Petrochemical differentiation of the Silver Plume-type, Long’s Peak-St. Vrain granite and pegmatites and aplites associated with REE-rich pods and veins near Jamestown, Colorado

Jeremy Ross
Jeremy.Ross@Colorado.EDU

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Petrochemical differentiation of the Silver Plume-type, Long’s Peak-St. Vrain granite and pegmatites and aplites associated with REE-rich pods and veins near Jamestown, Colorado

Jeremy T. Ross
Department of Geological Sciences
University of Colorado-Boulder

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Thesis advisor
Dr. Charles Stern, Department of Geological Sciences

Committee Members
Dr. G. Lang Farmer, Department of Geological Sciences
Dr. Markus Raschke, Department of Physics
Abstract

Veins and pods of rare earth element (REE)-rich minerals occur northeast of Jamestown, CO, in the Silver Plume-type granites and pegmatites of the Long’s Peak-St. Vrain batholith as described by Goddard and Glass (1940) and Allaz et al. (in press). The REE-rich veins and pods consist of the epidote-member allanite, monazite, fluorite, and fluorbritholite. These veins and pods occur in association with texturally distinctive fine-grained aplites composed of oligoclase, alkali feldspars, quartz, and biotite. In this study I collected samples of the Idaho Springs formation metamorphic country rocks, Silver Plume-type granites and pegmatites from the Long’s Peak-St. Vrain batholith, and the aplites associated with and containing examples of the REE-rich mineralization. I prepared more than 30 thin sections of these samples, described them petrologically, determined their mineral chemistry using an electron microprobe, and obtained their Nd isotopic compositions and whole-rock chemistry. I conclude that the REE-rich veins, pods and associated aplites formed around the same Proterozoic time as their Silver Plume-type host rocks and are likely co-genetic as products of a F and REE-rich late-stage magmatic fluid intruding into the granite. However, I also determine that the felsic aplitic matrix found in association with the REE-rich veins and pods is petrochemically different from the granites and pegmatites of the Long’s Peak-St. Vrain pluton. I propose a model for separation of the F and REE-rich late-stage magmatic fluid into the felsic aplitic matrix and the REE-rich veins and pods by either sequential crystallization (aplite crystallizing first further concentrating the REE’s in the residual fluid) or by liquid immiscibility.
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Many thanks to my advisor, Charles Stern, for calm and consistent guidance. Thanks to G. Lang Farmer and Emily Verplanck for help with the isotopic analysis. Thanks to Paul Boni for help with thin section preparation and advice on elk hunting. Thanks to Julien Allaz for help with the microprobe and for sharing geochemical data. Thanks to Derek Weller for help with diagram building and general wisdom. Thanks to Joe Smyth for providing a sample of pegmatite from the Long’s Peak batholith.

Special thanks to my wife, Samantha, for putting up with this project over the last year through our wedding and pregnancy.
Chapter 1: Introduction and Geologic Setting

In this thesis I present petrographic descriptions of the suite of felsic Proterozoic rocks composing the Jamestown REE enrichment locality (JREL) (Goddard and Glass, 1940, Allaz et al., in press); mineral chemical data from electron microprobe analysis and whole rock major and trace element analysis of these rocks; and new Nd/Sm isotopic data.

The rocks examined in this study were collected approximately 5km northeast of Jamestown, CO, in the southeast corner of the St. Vrain-Long’s Peak batholith (Fig. 1). The REE-enrichments at the JREL occur in veins and pods, measuring between a decimeter to 10cm in thickness (Allaz et al., in press). The REE-rich veins and pods occur in zones, with the core being the dominant (thickest) feature and consisting principally of fluorbritholite, monazite, and fluorite. The core section is surrounded by a millimeter-thick rim of allanite, with monazite appearing occasionally on the inner part of the rim structure. Bastnasite, tornebohmite, and cerite form a thin (micron-scale) zone between the allanite rim and the core (Allaz et al., in press). Two localities of the REE-enrichment actually occur, although the samples I collected come from the northern site (1) in Figure 1 (c). The southern site (2) was not used for sample collection because no outcrop containing REE-mineralization is apparent there (Allaz et al., in press). The REE mineralization structures occur in a fine-grained matrix that is apparently aplitic in mineralogy and texture but that exhibits important differences from other granites and pegmatites in the area.
Figure 1

The JREL occurs in syeno- and monzogranites of the Long’s Peak-St. Vrain batholith, a 1422 Ma (+/- 3) (Graubard and Mattinson, 1990, from U-Pb dating in zircons) intrusion composed of the two-mica Silver Plume-type granite. Anderson and Thomas (1985) suggest that the Silver Plume-type granite is likely derived from a water-enriched, metasedimentary, mid-crustal source as evidenced by sharing a peraluminous character with orogenic intrusions. However, according to Anderson and Thomas, the Silver Plume is distinct in its relatively high enrichment in K₂O (4.8 to 6.2 wt%), light REEs, and other incompatible elements, suggesting that the Silver
Plume batholiths are anorogenic in origin while sharing the source rock for orogenic batholiths.

The granite batholith hosting the JREL in turn intrudes 1.7 Ga (from Rb/Sr, Peterman and Hedge, 1968) metasedimentary schists of the Idaho Springs formation. Outcrops of the metamorphic country rock are abundant in the vicinity of the JREL. Veins of pegmatite are found near the locality as well, and are similar mineralogically to the Silver Plume granite samples except for a higher concentration of quartz.
Chapter 2: Optical Petrologic Analysis

2.1 - Granite Descriptions

Two different granite samples were collected: a coarse-grained sample (JR-3) and a finer-grained sample (JR-11). Both samples were collected from within 100 m of the northern REE-enrichment locality near Jamestown.

JR-3: Coarse-grained granite, Silver Plume-type, collected at Northern Locality (Figure 1 (c)).

Mineralogy: Quartz, microcline, orthoclase, muscovite, biotite, plagioclase, apatite, opaques.

JR-11: Fine-grained Silver Plume-type granite collected at the Northern Locality (Figure 1 (c))

Mineralogy: Quartz, plagioclase, orthoclase, microcline, muscovite, biotite, opaques, apatite.
2.2 - Pegmatite Descriptions

Two pegmatites (JR-8 and JR-17) were collected within 100m of the REE-mineralization northern locality, and one sample, JR-18, was collected from the Long's Peak batholith.

**JR-8**: Pegmatite collected at Northern REE-enrichment locality (Figure 1(c))

**Mineralogy**: Microcline, plagioclase, quartz, biotite, muscovite, apatite.
JR-17: Pegmatite collected at northern REE-enrichment locality.

Mineralogy: Biotite, muscovite, plagioclase, quartz, microcline.

Figures 2-7 and 2-8: JR-17 in XPL and PPL

Figure 2-9: JR-8 (left) and JR-17 in hand sample.
**JR-18:** Garnet-bearing pegmatite collected by Joe Smyth from the Long’s Peak batholith, which is composed of Silver Plume-type granite. Not gathered from REE-enrichment locality.

**Mineralogy:** Quartz, plagioclase, orthoclase, biotite, garnet, epidote, zircon

![Image of JR-18](image1.png)

Figures 2-10 and 2-11: JR-18A in PPL and XPL

![Image of JR-18](image2.png)

Figures 2-12 and 2-13: Zircon and epidote grains in JR-18A.

### 2.3 - Country Rock Descriptions

Three samples of schists that are interpreted as roof pendant fragments of country rock were collected close to the northern locality of the REE-mineralized area. No
diagnostic metamorphic minerals (ex: sillimanite) were observed. This could indicate high-grade metamorphism to a degree that the mineralogy reverted to a granitic composition or that these minerals may not be present in the selected sample.

**JR-2:** Metasedimentary Biotite/Muscovite Schist collected from Northern Locality. 
**Mineralogy:** Quartz, Microcline, Plagioclase, Biotite, Muscovite, Zircon, Opaques.

*Figures 2-14, 2-15, and 2-16: JR-2 in PPL, XPL, and hand sample.*
**JR-9**: Metasedimentary biotite/muscovite schist collected from northern locality.

**Mineralogy**: Quartz, Microcline, Plagioclase, Biotite, Muscovite, Zircon, Opaques.

Figures 2-17, 2-18, and 2-19: JR-9 in PPL, XPL, and hand sample.
**JR-10:** Metasedimentary Biotite/Muscovite Schist from Northern Locality.

**Mineralogy:** Quartz, Microcline, Plagioclase, Biotite, Muscovite, Zircon, Opaques.

Images: Figures 2-20, 2-21, and 2-22: JR-10 in PPL, XPL, and hand sample.

### 2.4 Aplite and REE-rich Structure-Bearing Sample Descriptions

Several samples of aplites were collected from the northern locality of REE-enrichment near Jamestown. These samples have been termed aplites (Goddard and
Glass, 1940, Allaz et al., in press) for their granitic mineralogy (quartz, oligoclase, microcline, and micas) and fine-grained texture. Some of these samples bear biotite, and components of the REE mineralization sequence found at the JREL (see Introduction and Geologic Setting) but muscovite is uncommon and their modal quartz abundance is less than that observed in the Silver Plume-type granite samples.

**SK-11:** Sample bearing aplitic matrix and REE-rich veins and pods.

**Mineralogy:** Quartz, oligoclase, microcline, biotite, allanite, fluorbritholite, fluorite, apatite, zircon.

*Figures 2-23 and 2-24: SK-11 in PPL and XPL.*
Figures 2-25 and 2-26: Feldspars (oligoclase and microcline) in SK-11. Fig. 4: Zircons and allanite in the aplitic (quartz, oligoclase, microcline, and biotite) matrix of SK-11.

Figures 2-27 and 2-28: REE mineralization sequence (fluorbritholite and fluorite core enclosed by allanite rim and then aplitic matrix) in SK-11 in XPL and PPL.
Figures 2-29 and 2-30: REE mineralization sequence (fluorbritholite and fluorite core enclosed by allanite rim and then aplitic matrix) in SK-11 in XPL and PPL.

Figure 2-31: Aplitic component of SK-11 in hand sample. Note the homogenous, light-colored appearance.
**JR-12A:** Displays a continuum of facies in hand sample, with aplitic matrix and REE-rich pods and biotite giving way to a pegmatitic or very coars granitic texture on the margin of the sample. Thin section includes aplite and REE-rich pods.

**Mineralogy:** Quartz, biotite, muscovite, allanite, oligoclase, microcline.

*Figures 2.32 and 2.33: JR-12A in XPL and PPL. Note equigranular, aplitic texture.*
Figure 2-34: JR-12 in hand sample. Note the change in texture from left to right across the sample face, with aplite and REE-rich structures on the left-hand margin giving way to pegmatite or coarse-grained granite on the right-hand margin.

Figures 2-35 and 2-36: Allanite and other components of mineralization sequence in JR-12A.
Figures 2-37 and 2-38: Muscovite and biotite together in the aplitic matrix of JR-12A.

**SK-15:** A sample containing a REE-rich pod or vein intergrown with quartz and biotite.

**Mineralogy:** Quartz, oligoclase, microcline, biotite, allanite, fluorbritholite, fluorite.

Figure 2-39: SK-15 in XPL.
Figures 2-40 and 2-41: Quartz and plagioclase pocket in the REE mineralization sequence in SK-15.

Figures 2-42 and 2-43: Pockets of quartz and feldspar matrix, biotites, and allanites between two pods or veins of REE mineralization sequence in SK-15.
Figures 2-44 and 2-45: Allanite and fluorite crystals in SK-15 in XPL and PPL.

JR-13: Contains aplitic matrix and REE-rich pods and veins with zones of biotite and accessory allanite.

**Mineralogy:** Oligoclase, quartz, microcline, zircon, allanite, biotite, fluorbritholite.

Figures 2-46 and 2-47: JR-13 in PPL and XPL. Note plagioclase-heavy matrix and biotite not abundant throughout matrix.
Figure 2-48: JR-13 in hand sample. Note REE-rich pods and biotite zones.

Figures 2-49 and 2-50: Matrix of JR-13 in PPL and XPL. Note abundance of feldspars and small size of quartz grains. REE mineralization sequence at bottom of pictures.

**JR-15**

Contains aplitic matrix, REE-rich pods and veins, with accessory allanite and zonal biotite.

Mineralogy: Plagioclase, microcline, quartz, biotite, allanite, fluorbritholite, fluorite.

Figures 2-53 and 2-54: JR-15 in PPL and XPL. Note feldspar abundance in matrix and low abundance of biotite.
Figure 2-55: JR-15 in hand sample.

Figure 2-56: Quartz pocket in REE-mineralization in JR-15. Figure 2-55: Matrix in JR-15 displaying higher abundance of feldspars relative to quartz, which mostly appears as small grains within feldspars.
2.5 - Comparative Photos of Hand Samples

Comparison photographs are provided for two sets of hand samples: (1) JR-8 (a pegmatite) and JR-12, an aplite matrix and REE-rich pod-bearing sample with pegmatite texture on its margin; and (2) JR-11 (a fine-grained Silver Plume-type granite) and SK-11, an aplite matrix and REE-rich pod-bearing sample. The comparison is offered between JR-8 and JR-12 due to the gradational shift from aplite matrix with pods in JR-12 to an apparent contact with pegmatite similar to JR-8 on the margin of the sample. The comparison between JR-11 and SK-11 is offered to show the obvious differences in character between the fine-grained Silver Plume-type granite at the locality and the aplitic matrix found in the REE-rich samples.
Figure 2-57: Sample JR-12 (left) and JR-8. Note the aplitic matrix and REE-rich pods in JR-12 at bottom of photo giving way to pegmatite or coarse textured granite at top that appears similar to the texture of JR-8, a pegmatite from the locality.

Figure 2-58: JR-12 pegmatite margin in hand sample.
Figure 2-59: SK-11 (left) and JR-11. Note the difference in texture between the aplite matrix of SK-11 (aplite and REE-rich structure-bearing sample) and JR-11 (fine-grained Silver Plume-type granite).
Chapter 3: Geochemical Data

3.1 - Whole Rock Chemistry

Whole rock chemical and electron microprobe analysis of selected samples was performed. Whole rock chemistry was obtained by ACT labs and electron microprobe analysis was performed at the University of Colorado. Samples were chosen for analysis based on the goal of obtaining a representative suite of local Silver Plume-type granites and pegmatites and examples of the aplite associated with the REE-enrichment. Metasedimentary country rocks were also included for comparison for each type of analysis. The results of the whole rock chemical analysis are presented in Table 3-1:
The whole rock chemistry of these samples shows the aplite and REE enrichment bearing samples (JR-12 and SK-11) to be more Ca-enriched than the granite and pegmatite samples (CaO in the aplites samples up to 4.93 wt% oxide while the granites and pegmatites have a maximum of 0.89 wt% oxide of CaO). The aplite and REE enriched samples are also enriched in Na₂O relative to the granitic
suite (5.65 and 4.78 wt% oxide in the aplites versus a maximum value of 2.57 wt% oxide Na$_2$O in the granite). The granitic samples are also slightly more silica-enriched than the REE-associated aplites (71.16 and 69.43 wt% oxide for SiO$_2$).

Combining the trace element geochemical data from whole rock chemical analysis of granites, pegmatites, aplites and REE-enriched structures, and samples of just REE-enrichment vein and pod rims and cores from this study and data gathered by Allaz et al. (in press) into a plot of whole rock/chondrite normalization yields the plot in Figure 3-1:

![Figure 3-1: Whole rock trace element concentration/chondritic normalization constant values for REEs from the Jamestown REE-enrichment locality. REE-enriched vein and core data from Allaz et al., in press. Chondritic norms used are from McDonough and Sun (1995).](image)

This figure shows that the samples containing only REE-enriched structures (rim or core) and the samples containing aplitic matrix and REE-enriched structures do not exhibit the Eu anomaly while the granites and pegmatites do, and the REE-enriched and aplitic samples are highly (greater than 100 times) enriched in light REEs (LREEs) relative to heavy REEs (HREEs). The figure also shows, as observed by Allaz et al. (in press), that the Silver Plume-type granites and pegmatites are
likewise preferentially enriched in LREEs to HREEs but not at the same rate observed in the samples containing the REE-enriched structures. The average ratio of chondrite normalized La to Yb (LREE/HREE) concentration in the core and rim only samples (from Allaz et al., in press) is 108, in the samples containing aplitic matrix and REE-enriched structures it is 128, while in the granite and pegmatite samples the La to Yb chondrite normalized concentration ratio is 8.8. Thus the samples containing the aplite matrix and REE-enriched structures and those containing only REE-rich core or rim display very similar LREE/HREE fractionation.

The granite and pegmatite samples and samples bearing both REE-rich structures and aplite matrix (but not the REE-enriched structure samples) also have similar concentrations of HREEs, with the samples containing aplitic matrix and REE-enriched structures having average Yb chondrite normalized concentration of 13 PPM, while the granite and pegmatite samples have an average normalized Yb concentration of 19 PPM. However, the aplite and REE-rich structure-bearing samples are as much as 10 times enriched in total REEs as the granite and pegmatite samples.

The overall effect is a three-tiered system of REE enrichment: (1) the samples containing only REE-enriched structures (from the Allaz et al. study currently in press) are most enriched in REEs and most fractionated between LREEs and HREEs; (2) the samples with aplite matrix and REE-enriched structures are up to 100 times less enriched in LREEs than the samples with just REE-enriched structures and up to 10 times more enriched in LREEs as the granite and pegmatite samples but with similar abundances of HREEs to the granites and pegmatites; and (3) the granite and pegmatite samples are also preferentially enriched in LREEs vs HREEs (as noted by Allaz et al., in press) but less so than the samples with aplite and/or REE-enriched structures.
3.2 - Mineral Chemistry

The results of the electron microprobe analysis on feldspar grains are presented in Table 3-2 Figure 3-2:
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Table 3-2: Electron microprobe data for feldspar grains from JREL samples.

This data also shows the Ca-enrichment in the aplite and REE-bearing samples seen in the whole rock chemical data above. The samples associated with the aplite and REE enrichment veins (SK-11, JR-13, and JR-15) contain at most 81%
albite in their plagioclase grains, with most samples displaying 70-76% albite range. This is in contrast to the granites, which have a low of 89% albite in measured grains, with most samples in the 90-97% albite range (see Figure 3-2 for ternary plot of feldspar mineralogy in samples).

Figure 3-2: Ternary plot of feldspar grains from JREL samples.

The results of the electron microprobe analysis on mica grains is presented in Table 3-3 and Figure 3-3:
Table 3-3: Electron microprobe data from mica grains from JREL samples.
This data shows an increase in Mg/Fe atomic ratio between the granites and the aplite and REE-rich structure-bearing samples. In the aplitic samples the Mg/Fe ratio is between 0.67 and 2.5, while in the granites the ratio is between 0.19 and 0.86. Figure 3-3 shows the disparity in Mg versus Fe content between all samples, with sample type and location in thin section in regards to REE-enriched structures indicated where applicable.

Figure 3-3: MgO wt% oxide versus FeO wt% oxide for biotite grains in all samples from the Jamestown REE enrichment locality. Sample rock type and location of grain in relation to REE-enriched structures indicated where applicable. The greater the proximity of the biotite grain probed in the aplite matrix to an allanite rim of a REE-rich pod, the greater the Mg/Fe ratio.
Chapter 4: Isotopic Analysis and Radiometric Dating

A solid-source mass spectrometer was used to measure Nd isotopic ratios in a range of samples, including granites and pegmatite from the northern REE-enriched locality, garnet and feldspar grains from a pegmatite in the Long's Peak batholith, metasedimentary country rocks from the northern locality, and aplites and core and rim structures of the REE-enriched pods at the northern locality. The Sm and Nd isotopic data gathered in this study is presented in Table 4-1:

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Sm (ppm)</th>
<th>Sm UCN 2 sigma</th>
<th>Nd (ppm)</th>
<th>Nd UCN 2 sigma</th>
<th>147Sm/144Nd ID</th>
<th>147Sm/144Nd error</th>
<th>143Nd/144NdM</th>
<th>143Nd UNC 2 sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>JR-3</td>
<td>11.331</td>
<td>0.002</td>
<td>70.07</td>
<td>0.01</td>
<td>0.0978</td>
<td>0.00002</td>
<td>0.511540</td>
<td>0.000015</td>
</tr>
<tr>
<td>JR-11</td>
<td>4.397</td>
<td>0.001</td>
<td>19.538</td>
<td>0.003</td>
<td>0.1362</td>
<td>0.00004</td>
<td>0.511859</td>
<td>0.000007</td>
</tr>
<tr>
<td>JR-8</td>
<td>8.873</td>
<td>0.001</td>
<td>28.232</td>
<td>0.005</td>
<td>0.1901</td>
<td>0.00004</td>
<td>0.512406</td>
<td>0.000009</td>
</tr>
<tr>
<td>JR-9</td>
<td>5.986</td>
<td>0.003</td>
<td>31.480</td>
<td>0.002</td>
<td>0.1150</td>
<td>0.00006</td>
<td>0.511754</td>
<td>0.000010</td>
</tr>
<tr>
<td>JR-10</td>
<td>21.738</td>
<td>0.006</td>
<td>139.55</td>
<td>0.02</td>
<td>0.0942</td>
<td>0.00003</td>
<td>0.511503</td>
<td>0.000013</td>
</tr>
<tr>
<td>SK-11</td>
<td>36.9</td>
<td>0.01</td>
<td>273.03</td>
<td>0.06</td>
<td>0.1177</td>
<td>0.00003</td>
<td>0.511166</td>
<td>0.000018</td>
</tr>
<tr>
<td>JR-12</td>
<td>54.979</td>
<td>0.014</td>
<td>463.7</td>
<td>0.6</td>
<td>0.0717</td>
<td>0.00009</td>
<td>0.511380</td>
<td>0.000008</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Sm (ppm)</th>
<th>Sm UCN 2 sigma</th>
<th>Nd (ppm)</th>
<th>Nd UCN 2 sigma</th>
<th>147Sm/144Nd ID</th>
<th>147Sm/144Nd error</th>
<th>143Nd/144NdM</th>
<th>143Nd UNC 2 sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>JR-18 Feldspar</td>
<td>55.77</td>
<td>0.01</td>
<td>286.73</td>
<td>0.06</td>
<td>0.1177</td>
<td>0.00003</td>
<td>0.511166</td>
<td>0.000018</td>
</tr>
<tr>
<td>JR-18 garnet</td>
<td>31.59</td>
<td>0.02</td>
<td>160.01</td>
<td>0.12</td>
<td>0.1194</td>
<td>0.00012</td>
<td>0.511707</td>
<td>0.000011</td>
</tr>
<tr>
<td>SK-11</td>
<td>36.9</td>
<td>0.01</td>
<td>273.03</td>
<td>0.06</td>
<td>0.0818</td>
<td>0.00003</td>
<td>0.511473</td>
<td>0.000009</td>
</tr>
<tr>
<td>JR-12</td>
<td>54.979</td>
<td>0.014</td>
<td>463.7</td>
<td>0.6</td>
<td>0.0717</td>
<td>0.00009</td>
<td>0.511380</td>
<td>0.000008</td>
</tr>
</tbody>
</table>

The data was used to construct isochrons to examine genetic and other relationships between these rock types. The Nd/Sm isochron for all sample types is presented in Figure 4-1, for granites and pegmatites in Figure 4-2, and for REE-enriched veins and surrounding aplites in Figure 4-3.

Radiometric dating has been performed previously on the Silver Plume-type batholiths, including Rb/Sr dating by Peterman and Hedge (1968) giving an age of 1450 Ma for the Long's Peak/St. Vrain batholith and a mean age of 1418 Ma for the Long’s Peak/St. Vrain batholith, the Log Cabin batholith, the Sherman granite, and biotite-muscovite granites not assigned to larger plutons. Graubard and Mattinson
(1990) performed U-Pb dating on the Silver Plume-type granite and determined a zircon crystallization age of 1422 Ma (+/- 3). Allaz et al. used an electron microprobe to perform U-Th-Pb\textsubscript{TOTAL} dating on the REE-rich structures and veins from the Jamestown locality and determined an age of 1420 Ma (+/- 25) for monzite and 1442 Ma (+/- 8) for uraninite (Allaz et al., in press).

![Figure 4-1: Isochron for all measured samples.](image)

The isochron in Figure 4-1 gives an age of 1260 Ga (+/- 120), which does not agree with the ages reported by Peterman and Hedge (1968) and Graubard and Mattinson (1990) for the batholith nor does it agree with the results reported by Allaz et al. (in press) for the REE-enriched structures.
Removing the samples that include the aplite matrix and REE-enriched pod and vein structures associated with the REE enrichment locality gives the isochron in Fig. 4-2. This isochron of metamorphic country rocks, Long's Peak batholith pegmatites, and Silver Plume-type granites and pegmatite from the vicinity of the northern REE enrichment locality gives an age of 1421 Ma (+/- 200), which does agree with the ages determined by Peterman and Hedge (1968) and Graubard and Mattinson (1990).
Figure 4-3: Isochron of samples bearing aplite matrix and/or REE-enriched rim and core sequences from the northern REE enrichment locality.

A third isochron, consisting of samples with the aplite matrix and REE-enriched veins and core structures from the northern REE enrichment locality is shown in Figure 4-3. This isochron gives an age of 1522 Ma (+/- 200). This age is older than that reported by Peterman and Hedge (1968) for the batholith, the age reported by Allaz et al. (in press) for the REE-enriched veins and structures, and the age reported by the isochron in Figure 4-3 above. However, this age agrees with each of these ages when analytic error bounds are taken into account.


**Chapter 5: Discussion**

The Silver Plume-type granites and pegmatites and the felsic aplite matrix present in samples containing allanite or portions of the REE-enriched pods and veins described by Allaz et al. (in press) are interpreted as having distinct origins from one another. The key differences between the felsic aplite matrix and the local granite suite are evident in the following observations: the aplitic samples are more Ca-enriched and possess a higher ratio of MgO vs FeO in biotite grains than the granites do; the aplites display chondrite-normalized La/Yb ratios similar to that produced by Allaz et al. in samples taken from the core and rim sequences of the REE-enriched pods and veins, while the granites display a different trend, including a lower La/Yb ratio and a negative Eu anomaly; and the petrologic appearance of the aplite matrix and the granites are noticeably different.

The radiometric age information shows some similarities between the REE-enriched rocks and the local Silver Plume and metamorphic rocks. The Nd/Sm isochrons of the metamorphic county rocks and granites and pegmatites from the Long’s Peak and St. Vrain batholiths in this study yield an age that agrees with those published in the literature for the Silver Plume-type granites, including Rb-Sr dating by Peterman and Hedge (1968) and U-Pb dating by Graubard and Mattison (1990) (1422 Ma +/- 3) while the Nd/Sm isochron for the aplite and REE-enriched structure bearing samples gives an age that agrees within the analytical uncertainty (which is large) with the U-Th-Pb\textsubscript{TOTAL} electron microprobe age generated by Allaz et al. (in press) for rim, core, and vein of the REE-enriched structures at the JREL.

**5.1 - Geochemical Differences**

The aplite samples contain CaO content between 2.03 and 4.93 wt % with an average value of 3.2% across four samples. The granite and pegmatite samples contain CaO content between 0.10 and 0.89 wt % for six samples, with an average content of 0.48%. Thus the samples containing the REE-associated allanite and aplitic matrix are at least twice and as much as 49 times as enriched in CaO as the granite and pegmatite samples.
The trend in Ca-enrichment in aplastic samples versus granitic and pegmatite samples is also seen in individual plagioclase grains. The plagioclase feldspars in the aplite are oligoclase while those in the granites and pegmatites are albite (Figure 3-2 and Table 3-2).

The aplastic samples are also different from the local granitic rocks in their MgO vs FeO content in biotite grains as shown in Table 5-1. Analysis by electron microprobe shows that biotite grains from the aplastic samples contain MgO/FeO wt % ratios ranging between 1.4 and 0.39, with an average ratio across 19 grains from four samples of 0.68. This marks a contrast to the biotite grains in the granite and pegmatite samples where biotite grains showed MgO/FeO wt % ratios between 0.49 and 0.11, with an average ratio of 0.22 across 12 grains from three samples. The MgO/FeO wt % ratio increases in biotites in samples within the aplitic matrix and allanite as compared to the ratio in the granites.

<table>
<thead>
<tr>
<th>MgO/FeO wt% in Biotite Grains from Samples Collected at JREL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applitic and allanite-bearing samples</td>
</tr>
<tr>
<td>SK11Biotite#1</td>
</tr>
<tr>
<td>FeO</td>
</tr>
<tr>
<td>MgO</td>
</tr>
<tr>
<td>MgO/FeO</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>JR15Biotite#3**</th>
<th>JR15Biotite#4**</th>
<th>JR15Biotite#5**</th>
<th>JR15Biotite#6**</th>
<th>JR15Biotite#7**</th>
<th>JR15Biotite#8**</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO</td>
<td>15.86</td>
<td>16.54</td>
<td>15.33</td>
<td>15.00</td>
<td>16.66</td>
</tr>
<tr>
<td>MgO</td>
<td>12.18</td>
<td>11.44</td>
<td>11.33</td>
<td>11.46</td>
<td>11.52</td>
</tr>
<tr>
<td>MgO/FeO</td>
<td>0.77</td>
<td>0.69</td>
<td>0.74</td>
<td>0.76</td>
<td>0.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SK15Biotite#3@</th>
<th>SK15Biotite#4@</th>
<th>JR13Biotite#1***</th>
<th>JR13Biotite#2***</th>
<th>JR13Biotite#3*</th>
<th>JR13Biotite#4*</th>
<th>JR13Biotite#5*</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO</td>
<td>11.47</td>
<td>12.16</td>
<td>19.36</td>
<td>18.11</td>
<td>18.79</td>
<td>18.65</td>
</tr>
<tr>
<td>MgO</td>
<td>15.55</td>
<td>17.35</td>
<td>10.19</td>
<td>10.22</td>
<td>10.31</td>
<td>9.78</td>
</tr>
<tr>
<td>MgO/FeO</td>
<td>1.36</td>
<td>1.43</td>
<td>0.53</td>
<td>0.56</td>
<td>0.55</td>
<td>0.52</td>
</tr>
</tbody>
</table>

* = Bt grain in contact with allanite  **=Bt grain in aplite matrix  @=Bt grain intergrown in REEJenriched structure

<table>
<thead>
<tr>
<th>MgO/FeO wt% in Biotite Grains from Samples Collected at JREL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite and pegmatite samples</td>
</tr>
<tr>
<td>JR11 Biotite #1</td>
</tr>
<tr>
<td>MgO</td>
</tr>
<tr>
<td>FeO</td>
</tr>
<tr>
<td>MgO/FeO</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>JR3Biotite#2</th>
<th>JR3Biotite#3</th>
<th>JR17Biotite#1</th>
<th>JR17Biotite#2</th>
<th>JR17Biotite#3</th>
<th>JR17 Biotite#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO</td>
<td>6.74</td>
<td>8.29</td>
<td>5.27</td>
<td>5.19</td>
<td>5.12</td>
</tr>
<tr>
<td>FeO</td>
<td>20.05</td>
<td>20.13</td>
<td>24.79</td>
<td>24.19</td>
<td>24.66</td>
</tr>
<tr>
<td>MgO/FeO</td>
<td>0.34</td>
<td>0.41</td>
<td>0.21</td>
<td>0.21</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 5-1: Table showing the MgO/FeO wt % ratio on biotite grains from aplitic and allanite-bearing samples and granite and pegmatite samples from JREL.

The increase in MgO/FeO wt % ratio varies further depending on the textural association between biotite and allanite and other REE-associated minerals in the samples. In SK-11, a sample with aplitic matrix and a large (>14 mm) REE-enriched pod of fluorite and fluorbritholite, the sampled biotite grains exist exclusively in the felsic aplitic matrix in a linear structure and are not in contact with allanite or other
components of the REE-enriched sequence of minerals described by Allaz et al. (in press). In SK-11 the MgO/FeO wt % ratio ranges between 0.36 and 0.41 with an average ratio of 0.39 across four sampled grains. In contrast, JR-15, a sample with aplitic matrix and a REE-enriched pod approximately 5cm across, contains biotites in a range of in situ arrangements with allanite (see Table 5-1 and Figures 2-53 through 2-56). The biotite grains intergrow with allanite in the rim of the REE-enriched structures) in JR-15, possess MgO/FeO wt % ratios between 0.66 and 0.80 with an average ratio of 0.75 across six samples, while the average for biotite grains not in contact with allanite is 0.68 across two samples, a difference of 10% MgO/FeO ratio.

In SK-15, a sample composed almost exclusively of REE-enriched vein structure with pockets and veins of quartz of biotite running through the structure (see Figures 2-39 through 2-43), the biotite grains display MgO/FeO ratios of 1.4.

The overall trend of increasing MgO/FeO content with increased association of biotite grains with allanite and REE-enriched structures suggests that a link exists between the minerals associated with REE-enrichment (allanite, etc.) and the MgO-enriched biotites. The whole rock content of MgO/FeO wt % in the aplitic and REE-enriched samples (SK-11, JR-13, JR-15, and SK-15) also possess significantly higher MgO/FeO wt % ratios than the granite and pegmatite samples. The granite and pegmatite samples are at least five times more enriched in FeO by wt % than MgO, as compared to the aplitic samples, which possess whole rock wt % MgO/FeO ratios between 0.36 and 1.4. A lower range of MgO/FeO wt % ratio in whole rock occurs in SK-11, which as mentioned above is an allanite and REE-enriched structure bearing sample but one that also displays the lowest MgO/FeO ratio in biotite grains and in which all observed and measured biotite grains were in the aplitic matrix rather than in contact or association with allanite. The trend of microprobe analysis of MgO/FeO wt % ratios in biotite grains and in whole rock analysis of the same ratio suggests that as association with the REE-enriched minerals and structures (allanite and pods or veins) increases, so too does the MgO/FeO ratio in the felsic aplite.

Another geochemical differentiation between the aplite samples and the local granitic rocks is seen in the plot of chondrite normalized REE concentrations for all
samples on which whole rock chemistry was determined (Figure 3-1). The samples composed of pure core and rim from the REE-enriched pods from Allaz et al. show a similar La/Yb trend to the aplitic and REE-enriched structure-bearing samples from this study, except that the aplitic-bearing samples are about two orders of magnitude less concentrated in REE’s than the pure core and rim samples. Neither possess the typical Eu-depletion anomaly that is seen in the granites. This data suggests that the aplitic and REE-enriched structure-bearing samples are more related to the core and rim samples than to the granites.

5.2 - Petrographic Differences

Petrographic inspection of the Silver Plume granites and pegmatites reveals differences with the aplitic matrix in the REE-enriched samples as well. As seen in Figures 2-1, 2-2, 2-3, and 2-4, the granites from the pluton hosting the REE locality vary between fine and coarse textures, with JR-3 being coarse and JR-11 being fine. There are aplitic and REE-enriched samples that are roughly analogous to both in terms of typical grains size and texture, such as SK-11 to JR-3, and JR-12 to JR-11. However, comparative inspection in thin section reveals differences in both cases.

One difference between the aplitic, REE-enriched SK-11 and JR-12 and their granitic counterparts is that the granites are muscovite and biotite-bearing, while the only REE-enriched structure-bearing sample observed to bear muscovite in this project is JR-12. Another difference is that the granites each bear microcline and orthoclase, while the aplitic matrix around the REE-enriched structures in SK-11, JR-12, and the other aplitic samples contains only microcline. Finally the arrangement of the mineral grains in the samples is different. JR-3 and JR-11 are typical of an expected igneous texture, with interlocking grains of minerals associated with granites dispersed throughout the slide. In the aplitic matrix of SK-11, JR-12, and the other REE-enriched structure-bearing samples, more variable and somewhat unusual textures occur as described below.

An example of mineral segregation is in JR-15. While the aplitic matrix in this sample bears quartz, plagioclase, potassium feldspar, and biotite (a typical suite of granitic minerals), optical and microprobe inspection showed that the matrix is
heavily dominated by feldspars, with quartz appearing as small grains within feldspars and the REE-enriched pod in the slide (see Figures 2-46, 2-47, 2-48, and 2-49). Biotite appears very rarely within the aplite matrix and in contact with the allanite rim of the REE-enriched pod. Quartz also appears in pockets in the REE-enriched pods. JR-13 (Figures 2-46, 2-47, 2-48, and 2-49) also possesses a feldspar-heavy matrix with quartz appearing intermittently within feldspar grains. In this sample biotite is more abundant throughout the matrix, but is still more segregated than the textures of the granite samples in JR-3 and JR-11.

Another example of mineral segregation is in SK-15. In this sample biotite appears in a vein-like structure within the REE-enriched mineralization sequence (Figures 2-42 and 2-43), while quartz appears as homogenous grains in pockets within the pods (Figures 2-40 and 2-41). This offers an appearance of the granitic minerals (feldspars, quartz, biotite) crystallizing separately from the pods.

5.3 - Hand Sample Comparisons

Two comparisons of hand samples are instructive in suggesting differences between the aplite matrix and the Silver Plume-type granites and pegmatites. The first is a comparison between JR-8 (pegmatite from the JREL) and JR-12 (aplite and REE-rich pod-bearing sample). JR-12 displays a sharp change in texture from aplite with REE-rich pod inclusions (see Figures 2-34) to what appears to be pegmatite or very coarse granite similar to that seen in JR-8 (see Figures 2-9 and 2-58). The abrupt shift from aplitic and REE-rich bearing texture to pegmatite or coarse granite could represent a contact between the aplite bearing the REE-rich structures and the Silver Plume-type batholiths.

The second comparison is between JR-11 (a fine-grained granite) and SK-11 (an aplite and REE-rich structure-bearing sample). This comparison (see Figure 2-59) shows the different textures and mineralogies between the aplite and the host granites (the granites are equigranular with regular distribution of mineral types while the aplite is pre-dominantly homogenized and segregated by mineral types with abundant feldspar matrix).
5.4 - Radiometric Ages

Using the Nd/Sm isotope method, an age for the granites, pegmatites, and metamorphic country rocks was determined to be 1421 Ma (+/- 200) (see Figure 4-2). The same method yielded an age of 1522 Ma (+/- 200) (see Figure 4-3) for the REE-enriched structure bearing samples with aplitic matrix, and the age for all samples was determined by Nd/Sm isochron to be 1260 Ma (+/- 120) (see Figure 4-1). The isochron for all samples is approximately linear as well.

These observations and data suggest that: all of the samples examined in this study were uniformly enriched in $^{143}$Nd between approximately 1.4 and 1.5 Ga. This does not necessarily indicate that the samples and their associated rocks are co-genetic, but that they were uniformly enriched in the isotope at some point around that time interval.

The observations that the age determined for the Silver Plume-type rocks agrees with ages determined in the literature by various other methods (Graubard and Mattinson, 1990, and Peterman and Hedge, 1968) and that the age determined for the REE-enriched and aplite-bearing rocks agrees (when uncertainty is allowed) with the age determined for the REE-enriched structures by Allaz et al. (in press) and that all of these methods yield ages of around 1.42 Ga (with the Silver Plume-type granite intruding 1.7-1.8 Ga metamorphic country rock) suggests that the current iteration of the granites, the aplitic matrix, and the REE-enriched structures crystallized at the same time.

5.5 - Proposed Model of Aplite Separation and Crystallization from Late-stage F and REE-rich Magmatic Fluid

Allaz et al. (in press) suggest a late-stage, F and REE-rich magmatic fluid as being the likely source of the REE-enriched structures found at the JREL. The results of this study agree with that finding. I suggest a magmatic fluid is the mechanism of REE transport rather than an external hydrothermal fluid because the samples do not show signs of hydrothermal alteration (after Agangi et al., 2010). The aplitic matrix is interpreted to be the result of segregation and sequential crystallization of
granitic minerals from the F and REE-rich magmatic fluid according to the following model (see Figure 5-1):

1. Late-stage magmatic F and REE-rich fluid, derived by some unknown process from deeper in the plutonic system, bears REEs toward roof of pluton. This late-stage F fluid also bears some characters of the melt that formed the pluton, such as preferential enrichment in LREEs to HREEs.

2. As the fluid reaches a specific low T and P condition the aplitic matrix begins to crystallize out, removing the apparently granitic components of the fluid. The aplite crystallizes progressively, resulting in the zones of abundant oligoclase and alkali feldspars, intermittent biotite and quartz along with accessory monazites and allanite. This aplite appears at a glance to be texturally similar to the fine-grained Silver Plume granite that can be found around the REE locality but is petrographically (examples: aplite and REE structure-bearing samples are more Ca-rich and contains biotite with higher Mg/Fe ratios) and geochemically (examples: higher total REE abundance than granites and higher LREE/HREE ratio and no negative Eu anomaly) different.

3. The remaining fluid is now super-enriched in REEs, either due to liquid immiscibility or by separation of the aplitic components by crystallization, while maintaining a similar LREE/HREE (La/Yb) ratio to the aplites. The aplitic matrix’s fine-grained texture suggests relatively quick cooling/crystallization, which can create micromiarolitic cavities (Agangi et al., 2010).

4. The remaining fluid forms the REE-structures zonally as described by Allaz et al. in the miarolitic cavities created by the formation of the aplitic matrix.
Proposed Model of F and REE-rich Late-Magmatic Fluid Separation by Crystallization or Liquid Immiscibility

(1) Late-stage magmatic F and REE-rich fluid, derived by some unknown process from deeper in the plutonic system, bears REEs toward roof of pluton. This late-stage F fluid also bears some characters of the melt that formed the pluton, such as preferential enrichment in LREEs to HREEs.

(2) As the fluid reaches a specific low T and P condition the aplite matrix begins to crystallize out, removing the apparently granitic components of the fluid. The aplite crystallizes progressively, resulting in the zones of abundant oligoclase and alkali feldspars, intermittent biotite and quartz along with accessory monazites and allanite.
Figure 5-1: A model of the proposed separation of the aplitic matrix from the REE-rich, zonal structures at the Jamestown locality.
**Chapter 6: Conclusion**

I conclude the following: the Silver Plume-type granite and the aplitic matrix found in the REE-rich structure-bearing samples at the Jamestown locality are geochemically and petrographically distinct from one another and that the granite and the aplite are likely co-genetic from the same Proterozoic magmatic processes but that the aplite is the product of a F and REE-rich late-magmatic fluid intruded into the pluton.

The geochemical differences between the granites and pegmatites and the REE-rich rocks are: higher concentration of REEs in the aplite and REE-rich structure-bearing rocks than the granites; a higher LREE/HREE ratio in the aplite and REE-rich structure-bearing samples than that found in the granite, including an absence of negative Eu abundance in the aplitic and REE pod samples; and Ca enrichment and higher Mg/Fe ratios in the aplitic and REE-rich structure-bearing samples as compared to the granites and pegmatites.

Isotopic dating using the Nd/Sm method affirms (within error bounds) earlier dating by Peterman and Hedge (1968), Graubard and Mattison (1990), and Allaz et al. (in press) for the host granites, pegmatites, and metamorphic rocks and the REE-rich samples. The ages gathered thus indicate a close, Proterozoic age for the REE-rich samples (1442 Ma (+/- 8) on uraninite and 1420 Ma (+/- 25) on monazite by U-Th-Pb<sub>TOTAL</sub> by Allaz et al. (in press) and 1522 Ma (+/- 200) by this study) and the Silver Plume-type granites and pegmatites (1422 +/- 3 Ma by Graubard and Mattinson (1990) and 1421 Ma (+/- 200). The similarity of these ages and the linear trend of an isochron with all sample types plotted on it suggests a Proterozoic age of all sample types at the locality. This age represents a Proterozoic crystallization age for both types of sample.

Finally, the aplite matrix is interpreted to be a product of a late-stage F and REE-rich magmatic fluid as suggested by Allaz et al. (in press) due to the geochemical similarities between the aplitic matrix-bearing samples and the REE-rich structure-only samples and the petrographic differences between the aplite matrix and the Silver Plume granites and pegmatites. The fluid began to crystallize the aplite as it reached a certain low temperature and pressure condition, which
removed the granitic aspects of the fluid and further enriched the remaining fluid in F and REEs and lead to the zonal formation of veins and pods of F and REE-rich minerals (Allaz et al., in press) in miarolitic cavities formed by the rapid crystallization of the aplite.

References


