	7.0	1.1	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Tourmaline	1.7	Tr	Tr	Tr	Tr	2.2	0.3	0.2	0.2	0.3	0.2	Tr	0.2
Opaque	0.4	0.2	0.8	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apatite	Tr	Tr	0.4	Tr	0.3	Tr	0.0	Tr	0.0	0.0	0.0	0.0	0.0
Zircon	Tr	Tr	0.1	0.2	Tr	Tr	Tr	Tr	Tr	0.0	0.0	0.0	0.0
Dumortierite	0.0	0.0	0.0	0.0	0.0	0.0	Tr	Tr	Tr	Tr	Tr	Tr	Tr
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Petrography and Geochemistry

The mineral assemblage in the analyzed schist is quartz + biotite + plagioclase + sillimanite + K-feldspar + muscovite. Typical modes for the schist are given in Table 1. Fibrolitic sillimanite is commonly intergrown with or totally replaces muscovite. Less common prismatic sillimanite coexists with fibrolitic sillimanite in several samples of the schist. The replacement of muscovite by sillimanite in these samples is in sharp contrast to the selective replacement of sillimanite knots by muscovite in many outcrops in the general area. K-feldspar is poikiloblastic, with inclusions of quartz, biotite, muscovite and tourmaline. Tourmaline is an accessory phase in schist that is in contact with the granite segregations (WC1, WC5).

The granitic segregations are typically zoned, with

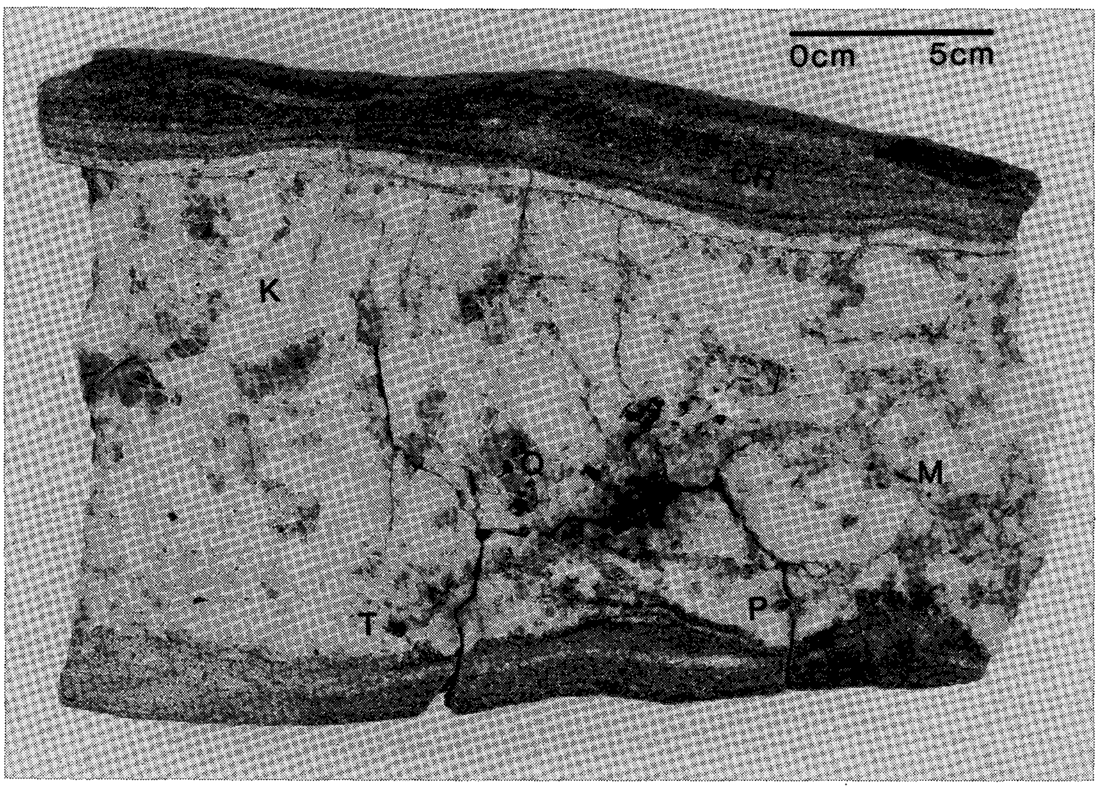

FIG. 2. Slab of granite pod with individual mineral phases identified. Potassium feldspar (Or_{71}): K, plagioclase (An_{7-15}): P, quartz: Q, muscovite: M, tourmaline: T, and country rock: CR. Scale bar equals 3 cm.

a coarse-grained core consisting of K-feldspar + quartz ± plagioclase and a medium-grained rim consisting of plagioclase + quartz ± K-feldspar (Table 1). The bulk K-feldspar composition is approximately $Or_{70}Ab_{30}$, and the plagioclase composition is approximately An_{12-7}. Tourmaline is dispersed throughout the granite. Traces of sillimanite and dumortierite occur in the outer portion of a few of the granitic pods. Textural relationships between mineral phases and the distribution of mineral phases are illustrated in Figure 2. In some of the larger granite segregations (≥ 0.6 m thick), quartz may form a small monomineralic core.

Results of major, minor, and trace-element analyses of the schist and granite are presented in Table 2, and the norms are plotted in Figure 3. The thermal minima at 2, 4, 7 and 10 kbars $P(H_2O)$ in the orthoclase – plagioclase $[An/(An+Ab) = 0.11]$ – quartz – H_2O system (Anderson 1980) are also plotted in Figure 3. Although the metamorphic mineral assemblages in the local greywackes and schists reflect sillimanite–andalusite-type metamorphism and pressures of 3.0 to 4.0 kbars (Redden *et al.* 1982), the norms of the granite segregations are displaced from the 4.0 kbar thermal minimum [at $An/(An+Ab) = 0.11$] toward the Or apex. Granitic veins associated with migmatites from the Palmer region of South Australia show a similar displacement toward the Or apex from the granite minimum (White 1966). White (1966) concluded that these granitic veins could not be explained by partial melting processes.

TABLE 2. CHEMICAL COMPOSITION AND NORMATIVE MINERALOGY OF SCHIST AND GRANITE FROM THE WILLOW CREEK SITE

	Schist			Granite		
	WC1	WC3b	WC4	WC9-I	WC9-III	WC9-X
SiO_2	65.50	67.85	72.53	74.04	74.18	74.09
TiO_2	.69	.61	.65	.06	.05	.05
Al_2O_3	17.49	17.22	14.26	14.43	14.49	14.57
Fe_2O_3	2.02	1.80	.73	.06	.05	.04
FeO	4.75	4.32	3.84	.31	.28	.31
MgO	2.64	1.65	1.57	.02	.05	.02
MnO	.07	.07	.06	.005	.004	.004
CaO	.30	.51	.34	.36	.33	.35
Na_2O	1.01	1.28	1.45	2.83	2.84	2.80
K_2O	4.15	3.70	3.50	6.90	6.80	6.60
P_2O_5	<.50	<.50	<.50	<.50	<.50	<.50
F	.12	.09	.10	.010	.01	.01
	98.74	99.10	99.03	99.025	99.084	98.844
Al/[K+Na+(Ca/2)]	2.6	2.4	2.1	1.1	1.1	1.1
$Na_2O/(Na_2O+K_2O)$	.20	.26	.29	.29	.30	.30
$Fe_2O_3/(Fe_2O_3+FeO)$	.30	.29	.16	.16	.15	.11
FeO/(FeO+MgO)	.64	.72	.71	.94	.85	.94
Normative Mineralogy						
Q	36.66	40.20	45.42	30.30	30.78	31.44
or	24.46	21.68	20.56	40.59	40.03	38.92
ab	8.38	11.00	12.05	24.10	24.10	24.10
an	1.39	2.50	1.67	1.67	1.67	1.67
c	10.91	10.20	7.55	1.60	1.84	2.13
hy	12.54	9.64	9.31	0.40	.40	.40
mt	3.02	2.55	1.16	0.00	0.00	0.00
ilm	1.37	1.22	1.22	0.15	0.15	0.15
	98.73	98.99	98.94	98.81	98.97	98.81

The granite segregations are peraluminous, with corundum in the normative mineralogy. Compared to the segregations, the schist contains a higher percentage of normative corundum, a lower [FeO/(FeO + MgO)] ratio, and similar $[Fe_2O_3/(Fe_2O_3+FeO)]$ and $[Na_2O/(Na_2O+K_2O)]$ values. The trace-

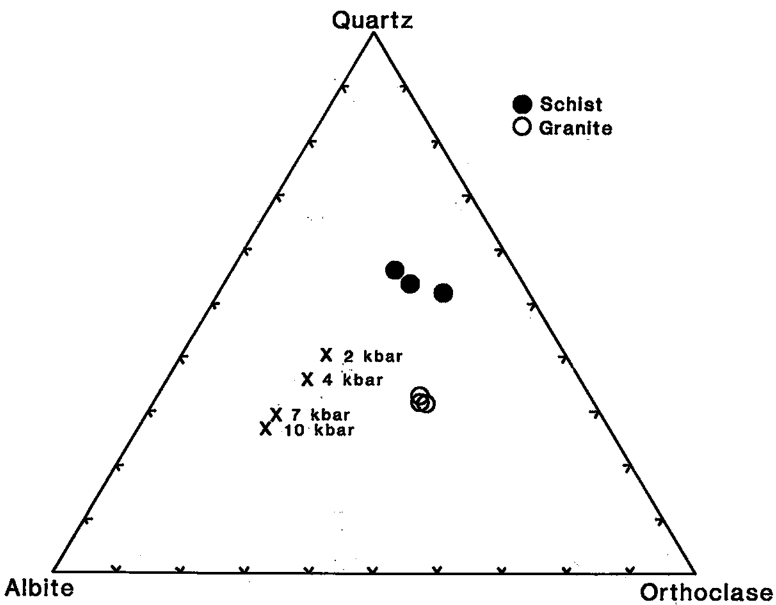

FIG. 3. Projection of normative Qtz–Ab–Or contents of the granite and schist at Willow Creek. Also plotted are minimum-melting compositions (X) for system Qtz–Ab–Or–H_2O at 2, 4, 7, and 10 kilobars (Anderson 1980).

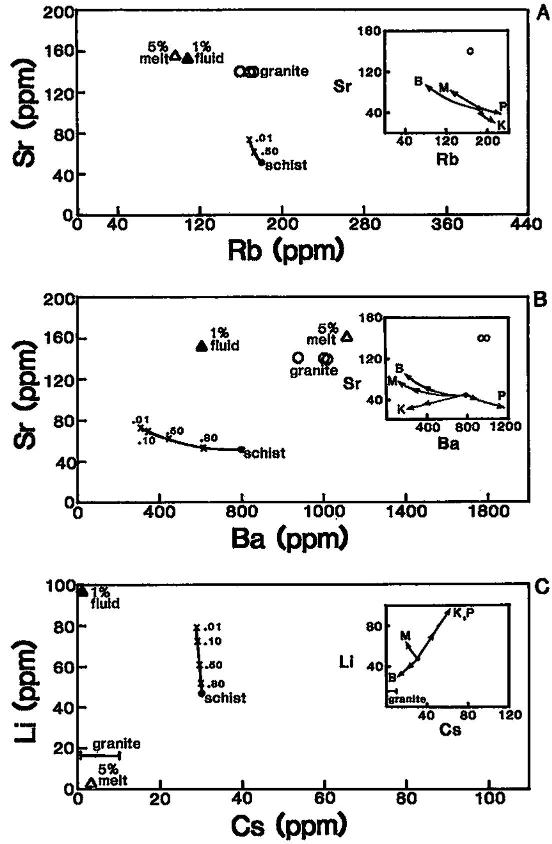

FIG. 4. Plots of Sr against Rb (A), Sr against Ba (B), and Li against Cs (C) for the granite and schist from the Willow Creek site. The granite composition in (C) is represented by a bar owing to the very low Cs content (< 10 ppm). Also shown are calculated curves of granitic melt compositions resulting from the partial melting of the schist (degree of partial melting noted on curves), the calculated composition of a K-feldspar-enriched accumulation derived from 5% fractional crystallization of the 10% partial melt (noted as 5% melt), and the composition of a K-feldspar-enriched accumulation derived from 1% crystallization of the silicate component of a fluid phase (noted as 1% fluid). Shown in inserts are trajectories that indicate the change in composition of a granitic melt as a result of the partial melting of the schist, assuming only a single mineral in the residual (B biotite, M muscovite, K potassium feldspar, P plagioclase). Arrows point in the direction of lower degrees of partial melting.

element abundances of Li, Rb, Zr, Zn, Ga and Y are higher in the schist compared to the segregations, whereas Sr, Ba, and Pb are more abundant in the segregations compared to the schist. Figure 4 illustrates the differences in Rb–Sr, Sr–Ba and Cs–Li values between the schist and granite.

Chondrite-normalized *REE* abundances for the schist (Fig. 5) at Willow Creek are similar to other analyzed Precambrian schists of the Black Hills (Walker 1984, Shearer *et al.* 1984, 1985, 1986) and closely resemble those of the North American Shale Composite Average crustal rock compiled by Haskin & Paster (1979) and Gromet *et al.* (1984). The schist is *LREE*-enriched (Ce/Yb = 28.9), and there is a small negative Eu anomaly. In the granitic segregations at Willow Creek, *REE* abundances are lower than in the schists, Ce/Yb equals 8.8, and there is a large, positive Eu anomaly. Similar *REE* patterns have been observed in some units of the Harney Peak Granite (Walker 1984).

The granitic segregations and the schist at Willow Creek have $\delta^{18}O$ values of +13.8 and +13.7 ‰ relative to SMOW, respectively (Walker 1984). The $\delta^{18}O$ values of the Willow Creek rocks overlap with the range determined for the Harney Peak Granite (Walker *et al.* 1984). In a Sm–Nd isotopic study of Precambrian granites and schist in the Black Hills, Walker (1984) has shown that the granitic segregations yield values of the initial $^{143}Nd/^{144}Nd$ ratio identical within analytical uncertainty to those of the enclosing schist throughout the Early Proterozoic. The isotopic data for the Willow Creek rocks are consistent with the derivation of granitic segregations from the enclosing schist through partial melting.

DISCUSSION

At the Willow Creek site, the general coincidence of the dehydration of muscovite–quartz assemblages with the appearance of granitic segregations suggests that these segregations may have been produced by H_2O-saturated minimum melting. In the low-pressure metamorphic regime (andalusite–sillimanite facies series, 3–4 kbars) suggested for the southern Black Hills by Redden *et al.* (1982), the generation of a granitic minimum melt may, however, be inconsistent with the approximate 50°C offset of muscovite–quartz dehydration reactions from reactions producing a water-saturated minimum melt (Thompson 1982). Thompson & Tracy (1979) and Thompson (1982) suggested that in low-pressure conditions, the fluid produced by muscovite dehydration may migrate out of the system prior to the attainment of temperatures necessary for melting. The association of remnants of partial-melting reactions (*e.g.*, migmatites) with low-pressure regimes may be the result of dehydration and melting at higher pressure (sillimanite–kyanite) followed by uplift faster than cooling (Thompson & Tracy 1979). The formation of the Harney Peak dome during regional deformation and metamorphism uplifted the Willow Creek area to lower-pressure regimes. Unpublished regional studies by Redden suggest that the doming of the area occurred prior to the dehydra-

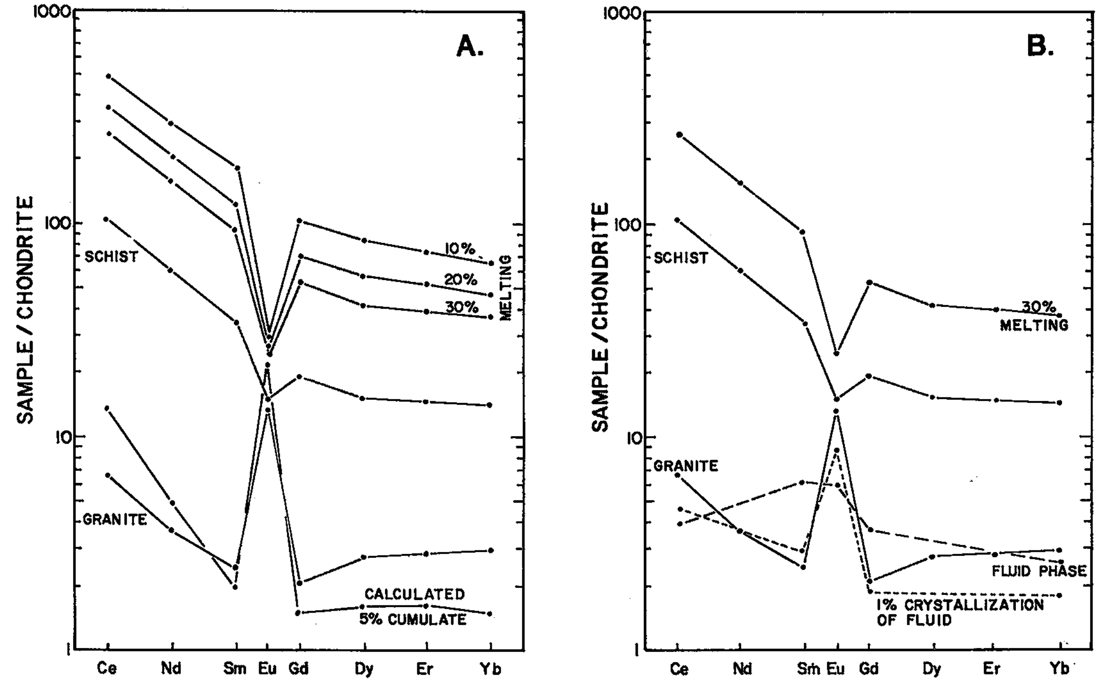

FIG. 5. (A) Chondrite-normalized *REE* patterns for the schist and granite from the Willow Creek site. Also shown are calculated chondrite-normalized *REE* patterns for melts derived from 10%, 20% and 30% partial melting of the schist and for a "cumulate" derived from the 5% fractional crystallization of a 30% partial melt of schist. (B) Comparison between a chondrite-normalized *REE* pattern for the granite and schist from the Willow Creek site and calculated chondrite-normalized *REE* patterns for a fluid phase derived from 1% dehydration of schist and granite derived by the crystallization of that fluid phase.

tion and melting of the country rock. Therefore, for melting to occur at the Willow Creek site during regional metamorphism, a fraction of the fluids produced during muscovite dehydration would have had to reside at the site of generation until higher temperatures were reached, thereby resulting in the production of small volumes of partial melt.

Although the metamorphic conditions at the Willow Creek site could conceivably result in the production of minimum-composition granitic melts and the isotopic data suggest that an intimate relationship exists between the granitic segregations and the surrounding country-rock, do the granitic segregations represent pristine minimum melts? The displacement of the normative composition of the granitic segregation away from the Or–Ab–Qtz–H_2O 4 kbar thermal minimum [at An/(An + Ab) = 0.11] suggests that these granitic rocks do not represent minimum melts. This deviation from the granite minimum may, however, be attributed to the shift in the minimum composition due to the presence of other minor components. The effect of adding F, Li, or B to the haplogranitic system upon the minimum melt composition has been documented by Manning (1981), Stewart (1978) and Pichavant (1984). The composition of the granite segregations presented in Table 3 shows that Li and F are not abundant and therefore are not important variables in shifting

TABLE 3. CONCENTRATION OF ELEMENTS (PPM) IN SCHIST AND GRANITE AT WILLOW CREEK SITE

	Schist			Granite		
	WC1	WC3b	WC4	WC9-I	WC9-II	WC9-X
Li	55	43	47	16	16	16
Rb	230	210	180	170	170	160
Sr	46	60	52	140	140	140
Ba	530	540	800	1000	940	1000
Cs	40	<10	30	<10	<10	<10
U	14	<5	<5	5	4	<5
Pb	8	12	12	61	60	61
Zr	190	240	240	18	17	16
Nb	16	14	14	<2	<2	<2
Cr	120	130	90	<10	<10	<20
V	110	60	80	<20	<20	<20
Ni	50	45	35	6	2	4
W	12	24	10	10	9	9
Zn	120	90	80	6	4	5
Ga	25	20	17	11	9	10
Y	27	29	27	8	8	15
Ce	87	77	86.8	5.39	5	5
Nd			36.7	2.16		
Sm			6.68	.468		
Eu			1.09	.956		
Gd			5.15	.543		
Dy			5.00	.885		
Er			3.17	.600		
Yb			3.00	.614		

TABLE 4. VALUES OF K_d FOR MINERAL/MELT, MINERAL/FLUID, AND MELT/FLUID USED IN CALCULATIONS

A. Mineral/melt K_d used in calculations

	Kspar	Plag.	Biotite	Musc.
Li	0.01	0.02	2.0	0.50
Rb	0.66	0.041	3.26	1.5
Cs	0.036	0.005	1.5	1.5
Sr	3.9	4.4	0.12	0.4
Ba	6.1	0.31	6.36	12

B. Mineral/fluid and melt/fluid K_d used in calculations

	Kspar	Plag.	Biotite	Musc.	Melt
Li	2.3	3.0	2.6	0.50	
Rb	0.42	0.050	2.0	0.48	1.6
Cs	0.022	0.005	0.40	0.088	1.4
Sr	180	23	1.0	0.3	3.1
Ba	190	5.0	90	180	3.1

Data taken from Arth (1976), Carron & Lagache (1980), Hanson (1978), Volfinger (1976), Philpotts & Schnetzler (1970); Nagasawa & Schnetzler (1971), Flynn & Burnham (1978) and Walker (1984).

minimum-melt compositions. The modal abundance of tourmaline suggests that boron may occur in sufficiently high concentrations to influence the composition of the minimum melt. However, as demonstrated by Pichavant (1984), the addition of boron would shift the thermal minimum toward the albite apex of the Or–Ab–Qtz–H_2O system and not toward the potassium feldspar apex. Therefore, the addition of these minor components cannot account for the displacement of the granite segregations from the minimum-melt composition.

To further evaluate whether these granitic segregations represent minimum melts derived by *in situ* melting of surrounding schists, trace-element modeling of partial melting was conducted using the trace-element composition of schist sample WC4 (Table 3), a residual modal mineralogy of quartz (37%), plagioclase (12%), biotite (30%), K-feldspar (8%), sillimanite (12%) and muscovite (1%), combined with mineral/melt distribution coefficients from Hanson (1978) [Rb, Sr, Ba], Carron & Lagache (1980) [Cs], and Nagasawa & Schnetzler (1971) [Li] (Table 4). If the segregations were derived through *in situ* melting of local schist, WCl is the best approximation for C_0 because of its high muscovite content and its location away from the granitic segregations. The hypothetical residual mineralogy approximates WCl schist adjacent to high concentrations of granitic segregations.

The behavior of trace elements during batch melting and fractional fusion has been addressed by various researchers (*e.g.*, Schilling 1966, Shaw 1970, Arth & Hanson 1975, Allègre & Minster 1978, Martin 1979). During batch melting, the melt and residue remain in equilibrium until the melt is removed, whereas during fractional fusion, small fractions of melt are continually removed from the residue and accumulated elsewhere. Allègre & Minster (1978) presented a number of arguments favoring the probability of batch melting during anatexis. The small degrees of partial melting expected to have occurred in the Willow Creek area during regional metamorphism may have enabled the attainment of melt-residue equilibria. If so, this melting process may be better defined in terms of a batch-melting model rather than a fractional fusion model.

The behavior of trace elements during batch melting can be represented by the equation (Schilling 1966):

$$C_L/C_o = 1/[D(1-F) + F]$$

where C_L is the concentration of the trace element within the melt, C_o is the initial concentration of the trace element in the rock undergoing melting, F is the fraction of melt and D is the bulk distribution-coefficient of a given trace element for the residual mineral phases at the time of separation of melt and residue. The trace-element concentrations for a series of partial melts were calculated for Rb, Ba, Sr, Li and Cs using the batch-melting model (*e.g.*, Hanson 1978). As shown in Figure 4, the Rb, Ba, Sr, Li and Cs contents of the calculated melts deviate greatly from the composition of the granitic segregations.

Numerous trace-element studies have demonstrated that the *REE* pattern for granitic melts derived by the partial melting of a greywacke are typically *LREE*-enriched and have either no Eu anomaly or a negative Eu anomaly (*e.g.*, Arth & Hanson 1975). To illustrate this, model *REE* patterns for a granite produced by 10%, 20% and 30% partial batch-melting of schist sample WC4 were calculated (Fig. 5A). All modeled *REE* patterns contrast with the *REE* pattern of the granitic segregation by being enriched in *REE* relative to schist WC4 and having a negative Eu anomaly. *REE* patterns with large positive europium anomalies similar to the *REE* pattern of the Willow Creek granitic segregations have been interpreted as representing not melts but rather an accumulation of a feldspar-rich component (*e.g.*, Hanson 1980).

The partial melting model described above assumes that the proposed residual modal mineralogy is appropriate and that the trace-element character of sample WC4 approaches C_o. These assumptions are perhaps acceptable if the granite is derived from the melting of the surrounding country-rock. However, if the granitic melt was derived from outside that immediate area, these assumptions may be incorrect.

Based on field observations, Redden (1963, 1968) was able to recognize various sedimentological types of the Bouma sequence (Bouma 1962) in the schists in the southern Black Hills. The schist in the Willow Creek area consists predominantly of type-A Bouma sequence (massive, graded). Metamorphism of other lithologies of the Bouma sequence, such as type E (pelite), may produce a higher modal abundance of muscovite than type A. This will result in higher modal K-feldspar and sillimanite following muscovite dehydration and therefore modify the modal mineralogy of the residual by increasing the ratio of K-feldspar to biotite. Hanson (1978) illustrated the effect of biotite compared to K-feldspar in the residuum on the trace-element characteristics of the coexisting granitic melt. Based upon conclusions derived by Hanson (1978) and illustrated in Figure 4 (insert), variations in the ratio of K-feldspar to biotite in the residuum alone cannot account for the differences in the *REE*, Ba, Sr, Rb and Cs between the calculated granite and the granitic segregations.

Previous studies in the Black Hills have demonstrated that interaction between pegmatite-derived fluids and the surrounding country-rock schist has resulted in the enrichment of the schist in alkali elements (*e.g.*, Shearer *et al.* 1986). A large alkali-enrichment halo surrounding the entire Harney Peak Granite is indicated from studies by Tuzinski (1983) and J.J. Norton (pers. comm.). The sequential relationship between dispersion of alkali elements and partial melting in the Willow Creek area is unknown. If the granitic segregations were derived from the partial melting of alkali-enriched schists, this would expectedly affect the trace-element model. Derivation from an alkali-enriched schist, however, would increase the Li and Cs contents of the granitic melt. This contrasts with the actual Li and Cs concentrations of the granitic segregations. In addition, elements that pose more critical problems to the comparison between the modeled granite and granitic segregations (*REE*, Ba, Sr) have been found to be unaffected by schist–pegmatite interaction (Shearer *et al.* 1986).

In summary, the displacement of the granite composition from the quartz - albite - orthoclase thermal minimum, the results of the trace-element modeling, and the character of the *REE* pattern of the segregations strongly suggest that the granite segregations at Willow Creek do not represent a pristine minimum melt produced by the partial melting of the enclosing country-rock.

Alternative models to the simple *in situ* partial-melting process for the production of the granitic segregations at Willow Creek must account for the enrichments of Ba and Sr and depletions of Cs and Li in the granitic segregations relative to the enclosing schist, the lower *REE* content of the segregations compared to the schist and the positive Eu anomaly in the segregations. These characteristics suggest that the granitic segregations represent the accumulation of a K-feldspar-enriched component that may be derived from either a minimum melt or a fluid phase. The fluid phase may either have been exsolved from a minimum melt or been produced from the breakdown of hydrous silicates (*i.e.*, muscovite). A cumulate origin for some leucosomes in migmatitic terranes has been proposed by Cuney & Barbey (1982).

Trace-element characteristics of a granitic segregation produced by the accumulation of a K-feldspar-enriched component can be modeled by calculating the trace-element concentration of an accumulation of crystals derived from 5% fractional crystallization of a 10% partial melt. The modal composition of the "cumulate" was set at 45% K-feldspar, 28% plagioclase, 25% quartz and 2% muscovite to approximately correspond with the modal mineralogy of the granitic segregations. The concentration of a trace element in the "cumulate" was calculated by:

$$C_c = C_l \frac{(1 - F^D)}{(1 - F)}$$

where C_c is the concentration of element in "cumulate", C_l the concentration of element in the granitic melt, D the bulk-partition coefficient, and F the weight proportion of residual melt (Allègre & Minster 1978). Figure 4 illustrates the Rb, Ba, Sr, Li and Cs concentrations in the 5% "cumulate" compared to the granitic segregations and schist. Although not identical to the granitic segregations, the modeled compositions show the same type of enrichments for all five elements. The modeled *REE* pattern of the 5% "cumulate" compares favorably with the granitic segregation, with a lower *REE* content compared to the schist and a positive Eu anomaly (Fig. 5B).

The physical separation of a granitic melt from a potassium-feldspar-enriched crystalline component in a restricted conduit is a fairly difficult process to envision. Crystal settling (*e.g.*, McBirney & Noyes 1979) and flow differentiation (Bhattacharji 1967) have been shown to be possible mechanisms of separation in basaltic systems. The high viscosities associated with silicic melts (Urbain *et al.* 1982, Burnham 1963, Shaw 1963), even with the addition of volatiles (Burnham 1967), causes silicic magmas to behave more as a Bingham fluid than a Newtonian fluid (Sparks *et al.* 1977). The expected high viscosity of the granitic melt and the restricted character of the conduit make it unlikely that crystal settling and flow differentiation were important in a restricted granitic system such as Willow Creek.

Compressive forces generated during regional and local structural deformation could act as a mechanism for the physical separation of granitic melt and crystals. During the crystallization of these granitic bodies, melt polymerization may decrease due to an increase in the volatile content of the remaining melt (Spera 1980). The resulting increase in melt mobility could greatly increase the efficiency of such a "filter pressing" mechanism. The crystallization and separation of a K-feldspar-rich component from a granitic melt imply the existence of a complementary granitic melt that represents the separated melt phase. Field evidence for the existence of complementary granitic melts is insufficient. Numerous exotic veins (quartz + sillimanite + biotite + tourmaline assemblage) occur in the area; however, field recognition of such a melt might be difficult if not impossible.

Fluid-phase crystallization was modeled with a 1% dehydration of the schist (WC4), then a 1% crystallization of the anhydrous components of that fluid. Experimentally determined and calculated mineral/fluid partition coefficients were used in the calculations (Carron & Lagache 1980, Volfinger 1976, Papike *et al.* 1983, Walker 1984). The resulting fluid-phase-derived granite is similar to the actual composition of the granitic segregation, with an enrichment in Sr and depletions in Cs and *REE* (Fig. 4). In addition, the modeled granite has a positive Eu anomaly (Fig. 5B). The modeled granite contrasts with the previous model and the actual composition of the granitic segregations by being enriched in Li and depleted in Ba. Some of this inconsistency may be accounted for by poorly defined partition-coefficients.

Luth & Tuttle (1969) demonstrated that over the range of 2 to 10 kilobars and at a temperature above the solidus, the composition of the anhydrous component of a vapor phase in equilibrium with a granitic magma is depleted in the Or component relative to the minimum melt composition in the system Or–Ab–Qtz–H_2O. Below the solidus, the vapor phase is displaced away from the minimum toward the Qtz apex. The composition of the silicate constituents of the fluid phase approaches the minimum melt composition only at pressures exceeding 10 kilobars. Such pressures exceed the estimated conditions of metamorphism in the Willow Creek area. The solubility of the anhydrous component in the aqueous fluid phase is less than 10 wt.% (Luth & Tuttle 1969). Therefore, to precipitate these granitic segregations from an aqueous fluid requires a high ratio of fluid volume to rock volume. Based on a maximum solubility of 10% and approximate densities of fluid and solid, this fluid/rock volume ratio must exceed 30. The ability of such a large volume of fluid to flow through restricted conduits during regional deformation is problematical.

The applicability of the data from Luth & Tuttle (1969) to fluids derived from dehydration reactions in metamorphic rocks is uncertain. Many data suggest that a fluid phase is essential in triggering migmatization (Olsen 1982, 1983) and modifying the mineralogy and the trace-element character of leucosomes during subsolidus re-equilibration (Weber *et al.* 1985). Low *REE* contents of late-stage pegmatites and aplites have been attributed to crystallization from aqueous solutions (Hanson 1980, Nabelek 1983). Until complete solubility-products and information on speciation in supercritical fluids for direct application to feldspars and micas are available, rigorous evaluation of this process is not possible.

Conclusions

In conclusion, the granitic segregations studied do not represent pristine granitic minimum melts. Modeling of the various chemical data indicates that the segregations most likely represent the accumulation of a K-feldspar-enriched component derived from either a minimum melt or an aqueous solution. Both accumulation models result in a granitic segregation with high concentrations of Ba and Sr, low concentrations of Rb, *REE*, and a positive Eu anomaly. With the possible variability in schist composition (trace elements and mineral assemblage) and unknown accuracy of K_D values, these two models are indistinguishable using trace-element modeling. However, the physical mechanism of separation and emplacement poses a problem in both models, particularly in the second one involving aqueous fluid. Although we do not suggest that all granitic segregations in high-grade metamorphic terranes are not derived from pristine granitic minimum melts, our data indicate that other processes may be important in the development of the small pods and sills of granitic material in the Willow Creek area, and possibly in the development of layered composite bodies characteristic of the Harney Peak Granite.

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