

PETROGENETIC LINKS AMONG GRANITES AND PEGMATITES IN THE HARNEY PEAK RARE-ELEMENT GRANITE-PEGMATITE SYSTEM, BLACK HILLS, SOUTH DAKOTA

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ABSTRACT

Linkages between the fertile granite and associated pegmatites, linkages among pegmatites, and processes instrumental in defining their textural, chemical, and mineralogical uniqueness are obscured by their coarse grain-size and the transitional nature between magmatic and hydrothermal regimes. Our studies of the Harney Peak granite-pegmatite system in the Black Hills, South Dakota, indicate that these systems are a culmination of distinctive processes of partial melting and fractional crystallization. Both the Harney Peak Granite and the associated pegmatite field are mineralogically and chemically zoned. Superimposed on the general zoning in the pegmatite field are swarms of pegmatites that appear to define distinct compositional-textural arrays. These may be related to distinct fractional crystallization trajectories. The Harney Peak Granite and numerous pegmatites define a single trajectory of fractional crystallization, whereas Li-, Rb-, Cs-enriched zoned pegmatites and F-, Sn-, Be-enriched pegmatites represent trajectories of fractional crystallization involving chemically distinct magma-types. A fractionation trajectory (from biotite granites to tourmaline granites) does not represent an evolutionary path of a single magma, but most likely represents paths of fractional crystallization of similar batches of magmas. Within each trajectory of fractional crystallization are coherent sequences of textural and mineralogical characteristics. The extreme rare-element enrichments observed in pegmatites can in part be modeled by moderate to high degrees of fractional crystallization (up to 70-90%) of a suite of volatile-rich magmas. In addition to fractional crystallization, partial melting appears to be important in controlling the potential content and composition of the volatile component, and the incompatible element character of the distinct magma-types. Varying degrees of dehydration melting of compositionally diverse metasediments appear to be the most likely model for the production of these compositional diverse parental granitic magmas.

Keywords: granite, pegmatite, fractional crystallization, partial melting, Harney Peak, Black Hills, South Dakota.

SOMMAIRE

Les liens entre granite fertile et les pegmatites associées, et entre les différents massifs de pegmatite, et les processus importants dans leur individualisation texturale, chimique et minéralogique, sont rendus obscurs à cause de leur granulométrie grossière et de la transition entre régimes magmatique et hydrothermal. Nos études du système granitique et pegmatitique de Harney Peak, dans les Black Hills, Dakota du Sud, montrent qu'il s'agit d'une culmination de processus distincts de fusion partielle et de cristallisation fractionnée. Le granite de Harney Peak et les massifs de pegmatite associés sont zonés minéralogiquement et en composition. De plus, des essaims de pegmatites distinctes dans leurs compositions et leurs textures semblent superposés au schéma général, et pourraient résulter de trajectoires distinctes de cristallisation fractionnée. Le granite de Harney Peak et de nombreux massifs de pegmatite définissent une seule trajectoire de cristallisation fractionnée, tandis que les massifs de pegmatite zonés et enrichis en Li, Rb et Cs, ou en F, Sn et Be, représenteraient des trajectoires de cristallisation fractionnée de venues magmatiques distinctes. Une trajectoire de fractionnement à partir d'un granite à biotite pour donner un granite à tourmaline ne représente pas une lignée d'évolution d'un seul magma, mais plutôt des tracés de cristallisation fractionnée de venues de magmas semblables. A l'intérieur de chaque trajectoire, nous reconnaissons des séquences cohérentes de caractéristiques texturales et minéralogiques. Les taux d'enrichissement extrêmes en éléments rares reflètent en partie des taux moyens ou élevés de fractionnement (jusqu'à 70-90%) dans une suite de magmas riches en phase volatile. En plus de la cristallisation fractionnée, le taux de fusion partielle semble important pour déterminer la teneur éventuelle en phase volatile, sa composition, et le caractère distinct en éléments incompatibles des venues magmatiques. Des taux différents de fusion liée à la déshydratation de séquences métasédimentaires diverses nous paraissent responsables de la diversité dans la composition des magmas granitiques parentaux.

(Traduit par la Rédaction)

Mots-clés: granite, pegmatite, cristallisation fractionnée, fusion partielle, Harney Peak, Black Hills, Dakota du Sud.

INTRODUCTION

The transition in rare-element-enriched granite-pegmatite systems between magmatic and hydrothermal regimes (London 1986a,b) and the coarse grain-size of individual intrusions create problems in the interpretation of petrogenetic links among the granite intrusions. Numerous models have been proposed (e.g., Norton 1981, Stewart 1978, Zasedatelev 1974, 1977, Shmakin 1983, Černý *et al.* 1981, Černý 1982, Černý & Meintzer 1988, Shearer *et al.* 1987a, Nabelek 1992a,b, Jolliff *et al.* 1992) to elucidate both this petrogenetic linkage and the unique processes instrumental in producing the more exotic granitic magmas. These models collectively address (1) the uniqueness of the source area (composition, melting processes), (2) petrogenetic relations among lithologies constituting the fertile granitic complex, (3) petrogenetic relations between the fertile granitic complex and associated pegmatites, (4) petrogenetic relations among the various pegmatites, and (5) the nature of the collateral evolution of granitic magma system and associated fluid system. The general anatomy of a granite-pegmatite system is illustrated in Figure 1A.

Three "end-member" models for generating the fertile granite and associated pegmatites may be extracted from these previous studies (Fig. 1):

Model 1. A continuous crystallization model (Fig. 1B) consists of partial melting of lithologies capable of generating homogeneous melts or heterogeneous melts that are homogenized in a collective reservoir. Fractional crystallization of this parental magma produces the wide spectrum of granite lithologies. Small degrees of fractional crystallization will produce the biotite granites, whereas higher degrees of fractional crystallization will yield the more exotic granitic magmas.

Model 2. A partial melting model (Fig. 1C) involves varying degrees of partial melting capable of generating the wide compositional spectrum observed in the granite-pegmatite field. High degrees of partial melting (~40%) will produce the biotite granite, whereas smaller degrees of partial melting (<20%) will generate the more exotic alkaline earth-, Ta-, Nb-, Sn-, Be-enriched granitic magmas.

Model 3, which invokes partial melting of distinct compositional sources (at the same degree of partial melting) also will yield granitic magmas with a wide range of trace-, minor-, and volatile-element characteristics (Fig. 1D). Differences in sedimentary lithologies may result in differences among the protoliths in (1) bulk trace-element chemistry, (2) mineralogical reservoirs for alkaline earths (sheet-silicate-enriched lithologies may contain higher abundances of alkali elements), (3) stability fields of sheet silicates or accessory minerals and (4)

content of sheet silicates and accessory minerals in the residuum. In addition, "metasomatic" modification of the sedimentary lithologies also may influence their ability to yield exotic volatile-rich granitic melts.

Earlier geochemical and mineral-chemical modeling of the Harney Peak Granite in the Black Hills, South Dakota (Fig. 2) indicates that 60–80% fractional crystallization of the primitive biotite-muscovite-bearing granitic magma led to the production of the more evolved tourmaline-bearing granites (Shearer *et al.* 1987a, Duke *et al.* 1992). Extreme fractional crystallization (>99%), aided by high activity of volatile components, changing partitioning behavior, and filter-pressing mechanisms, produced the highly evolved rare-element pegmatites (Walker *et al.* 1989, Shearer *et al.* 1987a). This model is consistent with the comparative scarcity of these highly evolved pegmatites (Norton & Redden 1990). In addition, the occurrence of spodumene-bearing fracture-filling units in barren pegmatites (Page *et al.* 1953, Redden 1968, Norton *et al.* 1964) suggests that the crystallization of a fertile granite may yield small volumes of these exotic granitic melts. However, processes involving the extraction and accumulation of these small volumes of melts are intuitively difficult to envision and may be impossible to accomplish (Marsh 1981).

The objective of this study is to use the Harney Peak Granite and its associated pegmatites to address fundamental questions concerning the evolution of rare-element granite-pegmatite systems: (1) What processes generate the fertile granites? (2) What are the petrogenetic links among spatially associated pegmatites? How are these linkages reflected in mineralogical, geochemical, and textural differences? (3) What are the petrogenetic links between the fertile granite and associated pegmatites? (4) What processes and mechanisms are important to the evolution of the rare-element granitic systems (crystallization, partial melting, source protolith)?

ANALYTICAL APPROACH TO THE PROBLEM

The coarse-grained and mineralogically zoned character of individual pegmatite bodies limits the utility of many of the common "whole-rock" trace-element techniques used in defining petrogenetic links among spatially related intrusions. However, other techniques can be used in a qualitative to semiquantitative manner: (1) the nature, distribution, and textures of mineral assemblages (Jahns & Burnham 1969, Jahns 1982, Norton 1983, Norton & Redden 1990); (2) mineral chemistries (Černý 1982, Černý & Meintzer 1988, Trueman & Černý 1982, Shearer *et al.* 1985, Jolliff

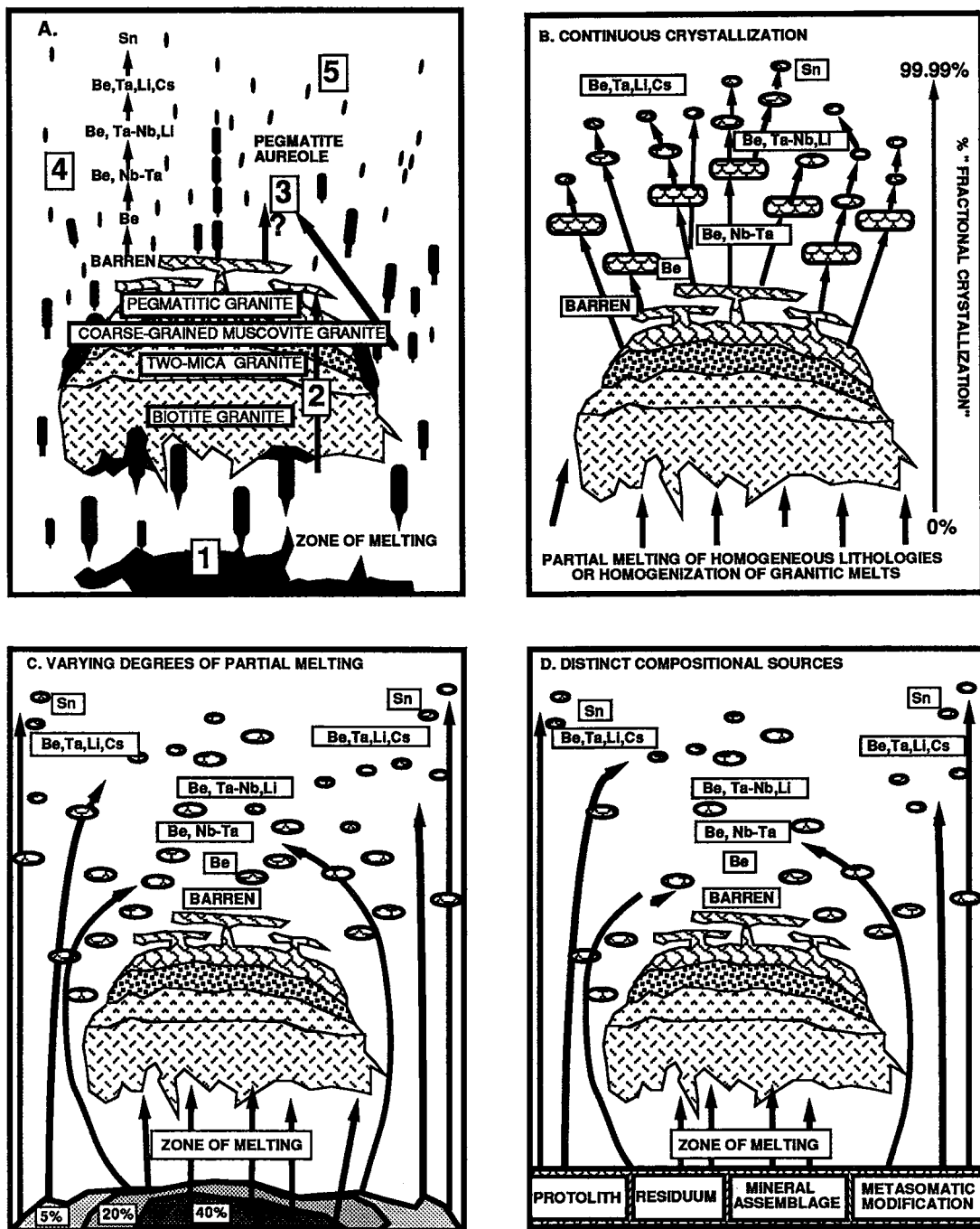


FIG. 1. Summary of end-member models suggested for the generation of peraluminous rare-element-enriched granite-pegmatite systems. A. An index of important features and concerns in petrogenetic models: (1) characteristics of the source for the granitic magmas and melting processes, (2) petrogenetic relationships among lithologies constituting the "fertile" granite complex, (3) the petrogenetic relations between the "fertile" granite and associated pegmatites, (4) the petrogenetic relations among the various pegmatites, and (5) the nature of the collateral evolution of the magmatic system and associated fluid system. B. "Continuous crystallization" model. C. Partial melting model. D. "Distinct compositional source" model.

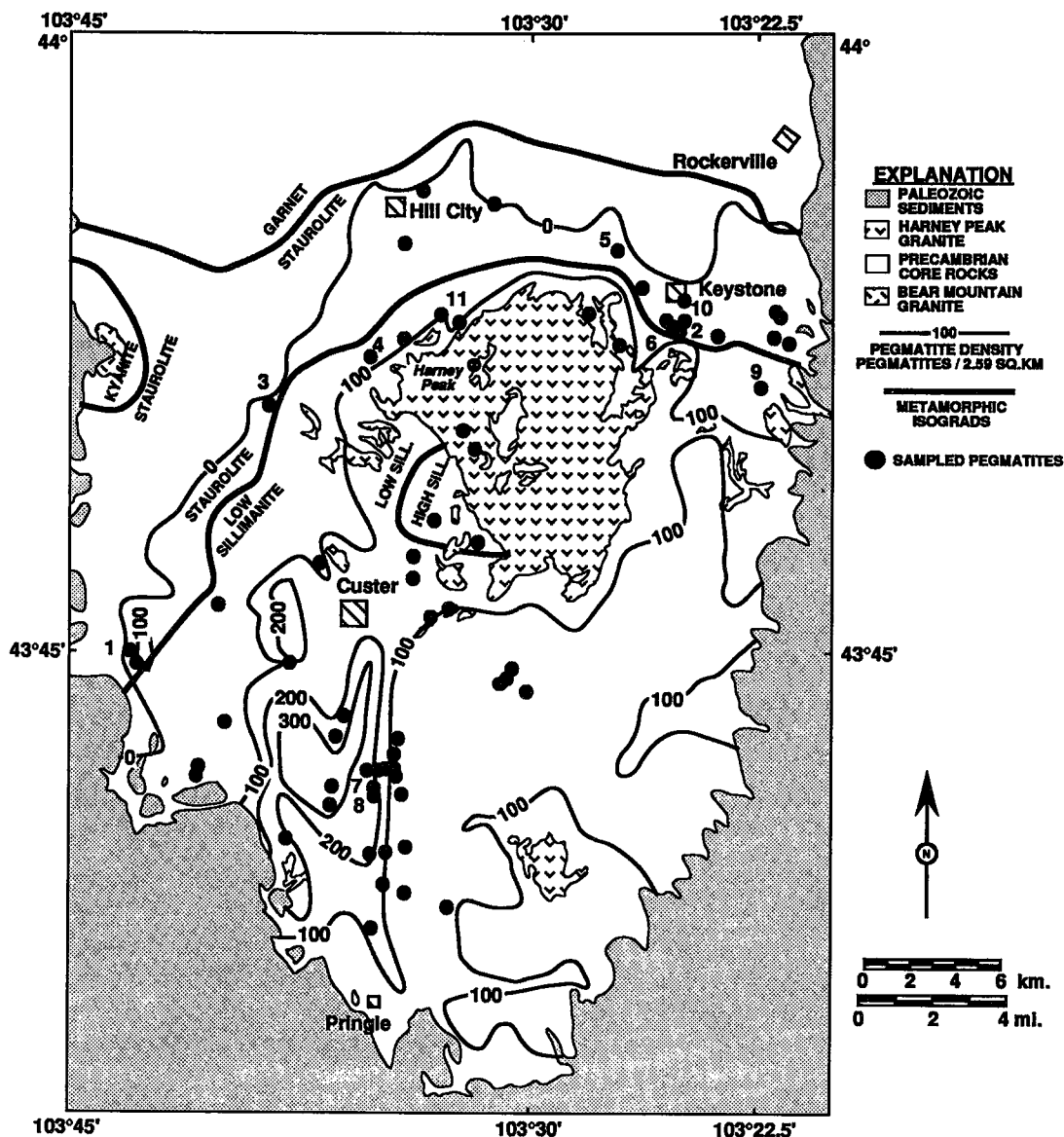


FIG. 2. Map of the southern Black Hills, South Dakota showing the locations of the Harney Peak Granite, metamorphic isograds, pegmatite density contours and pegmatites sampled in this study. Several pegmatites noted frequently in text are indexed: (1) Tin Mountain, (2) Etta, (3) Hunter-Louise, (4) Tin Queen, (5) Bob Ingersoll, (6) Diamond Mica, (7) Silver Dollar, (8) White Bear, (9) Soda Spar, (10) Peerless, and (11) Dewey. The locations of other pegmatites can be obtained from Page *et al.* (1953) and Norton & Redden (1990).

et al. 1986, 1987, 1992); (3) “pull-apart” studies of pegmatites (Norton *et al.* 1962, Norton 1970, Walker *et al.* 1986, 1989); and (4) characteristics of the metasomatic halo (Beus 1968, Trueman & Černý 1982, Shearer *et al.* 1986b, Shearer & Papike 1988, London 1986b, Morgan & London 1987).

Our major approach in this study focuses on the trace-element geochemistry of the K-rich feldspar. The trace-element chemistry of the K-feldspar may be used as a qualitative index of petrogenetic relationships (Černý 1982, Trueman & Černý 1982). In addition, the K-feldspar may be used with other

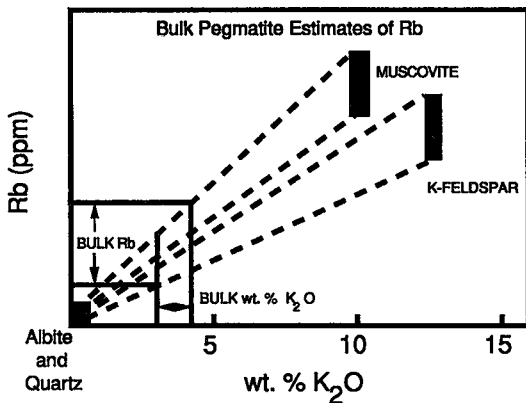


FIG. 3. Rb and K_2O relationships between whole-rock chemistry and individual mineral phases (K-feldspar, muscovite, quartz, albite). Rb content of the bulk pegmatite may be estimated using this simple graphical relationship. Ba may be estimated in the same manner. Comparison of graphical estimates to actual whole-rock determinations and pegmatite "pull apart" studies are presented in Table 1.

mineral phases (Na-feldspar, sheet silicates) in a graphical, semiquantitative determination of bulk-pegmatite abundances of Rb, Ba and Cs (Fig. 3). This approach is a rapid alternative to the bulk pegmatite "pull-apart" studies of Norton *et al.* (1962), Norton (1970), and Walker *et al.* (1986, 1989). Examples of this graphical index are illustrated in plots of K_2O versus Rb, and K_2O versus Ba for whole-rock samples and individual mineral separates from the Harney Peak Granite (Shearer *et al.* 1987a) and the Tin Mountain pegmatite (Fig. 3, Table 1).

TABLE 1. COMPARATIVE ESTIMATES OF WHOLE-PEGMATITE TRACE-ELEMENT CHEMISTRY BASED ON GRAPHICAL ANALYSIS, "PULL-APART" STUDIES (TIN MOUNTAIN PEGMATITE), AND RESULTS OF WHOLE-ROCK CHEMICAL ANALYSES (JR II)

	Harney Peak Granite (JR II)		Tin Mountain Pegmatite	
	Shearer <i>et al.</i>	This study	Walker <i>et al.</i>	This study
Rb ppm	1100	1150	3000 - 5000	2500 - 3000
Ba	420	490	40 - 80*	10 - 15*
Li	30		3000 - 5000	3000 - 4000

* Based on the analysis of eight feldspar samples. + Based on forty feldspar samples. The concentrations of Li are based on modal abundances of Li-bearing silicates and phosphates, and their Li content. References: Shearer *et al.* (1987), Walker *et al.* (1989).

The K-feldspar was sampled from 70 pegmatites in the pegmatite field surrounding the Harney Peak Granite (Fig. 2). Between 5 and 50 feldspar samples were collected from each pegmatite. K-feldspar from a wide range of mineral assemblages and zones were included in the selection of samples. Purposely included in the sampling were pegmatites noted by Cameron *et al.* (1949), Norton (1983), and Norton & Redden (1990) in their discussion of the sequence of mineral assemblages in differentiated granitic pegmatites. In addition, other mineral phases were sampled and analyzed, textural relations were defined, and the country rock was examined for the character of the dispersion halos.

In any semiquantitative to quantitative trace-element modeling, there are shortcomings in the assumptions of mineral/melt partitioning and mathematical models. It is, therefore, important to understand the assumptions and their impact on the proposed models. Mineral/melt distribution coefficients used in the modeling are from Hanson (1978), Arth (1976), and Walker *et al.* (1989). Fractional crystallization and batch melting models are summarized by Hanson (1978). Problems that may compromise these models are (1) variations in distribution coefficients with T, P, melt composition and phase composition, and (2) deviations from equilibrium as implied by pegmatitic textures. The effect of these assumptions will not make the proposed melt-evolution trajectories incorrect, but will make the estimates of the percent melt semiquantitative. For example, the effect of increasing K_D^{Ba} with decreasing temperature and increasing phosphorus content in K-feldspar will result in an overestimate of the extent of fractional crystallization required by the proposed models. However, the melt volumes calculated by the various mathematical models may be independently evaluated by the relative abundance of pegmatite types.

Dramatic and unpredictable variations in K_D as applied to this modeling are probably the exception rather than the rule. The dramatic textures and mineralogy (both assemblage and individual composition of phases) that may imply exotic chemistry of the melt and substantial deviations from equilibrium are commonly restricted to less than 2% of the pegmatites making up the Harney Peak Granite and pegmatite field (Norton & Redden 1990). In addition, these features are developed once a pegmatite has been emplaced and becomes a relatively closed system. Therefore, extreme and unpredictable trace-element behavior is less appropriate for modeling the total granitic system.

ZONING IN THE HARNEY PEAK GRANITE

The Harney Peak Granite (1.7 Ga; Riley 1970)

in the Precambrian core of the Black Hills, South Dakota is a well-exposed granite complex surrounded by a rare-element pegmatite field with barren to Rb-, Cs-, Nb-, Ta-, Be-, Li-enriched pegmatites (Fig. 2). The granite forms a complex structural dome that was developed late in the Precambrian structural history. It consists of hundreds of sill- and dike-like bodies of peraluminous granite. Previous studies by Duke *et al.* (1988, 1990) and Redden (pers. comm., 1986) suggest that successive intrusions of granitic magma were emplaced peripherally to earlier bodies, so that the Harney Peak Granite effectively "grew" upward and outward. Details of this model are presented by Duke *et al.* (1990). The characteristics of the pegmatite field surrounding the Harney Peak Granite have been described by Page *et al.* (1953), Redden *et al.* (1982), Černý (1982), Shearer *et al.*

(1986b, 1987a) and Norton & Redden (1990). Shearer *et al.* (1987a), Duke *et al.* (1990), Nabelek *et al.* (1992a, b), and Krogstad *et al.* (1991, 1992) recognized that the Harney Peak Granite is mineralogically, chemically, and isotopically zoned. The granitic intrusions, which are either structurally lower in the south-southeastern portion of the complex or appear to represent early emplacement, generally are biotite-bearing granites. Intrusions that are structurally higher or along the west-northwestern perimeter of the complex, generally are tourmaline-bearing granites (Fig. 4A). Single granitic intrusions have been observed to contain both biotite and tourmaline. Textural interpretation suggests that tourmaline followed biotite in the sequence of crystallization. The biotite-bearing granites have similar K/Rb and U/Th ratios, whereas these ratios decrease for the tourmaline-bearing granite (Fig. 4B). Substitutions of (Fe, Mn)Mg₁ in the ferromagnesian minerals, NaCa₁ in plagioclase, and RbK₁ in muscovite and potassium feldspar increase in the tourmaline-bearing granite and vary systematically with whole-rock K/Rb value (Shearer *et al.* 1987a, Duke *et al.* 1992). The tourmaline- and biotite-bearing granites also appear to be distinctly different in Ba and Sr (Fig. 5).

The wide variation of K₂O, Rb, and Ba within an individual intrusion results from layering in the granite defined by the pronounced modal variation in K-feldspar and plagioclase. The whole-rock composition of samples collected within a single intrusion lies along a join between low-K₂O, -Ba, -Rb components (albite and quartz) and high-K₂O, -Ba, -Rb components (K-feldspar and muscovite) (Figs. 3, 5 insert). This modal variation within individual intrusions creates interpretive problems of whole-rock compositions. Based on both K-feldspar data and whole-rock data (with selected K₂O concentrations), intrusions making up the Harney Peak Granite define a single trajectory, with biotite granite plotting at the high-Ba - low-Rb portion of the trajectory, and tourmaline granite plotting at the low-Ba - high-Rb portion of the trajectory (Fig. 6). We interpret this trajectory as representing a "general" path of fractional crystallization for the central granite complex.

Based on evidence from stable and radiogenic isotopes, Nabelek *et al.* (1992a, b) and Krogstad *et al.* (1991, 1992) suggested that the tourmaline-bearing granite and biotite-bearing granites represent magmas produced by partial melting of two distinct sources. The following points argue against an interpretation of the biotite- and tourmaline-bearing granites as representing two distinct batches of magma: (1) field observations in the Harney Peak Granite suggest that biotite and tourmaline may occur within the same intrusion; (2) mineralogical

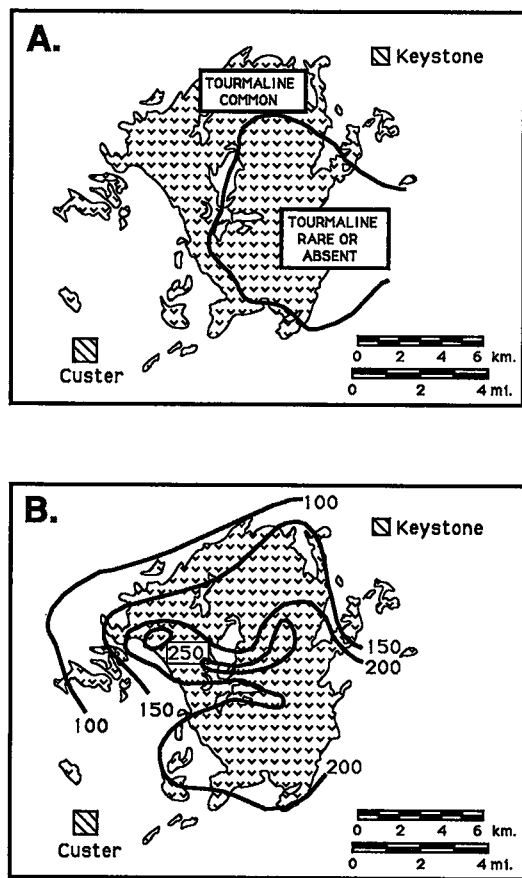


FIG. 4. A. Distribution of tourmaline in the Harney Peak Granite. B. K/Rb variation in the Harney Peak Granite.

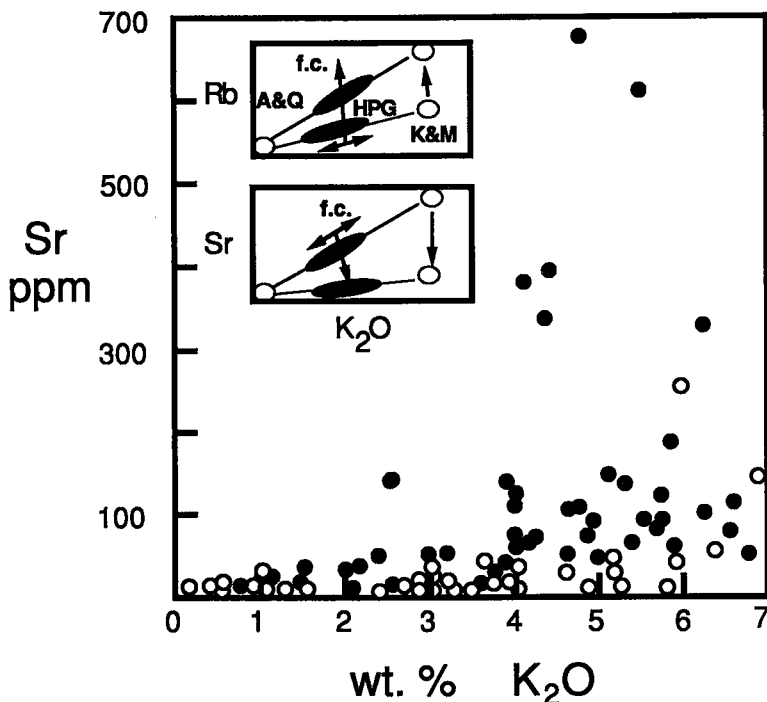


FIG. 5. Plot of Sr versus K_2O for whole-rock compositions of the Harney Peak Granite. Tourmaline-bearing (open points) and tourmaline-absent (closed points) lithologies define separate compositional regions; the data are from Shearer *et al.* (1987a) and Nabelek (1992a, b). Ba shows the same relationship. Inserts illustrate the effect of crystallization prior to and following emplacement of magma on compatible (Sr) and incompatible (Rb) element behavior in the granitic magma. K-feldspar (K), muscovite (M), albite (A), and quartz (Q).

and chemical data indicate a compositional continuum from the primitive biotite granite to the tourmaline granites (Figs. 5, 6), and (3) Taylor *et al.* (1979) observed that extensive isotopic exchange can occur between granitic magma and host rock. This exchange is dependent upon such variables as the dimensions of intrusion, distance travelled by the magma (integrated volume-ratio of country rock versus magma), and degree of volatile saturation prior to crystallization. Field observations indicate that granites along the perimeter of the Harney Peak Granite assimilated higher volumes of host rock, had a higher integrated ratio of country rock to magma, and may have reached volatile saturation earlier than magmas in the interior of the granitic complex. Most likely, the granitic intrusions making up the central Harney Peak complex represent compositionally similar batches of granitic melt. These were magmas derived by the partial melting of metasedimentary packages that contained varying proportions of Archean and Proterozoic lithologies. These mag-

mas crystallized to produce a continuum of biotite- and tourmaline-bearing granites.

ZONING IN THE PEGMATITE FIELD

Černý *et al.* (1981), Černý (1982), Trueman & Černý (1982), and Černý & Brisbin (1982) have defined geochemical zoning in the Birse Lake and the Rush Lake pegmatite groups in Manitoba based on K/Rb ratios of blocky K-feldspar. They concluded that those pegmatites that are extremely enriched in incompatible elements and exhibit textural diversity among bodies are located the furthest from the central fertile granite. The actual distribution is dependent upon structural history, thermal history, and geometry of the fertile granite body.

Based on contours constructed from 70 data points, each representing a single pegmatite, the trace-element characteristics of the K-feldspar of the Harney Peak pegmatite field define both a broad zonation of the pegmatite field and local compositionally distinct swarms of pegmatites.

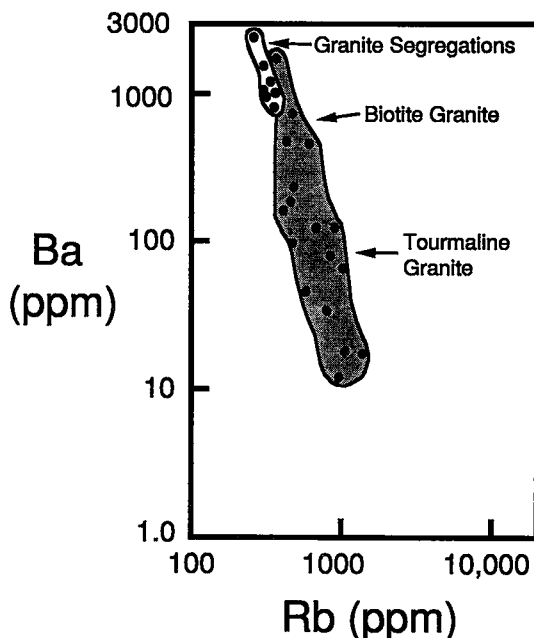


FIG. 6. Plot of Ba versus Rb for K-feldspar from the various textural units of the Harney Peak Granite. Also included are data on K-feldspar from granitic segregations in the surrounding country-rock. Each point for the granite represents an average result of five feldspar analyses in an intrusion. Each point for the granite segregations represents a single K-feldspar sample.

Pegmatites with K-feldspar relatively high in Ba (>140 ppm), K/Rb (>150), and Rb/Cs (>20) are distributed in regions having a high density of pegmatites (>200 pegmatites per 2.6 square km). Highly evolved pegmatites with K-feldspar low in Ba (<60 ppm), K/Rb (<50) and Rb/Cs (<10) are distributed in regions with a low density of pegmatites (<100 pegmatites per 2.6 square km) along the perimeter of the pegmatite field (Fig. 7). Within this broad regional zonation, swarms of compositionally distinct pegmatites are distinguished in the northwestern region [Cs-enriched; Rb/Cs <3] and southern region [Rb-enriched; K/Rb <50] of the pegmatite field.

COMPOSITIONAL COMPARISONS BETWEEN GRANITE AND THE SURROUNDING PEGMATITES

As shown in Figures 6 and 8, the K-feldspar from the Harney Peak Granite defines a compositional continuum that exhibits a wide compositional range for Ba (2000 to 10 ppm) and a more limited range for Rb (300 to 1500 ppm). The K-feldspar from pegmatitic segregations in the high-grade metamor-

phic region of the southern Black Hills (K-feldspar – sillimanite) (Shearer *et al.* 1987a, Faircloth 1988) plot at Ba concentrations (700–3000 ppm) overlapping or higher than the Harney Peak Granite. These various pegmatitic segregations are a product of metasomatism and metamorphism followed by melting (Shearer *et al.* 1987b, Faircloth 1988).

A majority of the pegmatites sampled in this study show an overlap of Ba–Rb in K-feldspar with that in the Harney Peak Granite. Examples of several of the better documented pegmatites are shown in Figure 8. These pegmatites generally occur in regions of high density of pegmatite bodies (>100 pegmatites per 2.6 square km). Pegmatites that plot within the low-Ba and high-Rb portion of this compositional group (*e.g.*, Diamond Mica pegmatite) occur in areas in which the pegmatite density is less than 100 pegmatites per 2.6 square km. In this group of pegmatites, the K-feldspar shows a limited range in Cs (<150 ppm), and the coarse-grained muscovite has concentrations of Rb less than 2500 ppm, Cs less than 100 ppm, F between 0.3 and 0.6 wt.%, and Li between 200 and 500 ppm (Fig. 8). Like the granite making up the central complex, pegmatite intrusions with the highest concentrations of Ba tend to have accessory biotite, whereas intrusions with lower concentrations of Ba have accessory tourmaline. Compared to the biotite of the Harney Peak Granite, the Fe/(Fe+Mg) of the biotite in the wall zones of the pegmatites tends to be variable and probably reflects the influence of host-rock contamination (Shearer *et al.* 1986a). Concentrations of trace elements in the biotite from the Harney Peak Granite (HP) and the wall zone of pegmatites (PWZ) in this overlapping group are as follows: Li: 1000–3500 ppm (HP), 600–3000 ppm (PWZ); Rb: 800–1600 ppm (HP), 600–2500 ppm (PWZ); Cs: 90–170 ppm (HP), 8–260 (PWZ). Although values of Rb/Cs (3–8), Rb/Li (0.31–0.83) and Rb/F (0.17–0.09) in the biotite are similar in most granite and pegmatites within this group, there are local variations in the homogeneous and layered pegmatites in the region of high density of pegmatites ($6.0 < \text{Rb/Cs} < 21.5$, $0.7 < \text{Rb/Li} < 1.4$, $0.41 > \text{Rb/F} > 0.22$).

The pegmatite bodies within the group that overlaps with the Harney Peak Granite are homogeneous to moderately zoned. All have wall zones consisting of plagioclase + quartz + muscovite $\pm$ K-feldspar assemblages. The dominant assemblage within each pegmatite is quartz + perthite + plagioclase. Much of the zoning observed is a result of vertical changes in the modal mineralogy of this mineral assemblage. This feature has been documented in numerous studies by Černý, Jahns and Norton. Quartz ($\pm$ K-feldspar) “cores”, pods and fracture-filling units

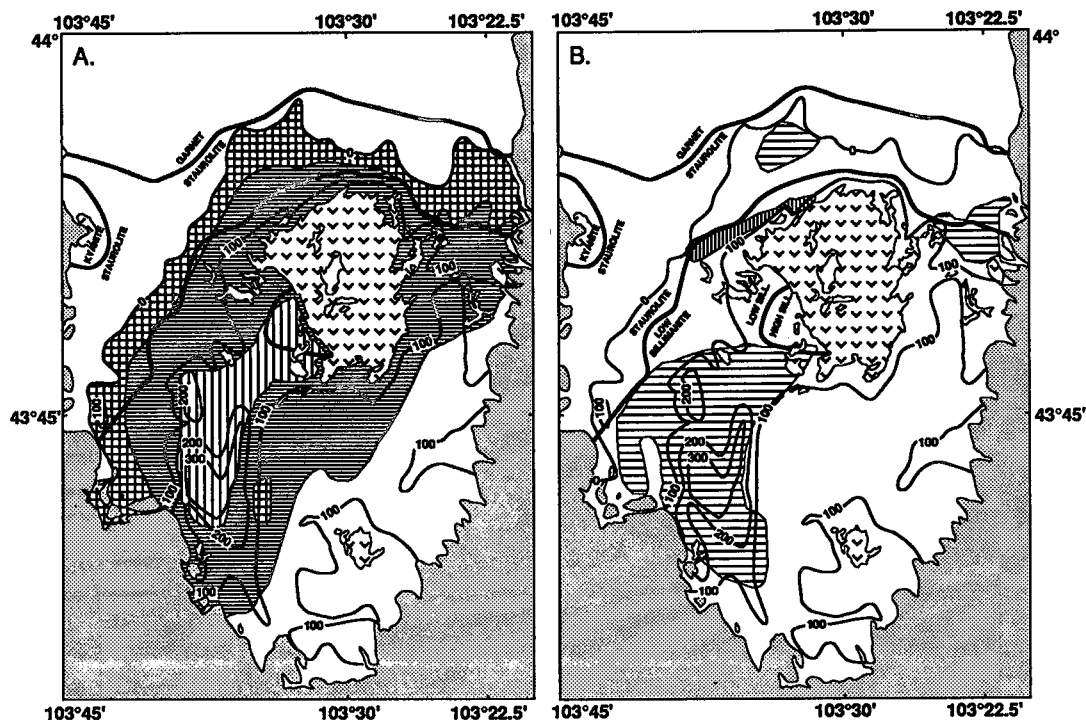


FIG. 7. A. K/Rb in K-feldspar contoured for the pegmatite field surrounding the Harney Peak Granite. Data points shown in Figure 2. Pegmatites with the lowest K/Rb are patterned in vertical lines, highest K/Rb are shown in cross-hatched pattern and intermediate K/Rb are horizontal lines. B. Rb/Cs in K-feldspar contoured for the pegmatite field surrounding the Harney Peak Granite. Pegmatites containing K-feldspar with Rb/Cs of less than 5 are patterned in vertical lines. Rb/Cs values greater than 25 are patterned in horizontal lines.

have been documented in some of these pegmatites. Fe-Mn phosphates and beryl are common accessory minerals. Beryl was of economic importance in some of the high-Rb and low-Ba pegmatites (Big Chief, Barker-Ferguson). Volumetrically small (<0.5%) quartz-spodumene fracture-filling units occur in only three of these granite-pegmatite intrusions (Soda Spar, Sky Lode, Barker-Ferguson). These intrusions plot at the high-Rb and low-Ba portion of this compositional group.

In many zoned pegmatites, the K-feldspar's composition is displaced toward higher Rb relative to the "Harney Peak Granite trajectory" (Fig. 8). These zoned pegmatites occur between the 100 and 0 pegmatite-density contour. Those pegmatites that contain feldspar whose Rb concentrations is furthest displaced from the Harney Peak Granite group commonly contain Li-Al silicates or Li-Al phosphate-bearing mineral assemblages (e.g., Dewey, Etta, Tin Queen, Tin Mountain pegmatites). Pegmatites with intermediate concentrations of Rb in their K-feldspar contain Li-Al

silicates and phosphates at low Ba concentrations (e.g., Peerless Hugo, Bob Ingersoll). As observed on Ba-Rb plots, the Rb-enriched pegmatites commonly are biotite-bearing at high concentrations of Ba and tourmaline-bearing at low concentrations of Ba (Fig. 8). In the pegmatites extremely enriched in Rb and Li, tourmaline is absent or rare in both the pegmatites and surrounding country-rock. Compared to the pegmatites that overlap the Harney Peak Granite on Ba-Rb diagrams, the Rb-enriched pegmatites have K-feldspar enriched in Cs (300–1200 ppm), and sheet silicates enriched in F (coarse-grained muscovite: 0.58–1.01 wt.%, biotite: 1.0–2.3 wt.%) and Li (coarse-grained muscovite: 500–800 ppm) (Fig. 8). Along a single Rb-enrichment trajectory (decreasing Ba), a variety of compositional, mineralogical and textural changes occur: (1) an increase in Cs concentrations in K-feldspar (300–1200 ppm), (2) an increase in Li and F in coarse-grained muscovite (Li: 500 to 8000 ppm; F: 0.58 to 1.01 wt.%), (3) contacts between mineral

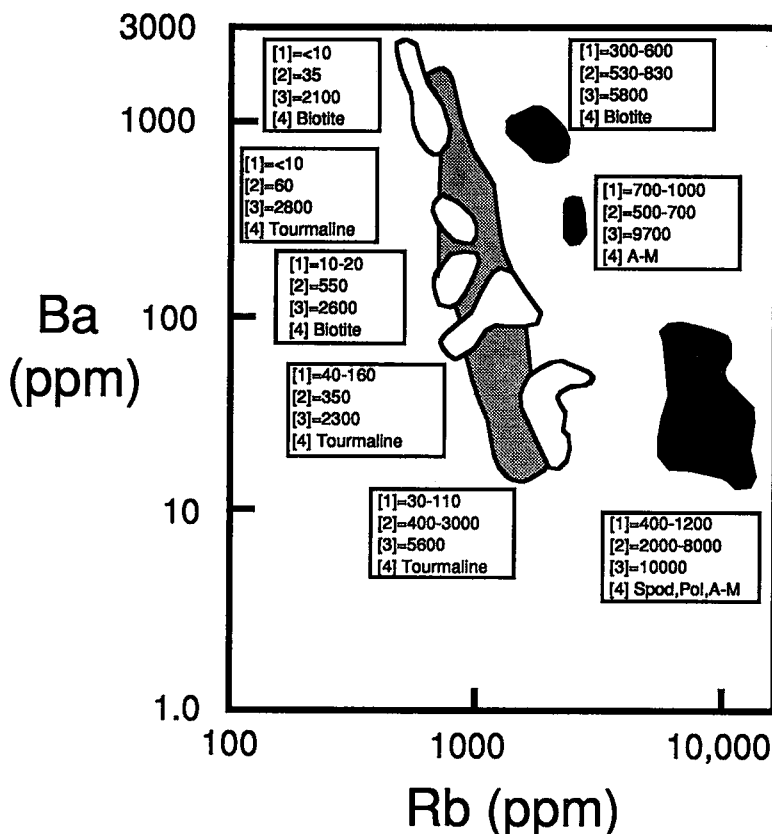


FIG. 8. Plot of Ba versus Rb for K-feldspar from selected pegmatites, illustrating the compositional overlap (open) and displacement of the pegmatites relative to the Harney Peak Granite. Additional data presented in the diagram are Cs content of the K-feldspar [1], F and Li in muscovite [2, 3] and noteworthy minerals that may occur in each pegmatite [biotite, tourmaline, Li-Al phosphates (A-M), spodumene (Spod) and pollucite (Pol)] [4]. All chemical data are in parts per million.

zones become sharper and less gradational, (4) the quartz + perthite + plagioclase assemblage increasingly becomes vertically segregated into perthite + quartz and plagioclase + quartz subzones, (5) Li-Al silicate assemblages (>10% spodumene $\pm$ lepidolite) become volumetrically larger (Tin Queen: absent; Tin Mountain: 30 to 40 vol.%), (6) replacement features involving fine-grained lithian mica become more common, and (7) aggregates of albite ("cleavelandite" habit) become more common.

Using feldspar chemistry as previously outlined, the range of bulk-pegmatite Rb and Ba concentrations was calculated. In addition, bulk concentrations of Li for a series of pegmatites were calculated using estimates of modal abundance of spodumene, amblygonite, and muscovite and the concentration of Li in each mineral phase. Figure 9A shows a

Rb-Ba trajectory of the Harney Peak Granite plus several of the pegmatites that overlap with that trajectory, and a trajectory defined by several of the most Rb-enriched pegmatites, which contain Li-Al silicate and Li-Al phosphate. Numerous other zoned pegmatites define a continuum of intermediate trajectories. In Figure 9B, the Rb-Ba trajectories are further subdivided to indicate "families" of paths of Rb, Li, Ba fractionation.

An array of magma-evolution paths for a series of parental melts having constant Ba and variable Rb and Li were calculated based upon approximate composition of the 4-kilobar pseudoternary minimum melt (31% quartz + 43% albite + 22% orthoclase + 4% muscovite) (Von Platen 1965), and K_D values for that proportion of phases (Rb: 0.43, Ba: 5.9, Li: 0.074; Walker *et al.* 1989). The calculations assume a Rayleigh fractional crystal-

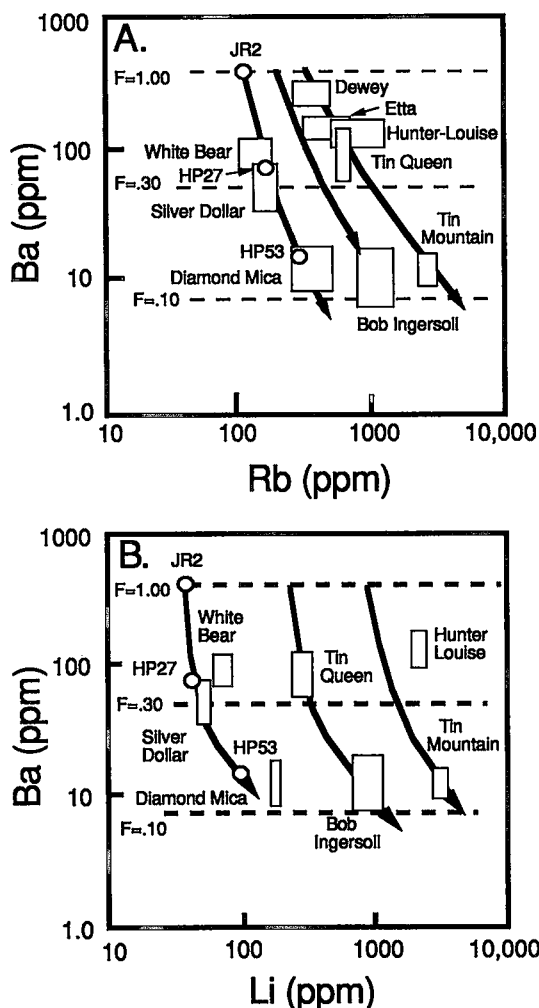


FIG. 9. A. Plot of Ba versus Rb for calculated bulk-compositions of selected pegmatites. Bulk compositions are calculated graphically from Figure 3. Superimposed upon this plot are a fractional crystallization trajectory calculated for the Harney Peak Granite (JR2, HP27, HP53), a possible trajectory of fractional crystallization for the Rb-enriched pegmatites (Dewey, Etta, Tin Queen, Hunter-Louise, Tin Mountain), and values for the extent of fractional crystallization (F = magma remaining during crystallization). B. Plot of Ba versus Li for calculated bulk-compositions of selected pegmatites. Superimposed are possible trajectories of fractional crystallization.

lization model [$C_L/C_o = F^{D-1}$ (Neumann *et al.* 1954)]. A constant Ba was selected at 400 ppm because that is the uppermost limit for the primitive Harney Peak Granite. Results from this modeling indicate that the range of pegmatite compositions

may be produced by different degrees of fractional crystallization (0–90%) of parental granitic melts that show a range of Rb (100–400 ppm) and Li (50–1000 ppm) (and probably Cs) concentrations. The Harney Peak Granite and a very large volume of pegmatites (*cf.* Figs. 6, 8, 9) appear to be derived by the fractional crystallization of parental granitic magmas of similar bulk composition. The more exotic (Rb-, Li-, Cs-enriched) and volumetrically less common pegmatites may be modeled as being derived from parental melts with a higher alkali element content.

Do zoning characteristics vary along these fractional crystallization trajectories? What is the origin for the enrichment in alkalis in the parental granitic magmas?

RELATIONSHIPS BETWEEN PEGMATITE CHEMISTRY AND ZONING CHARACTERISTICS

The zoned pegmatites associated with the Harney Peak Granite have a remarkable variability of zoning characteristics that may be unparalleled in other pegmatite fields (Norton & Redden 1990). Based upon zoning characteristics, mineralogy and economic commodities, Norton & Redden (1990) classified the zoned pegmatites in this field into seven different categories. A summary of their classification follows:

Category 1. The distinguishing characteristic of these pegmatites is the high concentrations of muscovite in a wall zone of quartz + sodic plagioclase. Some may have a quartz core and as many as three inner zones (examples: November, Victory, Dewey, Warren Draw).

Category 2. Differs from category 1 only by having perthite + quartz + sodic plagioclase in the wall zone (examples: Ruby Reef, White Bear, Silver Dollar).

Category 3. This type of pegmatite consists of an intermediate or core zone rich in large crystals of perthite. The wall zone is thin and commonly sparse in mica relative to categories 1 and 2 (examples: Dan Patch, Diamond Mica, Barker-Ferguson).

Category 4. This type of pegmatite is similar to Category 3, but has inner zones with Li-rich minerals like amblygonite-montebasite, spodumene, lithian muscovite (examples: Hugo, Bob Ingersoll 1).

Category 5. These pegmatites contain spodumene. They may be similar to Category 4, but have volumetrically larger spodumene-bearing assemblages (examples: Etta, Tin Mountain, Beecher).

Category 6. These pegmatites contain abundant beryl and muscovite in the inner portion of the wall zone or in the first intermediate zone. Similar to Category 4 and 5, but less abundant perthite zones

than 4 and less Li mineralization than 5 (examples: Peerless, High Climb).

Category 7. These pegmatites are quartz-rich, with cassiterite mineralization (example: Cowboy, Mohawk). This type of pegmatite tends to be concentrated to the northwest of the main body of the Harney Peak Granite, in the Hill City area. The pegmatites of categories 4–7 are enriched in Li, Nb, Ta, Be, Cs, Rb, Sn and may be appropriately classified as rare-element pegmatites. How are these pegmatite categories related to each other?

One of the noticeable similarities among the bulk composition of these pegmatites is that all groups overlap near the granite minimum in the albite – orthoclase – quartz pseudoternary system (Fig. 7 of Norton & Redden 1990). Only the quartz-rich, cassiterite-bearing pegmatites (Category 7) are displaced away from the granite–pegmatite population toward the quartz apex. This clustering of the pegmatites around the albite – orthoclase – quartz minimum is somewhat deceptive. The Li-mineral-bearing pegmatites contain up to 8000 ppm Li. These bulk compositions do not lie in the albite – orthoclase – quartz plane, but within the albite – quartz – eucryptite system (Stewart 1978). The textural–mineralogical groups must plot along paths of crystallization within these systems. We suggest that these paths are slightly different for different parental granitic magmas and that there is a general progression of zones along each path.

Approximate bulk compositions of the pegmatites indexed to the categories proposed by Norton & Redden (1990) are plotted in terms of Rb and Ba in Figure 10. Most of the textural groups of pegmatite define coherent compositional groups (layered or “unzoned” pegmatites, categories 2, 3, 4, 5, 6), whereas group 1 (mica pegmatites) is compositionally much more variable. The wide dispersion of the sheet muscovite pegmatites (Category 1) may reflect the dependency of mineable muscovite on the configuration of the pegmatite – country rock contact rather than bulk pegmatite composition [November (Category 1): estimated bulk Rb = 250 ppm, Ba = 20 ppm, Li = 200 ppm; Dewey (also Category 1): estimated bulk Rb = 400 ppm, Ba = 320 ppm, Li = 600 ppm]. The largest concentrations of muscovite are in rolls in the contact on the hanging-wall side of the pegmatite (e.g., Crown pegmatite; see Page *et al.* 1953, Norton & Redden 1990). These rolls in the contact zone may have acted as a structural cavity that concentrated volatile components and muscovite.

Based upon fractionation trends illustrated in Figure 9, mineral chemistries (e.g., F in micas) and mineral assemblages (lepidolite *versus* spodumene, Sn mineralization *versus* Nb–Ta mineralization), we have suggested several general petrogenetic

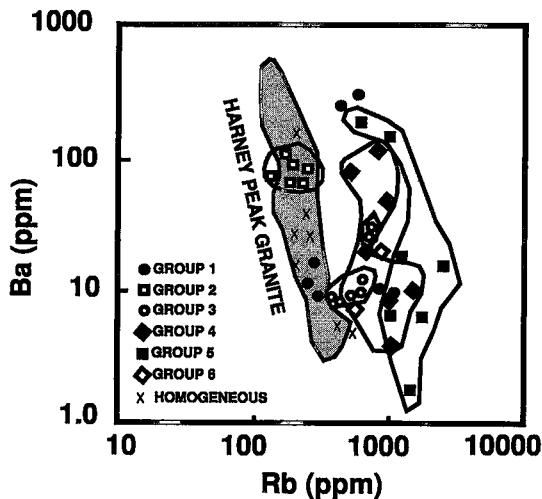


FIG. 10. Average compositions of pegmatites sampled in this study, indexed to categories from Norton & Redden (1990). Also included is the range of Harney Peak Granite determined from bulk-rock compositions (within the 3.5 to 5.4 wt. % K_2O range) and K-feldspar reconstructions of bulk compositions.

scenarios that may relate some of the different textural types with the composition of the bulk magma and extent of fractional crystallization (Fig. 11). Within this petrogenetic flow-diagram, the same zoning category may occur along different fractional crystallization trajectories. The sequence generally reflects the effect of volatile constituents and extent of fractional crystallization.

Superimposed upon the Harney Peak Granite trajectory in the plot of Rb *versus* Ba are homogeneous, layered, and zoned pegmatites. Although lying in the Harney Peak Granite trajectory, these pegmatites possess distinct textural characteristics. A slightly higher content of H_2O [in addition to B, P, F (London 1990, 1991)] in the magma from which these pegmatites crystallized may result in dramatic changes in silicate-melt equilibrium, crystallization kinetics, material transport and efficiency of processes of concentration of trace elements (Jahns & Burnham 1969, London 1990, 1991). A possible compositional trajectory for zoned pegmatites whose bulk composition overlies that of the Harney Peak Granite, but whose volatile budget may be slightly different, is [Category 2] → [Category 1] → [Category 3] → [Category 3 with spodumene fracture-filling units] → [Category 6 with minor lithium mineral assemblages]. Within this sequence, apatite and Fe, Mn phosphates are common, whereas Li, Al phosphates are extremely rare. Other possible

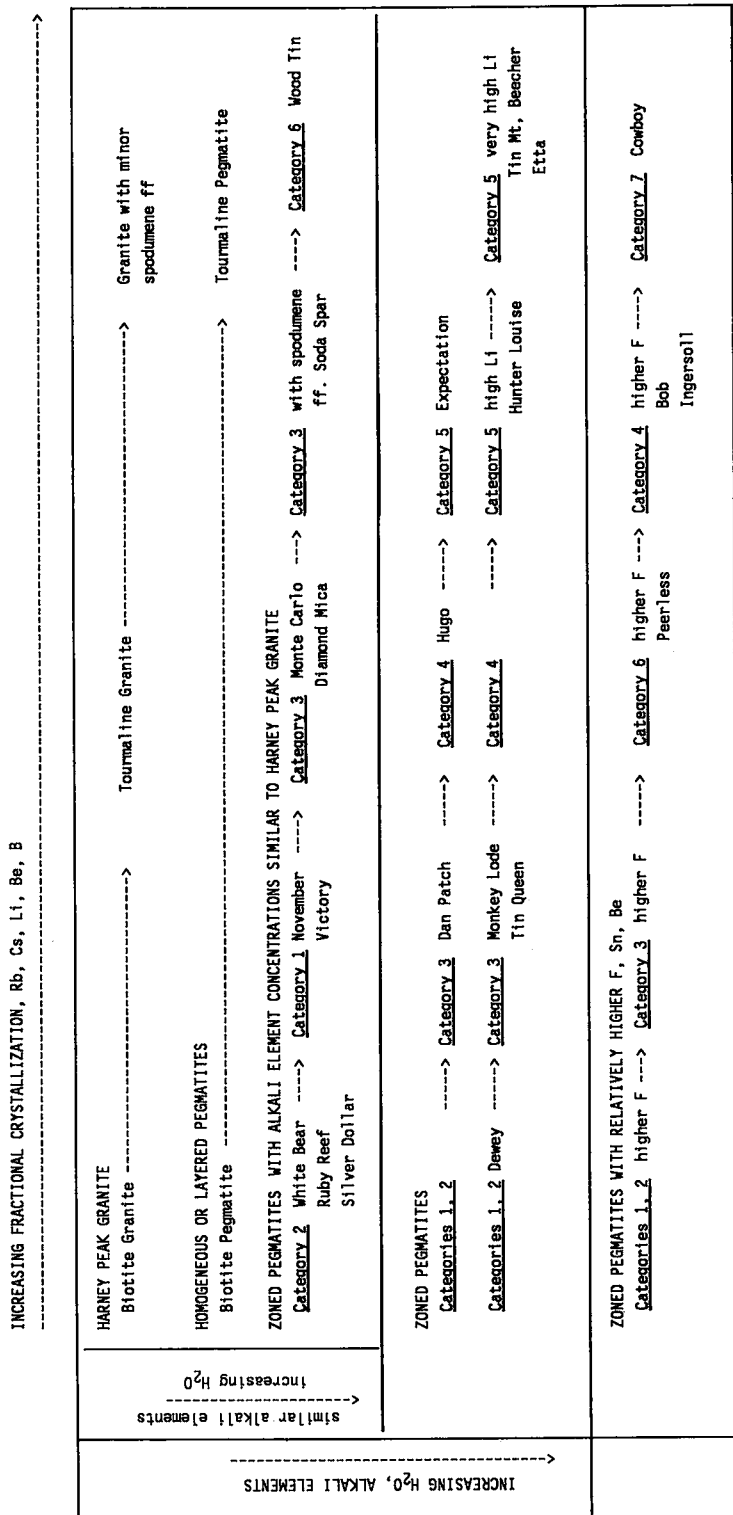


Fig. 11. A flow diagram relating fractional crystallization to textural types of pegmatites.

textural characteristics and petrogenetic relationships are illustrated in Figure 11.

One particular group of pegmatites is represented by a chemical trajectory that has higher F than the other pegmatites. Pegmatites included in this group are the Peerless, Bob Ingersoll and the quartz-rich, cassiterite-bearing pegmatites (Category 7). The pegmatites within this trajectory appear to have numerous lines of mineralogical evidence to suggest higher concentrations of F: abundant Sn mineralization (Spilde & Shearer 1992, Černý & Ercit 1985, Norton & Redden 1990, Dietrich 1968, Collins *et al.* 1982), Fe-Mn trajectories of Nb-Ta oxides (Spilde & Shearer 1992, Černý & Ercit 1985), lithian mica stability (London 1982), mineral assemblages (Norton & Redden 1990, Manning *et al.* 1980, Manning & Pichavant 1985), F concentration of amblygonite-montebrazite (Loh & Wise 1976), abundant Be and U mineralization (Roberts & Rapp 1965, Page *et al.* 1953, Norton & Redden 1990, Dietrich 1968, Collins *et al.* 1982), and F-enriched silicates in the exomorphic halos (Shearer *et al.* 1986b).

ALKALI ENRICHMENT OF PARENTAL GRANITES

Our data suggest that the Harney Peak Granite and associated pegmatites were generated by the fractional crystallization of various parental granitic magmas with substantially different alkali element characteristics. How are these compositionally diverse parental magmas produced? The models for the generation of the parental magmas can fit into three end-member categories: (1) partial melting of a compositional range of primary metasediments, (2) partial melting of altered (metasomatized) metasediments, and (3) varying degrees of partial melting of a "single" primary composition of metasediment. The following discussion explores these types of models and their relevance to generation of rare-element-enriched magmas.

Partial melting of metasedimentary rocks

Duke *et al.* (1990) assembled a data-base of compositions (major and trace elements) of metasedimentary rocks (quartz $\pm$ plagioclase $\pm$ K-feldspar $\pm$ muscovite $\pm$ biotite) of the Black Hills Precambrian from Tuzinski (1983), Shearer *et al.* (1986b, 1987b), Faircloth (1988), DeWitt *et al.* (1986), Redden (1968) and Galbreath *et al.* (1987). Compositional variations in terms of trace elements within this suite are large: Rb: 130–640 ppm, Ba: 340–1040 ppm, Li: 30–100 ppm. To evaluate the possible range of magmas produced by partial melting of compositionally varied metasedimentary rocks, we calculated the Rb, Ba

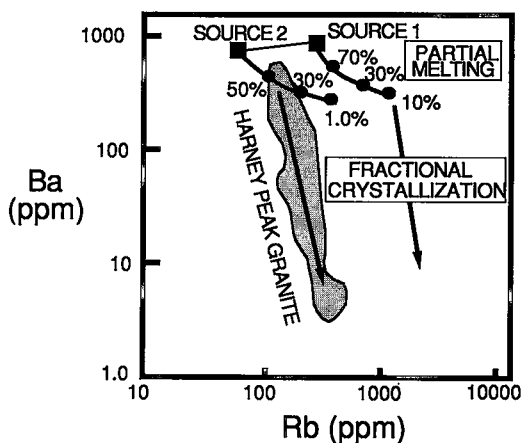


FIG. 12. Ba versus Rb ($Rb \approx Li \approx Cs$) plot showing the compositions of melts derived by batch melting of a series of metasedimentary rocks from the Black Hills. Possible trajectories of fractional crystallization of the "primary granitic magmas" produced by partial melting also are illustrated.

and Li contents of magma produced by batch melting. We assumed a near-constant concentration of Ba, varied bulk Rb and Li concentrations of metasediments with a single residual mineral assemblage, and variable degrees of partial melting. We selected residuum assemblage 4 of Walker *et al.* (1989) (35% quartz, 15% albite, 10% K-feldspar, 20% sillimanite, 20% garnet, with a K_D^{Rb} of 0.037, a K_D^{Li} of 0.02 and a K_D^{Ba} of 0.64) which, according to these authors, produced the largest range in trace alkali-element concentration in calculated granitic melts. As shown in Figure 12, at a constant degree of partial melting, differences in concentration of trace elements in sedimentary lithologies subjected to melting cannot alone account for the compositional variation in the parent granitic magmas. In addition, the upper limits for Li and Rb taken from the literature (source 1 in Fig. 12) exceed the range of alkalis for other Precambrian metasedimentary rocks reported by Taylor & McLennan (1985) and for the background values ($Li < 50$ ppm, $100 < Rb < 200$ ppm) calculated by Tuzinski (1983) based on 300 samples of Black Hill metasedimentary rocks. The high alkali-element values reported in the literature may be a function of alkali-element metasomatism (Norton 1984).

Partial melting of metasomatized metasedimentary rocks

Is it possible that metasomatically enriched

metasedimentary rocks could be a source protolith for some of the alkali-enriched magmas? Stewart (1978) and Shearer *et al.* (1987a) noted that the melting of metasedimentary protoliths enriched in rare alkalis (Li, Rb, Cs) could potentially produce Li- and Rb-enriched granitic melts. Metasomatism has enriched the metasedimentary rocks surrounding many pegmatites in rare-alkali elements (e.g., Li and Rb concentrations as high as 2600 ppm and 1100 ppm, respectively: Shearer *et al.* 1986b, Tuzinski 1983). Walker *et al.* (1989) argued that these alkali-enriched rocks were localized around individual pegmatites and were, therefore, too small in volume to be important in producing alkali-enriched granitic melts. Numerous other studies (Tuzinski 1983, Norton 1984, Faircloth 1988) have shown that this alkali enrichment is not a local phenomenon, but is related to a larger hydrothermal-metasomatic system that permeated the metasedimentary units surrounding the Harney Peak Granite.

Within this type of model, the compositional diversity in the granitic magma is produced in a sequence of events: STAGE [1]: during the emplacement of the primitive, biotite-bearing granites and products of fractionation, the associated hydrothermal system enriched the adjacent metasedimentary rocks in alkali elements. STAGE [2]: the rare-alkali-enriched metasedimentary rocks were then either tectonically transported into the zone of melting by downwarping along major F2 folds (Redden *et al.* 1990) or upwarping of isotherms moved the zone of melting to higher crustal levels. STAGE [3]: continuous "conveyor belt" processing *via* melting of the metasomatized metasedimentary rocks produced a broad compositional spectrum of alkali-enriched granitic melts.

Several lines of evidence contradict this type of model for the Harney Peak Granite. The alkali-rich granites and alkali metasomatism are more closely associated with the post-F2 domal structure resulting from the emplacement of the granite. In addition, the downwarping event (F2) may be closer to 1.84 Ga rather than the 1.7 Ga age of the granite (Redden *et al.* 1990). Also, the transport of volatiles and alkali elements out of the granitic system would have followed final emplacement or would have, at the very least, resulted in crystallization of the granite and retardation of the movement of the granitic magma. Regions of emplacement probably did not experience pressure and temperature regimes that would have resulted in the production of granitic melts.

Varying degrees of partial melting

A third alternative is that these compositionally diverse Harney Peak "parental" magmas are a

product of either differing degrees of partial melting of appropriate metasedimentary compositions (Fig. 12) or changing mineral assemblages in the residuum during episodes of partial melting (Fig. 13). Using a variety of modal mineralogies for the residuum, Walker *et al.* (1989) demonstrated that different degrees of partial melting of numerous mineral assemblages of similar trace-element composition would produce melts with a wide range of trace-element signatures. Although the partial melting trajectories of Walker *et al.* (1989) overlap with the bulk composition of some pegmatites, they concluded that the more evolved pegmatites could not be produced by simple partial melting. However, their models are capable of producing a wide variety of "parental" granite melts that could then fractionate to produce the demonstrated arrays of pegmatite compositions. Mineral assemblages in the residuum having minimal amounts of biotite or muscovite have the capability of producing melts with the widest range of alkali element chemistry at near-constant concentrations of Ba. An example of the role of biotite in the residuum assemblage is illustrated in Figure 13.

High degrees of partial melting (40%) will produce increasingly larger volumes of granitic melt with lower concentrations of rare-alkali elements. Smaller degrees of partial melting (0.1–5%) of typical sedimentary compositions will generate granitic melts capable of producing exotic granitic melts (similar to Tin Mountain: Walker *et al.* 1989) with moderate degrees of fractional crystallization (70–80%) (Fig. 12). The smaller volumes of rare-alkali-enriched melts predicted by this model are in agreement with the observed statistical rarity of zoned pegmatites (approximately 2% of all pegmatites) and spodumene-bearing pegmatites (less than 0.1% of all pegmatites) in the Harney Peak Granite pegmatite field (Norton & Redden 1990). The production of a variety of melts with a range of degrees of partial melting (Fig. 12) requires either production of more exotic melts in separate subsystems prior to or after the major episode of emplacement of the Harney Peak granite (high degrees of partial melting producing large volumes of granitic melt) or in a lower-temperature subsystem peripheral to the zone of extensive melting.

Two problems exist with this model: (1) Can small amounts of melt be extracted from the zone of melting? (2) If small degrees of partial melting are the only requirement to produce these exotic melts, why are they compositionally distinct from remnants of failed extraction of melt (migmatites)?

In this model, the compositional array of parental melts (high-Ba) represents a continuum of

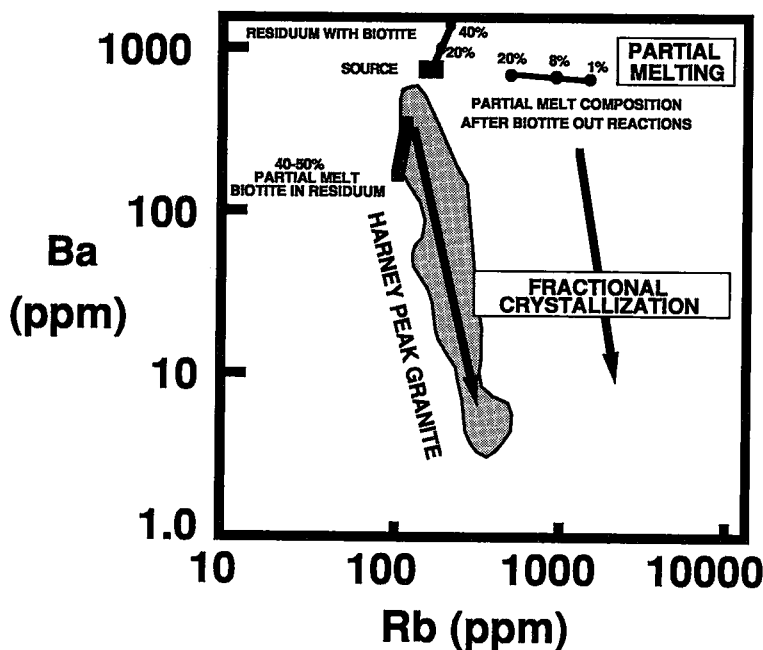


FIG. 13. Ba versus Rb plot showing the composition of melts produced by batch melting of a single rock composition with a biotite residuum. Also illustrated are the paths of solid compositions for a residuum (with biotite) during partial melting and of the melt compositions produced upon biotite dehydration and remelting of residuum.

melting, from voluminous low-alkali, high-Ba melts to much smaller volumes of alkali-element-enriched melts in subsystems along the perimeter of the main zone of melting. The extraction of melt from the source is dependent upon such variables as viscosity of melt, stress gradients related to local tectonic environment, and permeability, which is partially dependent on porosity (volume of melt fraction). Considering equal values for viscosity and stress gradient, the extraction rate for a 30% partial melt is approximately 6500 times greater than a 2% partial melt (Spera 1980). The efficiency of extraction for small amounts of silicate melt may be improved by decreasing viscosity of the melt or increasing the stress gradient. An increase in H_2O content of the granitic melt has been illustrated to dramatically decrease melt viscosity, from 10^{11} poises at $800^\circ C$ and 0% H_2O to 10^4 poises at $800^\circ C$ and 6% H_2O (McBirney 1984). A higher content of H_2O in the low-partial-melt fraction may be a consequence of enhanced silicate liquid - H_2O miscibility (Manning *et al.* 1980, London 1986b), low degree of partial melting (Manning & Pichavant 1985), or an influx of free fluid during

near-solidus melting (Lundgren 1966, Thompson 1982). A reduction in viscosity from 10^8 poises (2% H_2O) to 10^4 poises (6% H_2O) results in an effective efficiency of extraction of a 5% melt equivalent to a 40–50% partial melt (Spera 1980, equations 52 and 53).

Changes in the local stress-gradient also appear to be an effective means of extracting granitic melt from its protolith. An increase in the stress-gradient from 0.1 bars/km to 10 bars/km for a 10% melt fraction increases the extraction velocity equivalent to a volume fraction of melt of approximately 35% (Spera 1980, Table 6). A higher local stress-gradient within the low-melting subzones along the perimeter of the major zone of melting and doming may then be an effective means of extracting small amounts of exotic melt. Field and experimental studies (Bateman 1985, Dixon 1975) suggest the possibility of high strain in country rocks adjacent to the dome. In addition, previous fluid-flow studies suggest the possibility that as effective stresses approach zero, fluid permeabilities increase enormously (Spera 1980). The consequence would be an increase in melt extraction from the source.

It is apparent that the flow velocity of granitic melt can be effectively modified through increased volatile content or differential stress to efficiently extract small amounts (5–10% partial melt) of alkali- and volatile-enriched granitic melts from the source protolith. The mechanisms are also important for extraction of melt from crystal mush during extreme fractional crystallization. If the rate of segregation exceeds the rate at which diffusing elements enter the melt from the solid, trace-element equilibrium will not be attained. However, this mechanism would deplete, not enrich, the melt in rare alkali elements. Differences in the rate and efficiency of melt segregation may explain the compositional differences between migmatites and these small batches of rare-alkali-enriched magmas. It seems reasonable, therefore, to produce and extract small amounts of rare-alkali-element-enriched granitic magma from a source adjacent to zones of extensive production of granitic magma.

GENERATION OF FERTILE RARE-ELEMENT-ENRICHED GRANITIC MELTS

Understanding the possible variables (P, T, H₂O, bulk composition and mineral assemblage of protolith, and melting reactions) that may influence bulk composition and volume of magma generated during melting is important to any critical evaluation of the generation of rare-element-enriched granitic magmas in the crust. We review three aspects critical for the production of these fertile melts: (1) the possible compositions of the protolith, (2) the conditions of melting (reactions, T, P, melt characteristics and volume), and (3) mineral stabilities during melting.

The fertile granitic magmas represent a late-tectonic to post-tectonic emplacement of generally strongly peraluminous, near-minimum-melt magmas into an Abukuma-type regional metamorphic facies (Černý & Meintzer 1988). The P–T conditions recorded at the levels of emplacement for the Harney Peak Granite are a maximum of 680°C and 4 kbars (Shearer *et al.* 1985, Helms & Labotka 1991, Terry & Friberg 1990). However, an earlier high-pressure regional metamorphism of 7 to 8 kbars is suspected (Redden *et al.* 1982, Terry & Friberg 1990). The forcible style of emplacement observed in the Black Hills and other pegmatite fields and the general lack of extensive melting phenomena (Shearer *et al.* 1987b) indicate ascension of magma from depths below the level of emplacement. The only evidence for localized melting is the presence of small pods of pegmatite in high-grade metamorphic regions of the Black Hills (Shearer *et al.* 1987b, Faircloth 1988).

Anatexis of ultramafic and mafic protoliths has been suggested as a source for strongly

peraluminous granitic magmas (Kushiro & Yoder 1972, Helz 1976, Stern & Wyllie 1978, Cawthorn & Brown 1976, Zen & Hammarstrom 1982). However, factors such as high $\delta^{18}\text{O}$ [+8.1 to +14.1‰ for fertile rare-element granites in general (Černý & Meintzer 1988); +10.4 to +14.3‰ for the Harney Peak Granite (Shearer *et al.* 1984, Walker *et al.* 1986, Nabelek *et al.* 1992b)], high initial $^{87}\text{Sr}/^{86}\text{Sr}$ [~0.7143 for the Harney Peak Granite (Riley 1970, Shearer *et al.* 1984, Walker *et al.* 1986)], Pb isotopic compositions (Krogstad *et al.* 1991, 1992), low concentrations of Ca, Mg, and Fe, and trace-element signatures (for the Harney Peak Granite: Rb > 100 ppm; Sr < 100 ppm, Ba < 600 ppm, Rb/Ba > 0.25) are consistent with derivation by partial melting of a pelitic source (Miller 1985). These characteristics of the Harney Peak Granite and the ϵ_{Nd} (1711 Ma) for the Harney Peak Granite and adjacent Proterozoic metasediments (Walker *et al.* 1986) suggest that both Proterozoic and Archean metasediment lithologies were melted in various proportions to produce the Harney Peak granitic magma.

Scenarios for the generation of the fertile granitic magmas may be summarized within the context of the extensive studies of crustal melting processes (Winkler 1976, Abbott & Clarke 1979, Huang & Wyllie 1973, 1981, Thompson 1982, Thompson & Tracy 1979, 1982, Miller 1985). Critical factors in the extent and composition of melt produced by crustal anatexis are the composition of the protolith and the availability of water. Initial bulk composition will obviously influence mineral assemblage, modal abundance of minerals, and mineral assemblages in the residuum. In addition, the potential volume of melt produced is predetermined during the sedimentation process. Protoliths with bulk compositions and mineral properties coinciding with the eutectic composition will have the potential for generation of large volumes of eutectic melt (Thompson & Tracy 1982). The availability of H₂O and hydrates and the retention of H₂O in the zones of dehydration and melting partially dictate the extent of melting, the P–T conditions at which melting occurs, and the reactions influencing melting. Hyndman (1981) and Miller (1985) summarized scenarios involving possible melting reactions in the crust: (1) “wet solidus” melting, (2) melting accompanying muscovite dehydration, (3) melting accompanying biotite dehydration, and (4) anhydrous melting. These scenarios are summarized in the following discussion.

Scenario 1

Melting reactions at the “wet solidus” must be eutectic in character and must involve water saturation (Thompson 1982). Both dehydration of

a hydrate and a free fluid are necessary to saturate the melt (Lundgren 1966, Thompson 1982). Assuming that water-saturated melts at $P \geq 4$ kbars contain more than 10% H_2O (Wyllie 1977) and that high-grade metamorphic terranes typically contain less than 1% free water, Miller (1985) calculated that "wet solidus" melting would produce less than 10% water-saturated melt. The assemblage of restite minerals would include quartz + biotite + aluminous silicate $\pm$ plagioclase $\pm$ muscovite $\pm$ garnet $\pm$ cordierite (Miller 1985, Clemens 1984). Appreciably larger volumes of water-saturated melt could be produced if additional fluid was transported into the melting zone. Fluid-induced melting has been proposed for the origin of granites in central Nepal (Le Fort 1981) and Sweetwater Wash granite (Höisch & Hamilton 1990). Le Fort (1981) and Höisch & Hamilton (1990) interpreted chemical and isotopic data as supporting fluid release from underthrust crust. In a vapor phase composed of H_2O and CO_2 , H_2O can be transported along a potential gradient. Furthermore, H_2O may move from dehydration zones to melting zones or *vice versa* (Johannes & Holtz 1990). Fluid-induced disequilibrium melting produces melts with distinct major-element signatures (Brearley & Rubie 1990). The behavior of trace elements during this style of melting is unknown.

Scenarios 2 and 3

Muscovite and biotite dehydration reactions in the presence of quartz are divariant in nature, resulting in extensive P-T regions of dehydration (Fig. 1, from Hyndman 1981). The most efficient melting occurs in those P-T regions in the divariant fields where dehydration and melting reactions coincide (Thompson 1982). For example, at low P (less than 4 kbars), muscovite dehydration reactions may be offset from melting reactions by greater than 100°C. If the system is open to H_2O , the system may be desiccated prior to reaching the melting reactions (see Thompson 1982, for more detail). The presence of CO_2 will reduce the activity of H_2O , which results in changing the T of melting, the amount of H_2O available for melting, and the volume of melt produced.

Melting accompanying muscovite dehydration in a muscovite-rich lithology could generate approximately 10–15 wt% water-undersaturated melt (Miller 1985), whereas melting accompanying biotite dehydration is a more efficient melt-producing mechanism, yielding up to 25% water-undersaturated melt from a lithology containing 25% biotite (Miller 1985). The formation of these melts leaves behind an assemblage of residual minerals quartz + Al_2SiO_5 phase + K-feldspar +

plagioclase $\pm$ garnet $\pm$ biotite $\pm$ cordierite $\pm$ orthopyroxene (Thompson 1982, Miller 1985). The composition of these melts should be controlled by quartz – feldspar – liquid equilibria (Winkler 1976, Green 1976, Miller 1985) and the AFM mineral assemblage (Clemens & Wall 1981, Thompson & Tracy 1979, Green 1976, Dimitriadis 1978, Miller 1985). The melt will be saturated in the AFM phase present in the residuum assemblage. The melt will also contain 2–5% normative corundum if an Al_2SiO_5 phase is present in the residuum assemblage. Initial melts will not radically change in terms of major-element composition until temperatures approach 900°–1000°C because of the large dT/dX of the liquidus isotherms (Thompson 1982). Unlike "wet solidus" melting, influx of fluids into the melting zone will not increase the volume of H_2O -undersaturated granitic melt produced during dehydration melting because the dehydration melting reactions control the extent of melting and amount of H_2O in the melt (Thompson 1982). The combined effects of melting accompanying the dehydration of muscovite and biotite can effectively produce large volumes of melt (Miller 1985).

Scenario 4

Melting at the dry solidus to produce granitic melts requires extreme conditions of temperature (greater than 1100°C at 6 kbars for the Harney Peak Granite: Huang & Wyllie 1981) that generally exceed those of granulite-facies metamorphism (700° to 825°C: Bohlen & Essene 1977, Bohlen 1986). A slightly different style of dry melting may involve volatiles excluding H_2O . Defluorination of F-bearing biotite and F-bearing amphiboles at temperatures exceeding those of dehydration-melting reactions may provide volatiles capable of producing small amounts of melt. F-induced melting analogous to dehydration melting has been suggested as a process for generating topaz rhyolites (Christiansen *et al.* 1983).

Dehydration melting at the expense of biotite and muscovite at conditions of the kyanite–sillimanite facies appear to be the most efficient means of generating the water-undersaturated fertile, peraluminous melts. This melting will result in the production of homogeneous magmas (with regard to major elements). Quartz and feldspar will be the major components in the melting reactions. A sillimanite–kyanite-bearing residuum will result in a strongly peraluminous signature. The divariant nature and complexity of the dehydration-melting reactions (muscovite *versus* biotite) will control the volume of melt produced, the amount of H_2O in the melt and the trace-element characteristics of the magma. Neither "wet" nor "dry solidus" melting appears to be appropriate for the generation of

these melts. The higher content of H_2O in the granitic magma, as implied by the development of pegmatitic textures, only follows after ascent and extensive crystallization of the melt. Defluorination melting produces melts low in H_2O with peralkaline compositions. These may be similar to A-type granitic pegmatites (and not the Harney Peak Granite), which are enriched in Nb, Y, REE, Zr, U, Th, Ti, and F.

A characteristic trace-element signature of the rare-element-enriched fertile granitic magmas is their relatively high B_2O_3 , alkali elements, and H_2O concentrations. During partial melting, the behavior of these components should be controlled by the stability of tourmaline and sheet silicates in the source region. What is the stability of these phases during metamorphism? How do they dictate the trace-element signature of magmas during anatexis?

Although the bulk of the B in metasediments is carried by tourmaline, boron in sheet silicates (biotite, muscovite) and feldspar may reach concentrations of up to 300 ppm and 50 ppm, respectively (Shearer & Papike 1986). The non-detrital boron component may be added during sedimentation through absorption onto surfaces of clay minerals or substitution into structural sites of clay minerals or dolomite (Stubican & Roy 1962, Cody 1971, Lerman 1966, Eagar & Spears 1966) or by postdepositional movement of boron-rich fluids (Ethier & Campbell 1977, Shearer *et al.* 1986b, Černý & Meintzer 1988, Leeman *et al.* 1992). During low-grade metamorphism, the boron component of the clay surface or structure may be incorporated into metamorphic tourmaline, nucleate on the surfaces of detrital tourmaline, or be incorporated into sheet silicates. Boron behavior during partial melting will be controlled by the stability of either tourmaline or a sheet silicate.

The interpretation of tourmaline stability appears to be ambiguous. Based on field observations and experimental evidence, Robbins & Yoder (1962), Smith (1971), and Manning & Pichavant (1985) concluded that tourmaline would be retained in the residuum during partial melting. However, numerous studies of regional metamorphism have noted the disappearance of tourmaline under amphibolite-facies conditions (Grew 1988; D. London, pers. comm., 1991). In a survey of the geochemistry of boron in granulite terranes, Leeman *et al.* (1992) did not observe borosilicates and noted a decrease in B content from amphibolite grade to granulite-grade metamorphism. Experimental evidence suggests that tourmaline will break down incongruently between 600° and 775°C, leaving a residuum of cordierite + biotite + plagioclase + quartz + K-feldspar (Holtz & Johannes 1991; D. London, pers. comm., 1991).

Holtz & Johannes (1991) observed that except for Al, which is higher in the B-rich melts, the composition of the melts produced from the melting of tourmaline-bearing and tourmaline-absent lithologies are the same. On the basis of many of these recent observations, tourmaline should not be a residuum phase during extensive partial melting.

Alternatively, if B resides in sheet silicates, dehydration prior to melting results in either loss of B to the system or incorporation of B into high-temperature metamorphic phases (*i.e.*, sillimanite). Leeman *et al.* (1992) attributed the depletion of B in granulites to selective transport in fluids released by devolatilization reactions and not by the extraction of silicate melts. However, dehydration melting of the sheet silicates will result in the incorporation of B into the melt. Partial melting of 5–20% of a metasediment containing 25% biotite with 300 ppm B has the potential to produce granitic melts with approximately 200–1000 ppm B. The early biotite-bearing granites of the rare-element-enriched fertile granites contain less than 500 ppm B. In conclusion, B may be incorporated into these peraluminous melts by either the incongruent melting of tourmaline or melting accompanying biotite dehydration.

The highly compatible behavior of the alkali elements as they partition between biotite and melt (Walker *et al.* 1989, Hanson 1978) make biotite stability an important variable in controlling alkali-element concentrations in parental rare-element-enriched granitic magmas. Because the sheet silicates are complex solid-solutions, their dehydration melting is not a simple univariant reaction, but defines at least a divariant region. The F/OH and Fe/Mg in sheet silicates (Manning & Pichavant 1985, Thompson 1982) or Tschermak substitution in muscovite markedly change the field of stability of a sheet silicate. The result of extending the melting reaction due to biotite dehydration to higher T as a result of increasing the F/OH ratio of biotite (Fillippov *et al.* 1974, Manning & Pichavant 1985) would be to retain and concentrate alkali elements and perhaps Sn, Ta, Nb, and Be in the residuum during low degrees of partial melting. Final breakdown of biotite at elevated temperatures provides volatiles for melting in addition to rare-alkali elements, Sn, Ta, Nb, and Be. The production of peralkaline melts, rather than peraluminous melts, if F/ H_2O is high sets limits on the role of F-rich biotite.

CONCLUSIONS

Both the Harney Peak granite and the surrounding pegmatite field are mineralogically and chemically zoned. Superimposed on the general zoning

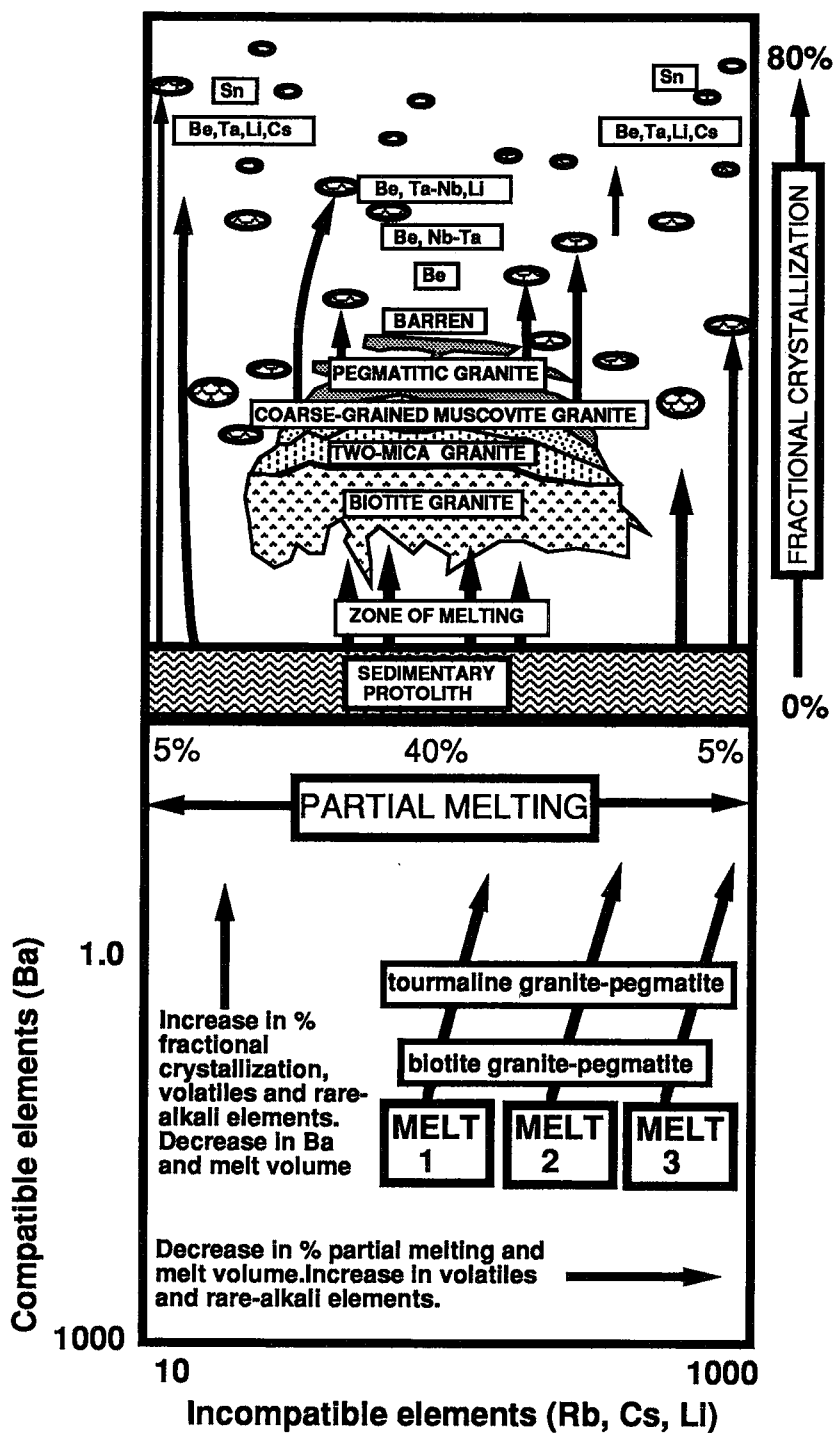


FIG. 14. Summary model, within the context of Figure 1, illustrating the importance of melting and crystallization processes and the behavior of incompatible and compatible trace elements.

of the field are distinct textural (zoning characteristics of individual pegmatites) and compositional swarms of pegmatites. Textural similarities of individual groups or swarms of pegmatites were recognized by Norton & Redden (1990) and are generally supported by the geochemical data presented in this study. The populations of granites and pegmatites appear to define distinct compositional arrays that may be related to distinct fractional crystallization trajectories. For example, the Harney Peak Granite plus numerous pegmatites (homogeneous pegmatites and zoning categories 1 and 2), the enriched Li-, Rb-, Cs-enriched, zoned pegmatites, and the F-, Sn-, Be-enriched pegmatites represent at the very least three distinct fractional crystallization trajectories. There appear to be distinct textural and compositional evolutionary paths along each trajectory. This situation may reflect deviations from equilibrium upon emplacement as a result of increased volatile content and supercooling. Isotopic data (Nabelek *et al.* 1992a, b, Krogstad 1991, 1992) suggest that these individual trajectories may represent melting of isotopically distinct sources.

In addition to fractional crystallization processes along various trajectories, the compositional diversity observed in the granite-pegmatite field also reflects melting processes that enrich parental magmas in rare-alkali elements and H₂O (Fig. 14). The melting model most likely to produce peraluminous magmas with a wide range of rare-element enrichment involves varying degrees of partial melting (1–40%) of numerous compositionally distinct packages of metasediments. The voluminous magmas represented by the Harney Peak Granite and pegmatites, with overlapping Rb–Ba, were generated by high degrees of partial melting (25 to 40%) during dehydration-melting reactions involving biotite. The rare-alkali- and relatively F-enriched granitic melts were produced by smaller degrees of partial melting (1–10%) during muscovite-dehydration melting or perhaps H₂O-saturated solidus melting (or a combination of both). This localized low degree of partial melting occurred along the perimeter of the main zone of melting. This resulted in the production of distinct, local compositions of melt not subjected to magma homogenization that occurred in regions of high partial melting. Higher volatile content resulting from melting reactions or local field of stress improved efficiency of the extraction of small volumes of rare-alkali-enriched melt. The higher H₂O content of these magmas also resulted in efficient fractionation of incompatible elements (Fig. 14). Although some magmas were higher in F, the peraluminous compositions (and not peralkaline) indicates F/H₂O in the magma was still low.

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