

Second Eugene E. Foord Pegmatite Symposium



View of pegmatites northwest of Quartz Creek, Quartz Creek pegmatite field, Gunnison County

Abstracts, Short Papers, Posters and Program

Sponsored by:
Colorado School of Mines Geology Museum
Friends of Mineralogy, Colorado Chapter
Denver Region Exploration Geologists' Society
Friends of the Colorado School of Mines Geology Museum

Berthoud Hall, Colorado School of Mines
Golden, Colorado

July 15 - 19, 2016

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Colorado School of Mines campus, Golden, Colorado

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Managing editor: Mark Ivan Jacobson
Editors: Markus Raschke, Fred Barnard, Peter J. Modreski

Front cover photograph: View, looking at the northwestern portion of the Quartz Creek pegmatite field, across Quartz Creek, Gunnison County, Colorado. Mark Jacobson photo.

Back cover photograph: upper - Amazonite from the keyhole vug pocket 1986, Teller County, Colorado. Collectors Edge Minerals, Inc. specimen and photograph. lower - George H Weed and James D. Endicott digging at Crystal Peak, circa 1913. Douglas B. Sterrett, USGS photo.

Symposium coordinators: Mark Ivan Jacobson, Fred Barnard, and Peter J. Modreski
Symposium Treasurer: Fred Barnard

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Field trips would not have been possible without the help of a large number of people. Their kindness and friendship is much appreciated. Land access permissions were obtained from various governmental groups and private landowners. These people were: Joannah Merriman, Jack Pottle, Tim Ryan, Kristin Kahler, Matthew Pollart, Phillip Courtney, Kathleen Donahue, Ron Platt, Mike Tezak, Nicole Krauth, Bill Tezak, Steve Russell, Ray Berry, Tom Glor (Fremont County Acquisitions LLC), and Joseph Dorris.

Field trip leaders were recruited from across Colorado. Their help was vital in planning and executing the field trips. These people were: Stephen Zahony, Mark Ivan Jacobson, Jennifer Gerring, Steve Wolfe, Philip Persson, Jeff Self, Donna Ware, Amber Brenzikofer, and Mike Perkins.

Other symposium logistics were helped by many others; the tasks were almost endless. The University of Colorado symposium webpage was created by Chris Haddad. Gloria Staebler helped setup the bank account for the symposium. Iva Veselinova at Lithographie, Ltd. helped with completing the sales tax exemption for the symposium. Dorian Owen at the Colorado School of Mines assisted us in coordinating and planning the on-campus housing and meals. Bonnie Dyson assisted us with obtaining the needed third party insurance coverage documents. Steve Behling of Collectors Edge Minerals, Inc. kindly provided the back cover picture of amazonite.

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TABLE OF CONTENTS

WELCOME	4
MEETING SCHEDULE	5
POSTERS	8
CONTRIBUTIONS	9
Hints on the origin and evolution of spodumene pegmatites in southeast Ireland. (poster).....	9
Renata Barros, Julian F. Menuge, and Thomas Zack	
LCT pegmatites and the supercontinent cycle.....	14
Dwight C. Bradley and Andrew McCauley	
Crystallization of the Fisher quarry pegmatite, Sagadahoc Co., Maine: Preliminary insights from fluid inclusions (poster).....	18
Clara J. Brennan, Samuel M. Cameron, and Mona-Liza C. Sirbescu	
The mineralogy of the Waterloo quarry pegmatites, southern Wisconsin. (poster)	22
Thomas W. Buchholz, Alexander U. Falster and Wm. B. Simmons	
Vieirópolis pegmatite field, northwest of Paraíba State (Brazil): New occurrences of amazonite pegmatite	24
Sandra de Brito Barreto, Axel Müller, José Ferreira de Araújo Neto, João Pedro Santana Bezerra, Igor Manoel Belo de Albuquerque e Souza, Rafaela Henrique Mendes França, and Lauro César Montefalco de Lira Santos	
Mineralogy, geochemistry and geochronology of allanite pegmatites on the KIN property, eastern British Columbia	27
Dana Caudle, Jan Cempírek, Lee A. Groat, Leo J. Millonig	
Amazonite and smoky quartz pegmatites in the Smoky Hawk trend, Teller County, Colorado	29
Joseph Dorris	
Origin, geochemistry and mineral chemistry of the Post-Penokean LCT-type pegmatites in Florence County, Wisconsin	31
Alexander U. Falster and Wm. B. Simmons	
A large scale boundary layer texture in the Mt. Mica pegmatite, Paris, Oxford County, Maine (poster)	36
Myles M. Felch, William B. Simmons, Alexander U. Falster, and Karen L. Webber	
Exploring for topaz-bearing pegmatites near Pikes Peak	37
Richard Fretterd and Jean Cowman	
The role of pegmatites and acidic fluids for hydrothermal Zr and REE transport in the Strange Lake peralkaline granitic pluton	40
Alexander Gysi	
Using Pearce Discrimination Diagrams to Evaluate the Tectonic Regime for Pegmatite Parent Granite	43
Sarah L. Hanson	
Rare earth element pegmatites in the South Platte region of Colorado (poster)	45

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

**Rhiana Elizabeth Henry, Charles Stern, Markus Raschke, Julien Allaz,
Evan J. D. Anderson, and Alexandra Skewes**

Pegmatites of China: a bibliography (poster)	49
Mark Ivan Jacobson	
Experimental crystallization of the Macusani Obsidian. - Keynote speaker	51
David London and George B. Morgan VI	
Pegmatites of the Little Three mine, Ramona, San Diego County, California	53
David London, George B. Morgan VI, and James L. Maner	
The rise and fall of amazonite	55
Robert F. Martin and Maria Sokolov	
Geological setting and mineralogy of the LCT pegmatites of Leinster, southeast Ireland	57
Julian F. Menuge and Renata Barros	
The California Blue Mine: A recently discovered aquamarine pegmatite in the Mojave Desert	61
Ian Merkel	
A review of the 1986 and 1999 Colorado pegmatite symposia	62
Peter J. Modreski	
Crystallization-induced field diffusion as a driving force for pegmatite zonation	65
George B. Morgan VI, David London, and A. A. Acosta-Vigil	
Can pluton-related and pluton-unrelated granitic pegmatites be distinguished by their chemistry?	67
Axel Müller, Rolf L. Romer, Adam Szuszkiewicz, Slawomir Ilnicki, and Eligiusz Szeleş	
Primary (magmatic) and hydrothermal milarite-group minerals from Velká skála pegmatite, Písek pegmatite district, Czech Republic	70
Milan Novak, J. Cícha, R. Čopjaková, R. Škoda, and M. Vašinová Galiová	
Unusual REE and rare element minerals from pegmatites and alkaline granites: thalenite and brannockite from the Golden Horn Batholith, Washington, and South Platte Pegmatite district, Colorado, USA (poster)	73
Markus B. Raschke, Evan J. D. Anderson, Alexandra Skewes, Julien Allaz, Henrik Friis, Joseph Smyth, Charles Stern, Philip M. Persson, Rhiana Henry, Katharina Pfaff, Rudy Tschernich, and Randy Becker	
Mineralogy and petrology of a new REE pegmatite near Wellington Lake, in relation to the South Platte Pegmatite district, Colorado, USA	78
Markus B. Raschke, Evan J. D. Anderson, Alexandra Skewes, Julien M. Allaz, Charles Stern, Philip M. Persson, Rhiana Henry, and Katharina Pfaff	
Raman and Rayleigh scattering microscopy: Applications in alkali feldspars for the characterization of pegmatites	83
Luis Sánchez-Muñoz, Adolfo del Campo, and José F. Fernández	
Local structure of beryl group minerals from multinuclear NMR spectroscopy (poster)	89
Luis Sánchez-Muñoz, Isabel Sobrados, Virginia Díez, Zhehong Gan, Sandra de Brito Barreto, Federico Pezzotta, and Jesús Sanz	
Local structure of beta-eucryptite and beta-spodumene in the $\text{Li}_{1-x}\text{Al}_{1-x}\text{Si}_{1+x}\text{O}_4$ for $0 \leq x \leq 1$ in the LAS system by multinuclear NMR spectroscopy (poster).....	92

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Luis Sánchez-Muñoz, Isabel Sobrados, Virginia Díez, and Jesús Sanz

REE-Rich Pegmatites from the South Platte and Trout Creek Pass pegmatite districts, Colorado: Contrasting geochemical profiles and tectonic regimes. - Keynote speaker	95
William B. Simmons	
Evidence for an anatexitic origin of an LCT type pegmatite: Mt. Mica, Maine (poster).....	103
William B. Simmons and Alexander U. Falster	
What does it take to make a pegmatite? Direct observations of crystal nucleation and growth.....	104
Mona-Liza C. Sirbescu, Nathan J. Zielinski, Max Wilke, and Christian Schmidt	
Rare-Element Pegmatites of the Petaca District, New Mexico.....	107
Michael N. Spilde, Steve Dubyk, William P. Moats, and Brian Salem	
Role of liquid immiscibility in formation of F- and REE-rich segregations in aplite veins near Jamestown, Colorado, USA.....	110
Charles Stern, Jeremy Ross, Julien Allaz, Markus B. Raschke, Lang Farmer, and Alexandra Skewes	
Topaz on America's Mountain (Pikes Peak). (poster).....	114
Jack D. Thompson and Kaye Thompson	
A-type granites and their pegmatites: NYF or something else? - Keynote speaker	115
Michael A. Wise	
The rare earth minerals of Stove Mountain and Cheyenne Canyon near Colorado Springs.	116
Gary Zito	
FIELD TRIP SCHEDULES	118
BIOGRAPHIES OF PRESENTERS AND POSTER AUTHORS	119

Welcome

Welcome to the Second Eugene E. Foord Pegmatite Symposium. We are proud and excited to present this magnificent program of speakers and field trips. We hope that our participants are similarly excited. Many of our speakers have traveled great distances to present here – Czech Republic, Ireland, Norway, Spain, Canada, and many different U.S. states. The pegmatite subjects cover the same wide range both geographically as well as geologically- from pegmatite formation to radioactive minerals from niobium-tantalum-yttrium pegmatites and gemstone minerals from lithium-cesium-tantalum pegmatites.

This is the third symposium on pegmatites to be offered in Denver. In 1986, the “Colorado Pegmatites” symposium presented a broad spectrum of subjects that focused mainly on Colorado and the adjacent states. Only two field trips were offered. In 1999, the “Eugene E. Foord memorial symposium on NYF pegmatites” presented papers with an international geographical distribution. The papers discussed were restricted just to NYF or rare-earth element enriched pegmatites.

It took many people to prepare this third program. They were all unpaid volunteers from four organizations: the Geology Museum of the Colorado School of Mines; Friends of the Colorado School of Mines Geology Museum; the Friends of Mineralogy, Colorado Chapter; and the Denver Region Exploration Geologists Society. The individuals who have assisted in the planning and execution of this symposium are formally acknowledged in a different section of the proceedings.

The **Geology Museum** has the best mineral displays in the state of minerals from Colorado and other Western states; please visit and enjoy the museum and thank the curator, the museum and the school for their support of this symposium. Their collection dates back to the 1880s with specimens donated by or acquired from the pioneers of Colorado mineralogy.

The **Friends of the Colorado School of Mines Geology Museum** is a support group, formed in 2009, dedicated to promoting and assisting in the maintenance and expansion of the Geology Museum. This year they have executed an aggressive program of monthly geological presentations at the museum.

The **Friends of Mineralogy, Colorado Chapter** is a service organization that since 1977 has continued its tradition of planning symposiums and presentations dedicated to increasing the knowledge about minerals and their deposits. The chapter was active in organizing both previous pegmatite symposia as well as numerous others. Their webpage, <http://friendsofmineralogycolorado.org/>, contains historic newsletters, lists of publications, history and current activities. A digital copy of the *1986 Colorado pegmatite symposium* book may be downloaded from the website.

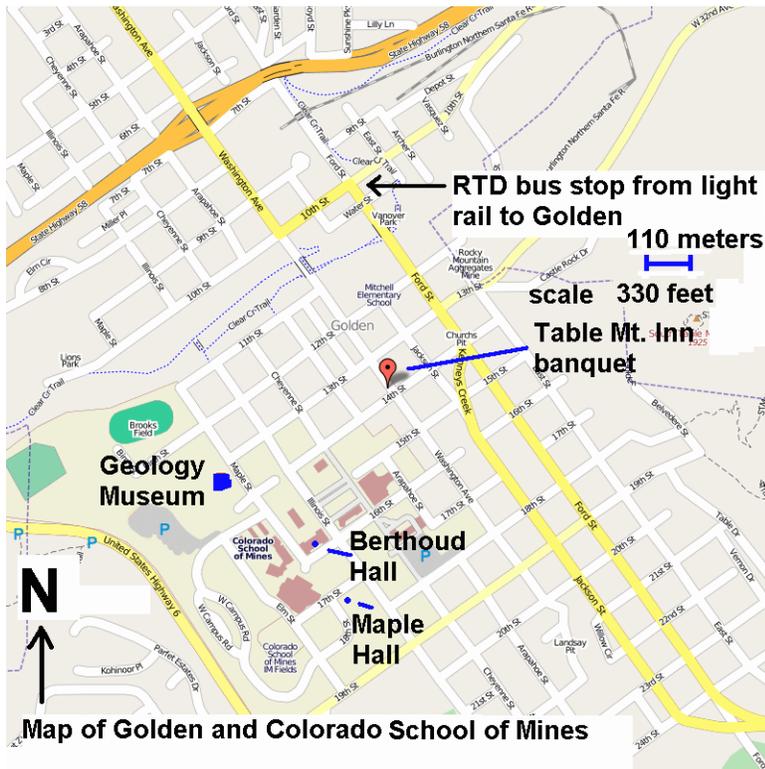
The **Denver Region Exploration Geologist’s Society** is an organization of mining and mineral exploration professionals with the mandate to meet monthly to enjoy mineral deposits-related presentations and professional camaraderie. The organization currently has 274 members. Meetings with presentations are held on the first Monday of each month, except for the summer months. Besides the monthly meetings, the organization organizes two field excursions each year to visit mineral occurrences and/or operating mines of interest to the members and makes modest annual financial contributions to other organizations active in the development of the exploration and mining industry.

Program Schedule

Friday, 15 July 2016 registration, package pickup and reception

- 3:00- 5:00 PM Pick-up of registration and field trip package at the Geology Museum, Colorado School of Mines, 1310 Maple Street, Golden, CO. Walk-in registrations for the symposium are allowed.
- 3:00- 7:00 PM Pick-up of dormitory key and dormitory information package Geology Museum, Colorado School of Mines, 1310 Maple Street, Golden, CO
- 5:00-8:00 PM Opening reception at the Geology Museum, Colorado School of Mines, 1310 Maple Street, Golden, CO

Parking Issues: Parking is free on the Colorado School of Mines campus on weekdays Monday to Friday only after 5 P.M. up to 7 A.M. the next day AND on weekends from 5 P.M. Friday evening until 7:00 A.M. on Monday mornig. In town, free parking is available at various locations. In the Golden business district, free parking is available for 2 or 3 hours segments as indicated by the signs.



The map to the left shows the location of the Geology Museum, Berthoud Hall and the dormitory rooms at Maple Hall. The cafeteria is just adjacent to Berthoud Hall. The Golden business district is along the northeast-southwest street that the Table Mountain Inn is located on. Commercial parking is possible just northeast of the Table Mountain Inn. Map image copyright 2016 and courtesy of Google.

Program Schedule

Saturday, 16 July 2016 presentations

- 8:00-10:00 AM Pick-up of registration and field trip package at Berthoud Hall, Colorado School of Mines, 1500 Illinois Street, Golden, CO
- 8:15-8:30 AM Opening remarks and logistics
- 8:30-9:30 AM **Michael A. Wise:** A-type granites and their pegmatites: NYF or something else? - **Keynote speaker**
- 9:30-9:55 AM **Axel Müller:** Vieirópolis pegmatite field, northwest of Paraíba State (Brazil): New occurrences of amazonite pegmatite.
- 9:55-10:20 AM **Peter J. Modreski:** A review of the 1986 and 1999 Colorado pegmatite symposia.
- 10:20-10:40 AM Coffee- rest break
- 10:40-11:05 AM **Robert F. Martin:** The rise and fall of amazonite.
- 11:05- 11:30 AM **Julian F. Menuge:** Geological setting and mineralogy of the LCT pegmatites of Leinster, southeast Ireland.
- 11:30-11:55 PM **Axel Müller:** Can pluton-related and pluton-unrelated granitic pegmatites be distinguished by their chemistry?
- 11:55-1:25 PM Lunch (and poster set-up starts)
- 1:25-2:25 PM **David London:** Experimental crystallization of the Macusani Obsidian. - **Keynote speaker**
- 2:25-2:50 PM **David London:** Pegmatites of the Little Three mine, Ramona, San Diego County, California.
- 2:50-3:15 PM **Mona-Liza C. Sirbescu:** What does it take to make a pegmatite? Direct observations of crystal nucleation and growth.
- 3:15-3:35 PM Coffee- rest break
- 3:35-4:00 PM **Milan Novak:** Primary (magmatic) and hydrothermal milarite-group minerals from Velká skála pegmatite, Písek pegmatite district, Czech Republic.
- 4:00-4:25 PM **George B. Morgan VI:** Crystallization: induced field diffusion as a driving force for pegmatite zonation.
- 4:25- 4:50 PM **Jan Cempírek:** Mineralogy, geochemistry and geochronology of allanite pegmatites on the KIN property, eastern British Columbia.
- 4:50-5:15 PM **Edward Raines:** Some textures, habits, and associations that help point the way to a better understanding of the crystallization process in the Pikes Peak batholith pegmatites.
- 5:15-7:00 PM Poster session
- 7:30 PM Dinner Banquet at Table Mountain Inn, 1310 Washington Ave, Golden

Sunday, 17 July 2016 presentations

- 8:45-9:00 AM Opening remarks and logistics
- 9:00-10:00 AM **William B. Simmons:** REE-Rich Pegmatites from the South Platte and Trout Creek Pass pegmatite districts, Colorado: Contrasting geochemical profiles and tectonic regimes. - **Keynote speaker**
- 10:00-10:25 AM **Charles Stern:** Role of liquid immiscibility in formation of F- and REE-rich segregations in aplite veins near Jamestown, Colorado, USA.
- 10:25-10:45 AM Coffee- rest break
- 10:45-11:10 AM **Markus B. Raschke:** Petrology of a REE pegmatite near Wellington Lake, South Platte, CO: an intermediary between NYF-type and miarolitic REE-poor pegmatites in the Pikes Peak batholith.
- 11:10-11:35 AM **Sarah L. Hanson:** Using Pearce Discrimination Diagrams to Evaluate the Tectonic Regime for Pegmatite Parent Granite.
- 11:35-12:00 PM **Steve Dubyk:** Rare-Element Pegmatites of the Petaca District, New Mexico.
- 12:00-1:30 PM Lunch
- 1:30-1:55 PM **Alexander Gysi:** The role of pegmatites and acidic fluids for hydrothermal Zr and REE transport in the Strange Lake peralkaline granitic pluton.
- 1:55-2:20 PM **Alexander U. Falster:** Origin, geochemistry and mineral chemistry of late Penokean LCT-type pegmatites in Florence County, Wisconsin.
- 2:20- 2:45 PM **Joseph Dorris:** Amazonite and smoky quartz pegmatites in the Smoky Hawk trend, Teller County, Colorado.
- 2:45-3:10 PM **Ian Merkel:** The California Blue Mine: A recently discovered aquamarine pegmatite in the Mojave Desert.
- 3:10-3:35 PM **Gary Zito:** The rare earth minerals of Stove Mountain and Cheyenne Canyon near Colorado Springs.
- 3:35-3:55 PM Coffee- rest break
- 3:55-4:20 PM **Richard Frettard:** Exploring for topaz-bearing pegmatites near Pikes Peak.
- 4:20-4:45 PM **Luis Sanchez-Munoz:** Raman and Rayleigh scattering microscopy: Applications in alkali feldspars for the characterization of pegmatites.
- 4:45- 5:10 PM **Dwight Bradley:** LCT pegmatites and the supercontinent cycle.
- 5:10 - 5:25 PM Comments about field trip logistics and travel to airport

Posters

- 1) Hints on the origin and evolution of spodumene pegmatites in southeast Ireland.
Renata Barros, Julian F. Menuge, and Thomas Zack
- 2) Crystallization of the Fisher quarry pegmatite, Sagadahoc Co., Maine: Preliminary insights from fluid inclusions.
Clara J. Brennan, Samuel M. Cameron, and Mona-Liza C. Sirbescu
- 3) The mineralogy of the Waterloo quarry pegmatites, southern Wisconsin.
Thomas W. Buchholz, Alexander U. Falster and Wm. B. Simmons
- 4) A large scale boundary layer texture in the Mt. Mica pegmatite, Paris, Oxford County, Maine.
Myles M. Felch, Wm. B. Simmons, A. U. Falster, and K. L. Webber
- 5) Rare earth element pegmatites in the South Platte region of Colorado.
Rhiana Elizabeth Henry, Charles Stern, Julien Allaz, and Markus Raschke
- 6) Pegmatites of China: a bibliography.
Mark Ivan Jacobson
- 7) Mineralogy and petrology of NYF-type pegmatites of the mesoproterozoic Mount Rosa peralkaline granite complex, El Paso County, Colorado, USA.
Philip M. Persson, Alexander Gysi, Katharina Pfaff, and Markus Raschke
- 8) Unusual REE and rare element minerals from pegmatites and alkaline granites: thalenite and brannockite from the Golden Horn Batholith, Washington, and South Platte Pegmatite district, Colorado, USA.
Markus B. Raschke, Evan J. D. Anderson, Alexandra Skewes, Julien Allaz, Henrik Friis, Joseph Smyth, Charles Stern, Philip M. Persson, Rhiana Henry, Katharina Pfaff, Rudy Tschernich, and Randy Becker
- 9) Local structure of beryl group minerals from multinuclear NMR spectroscopy.
Luis Sánchez-Muñoz, Isabel Sobrados, Virginia Díez, Zhehong Gan, Sandra de Brito Barreto, Federico Pezzotta, and Jesús Sanz
- 10) Local structure of beta-eucryptite and beta-spodumene in the $\text{Li}_{1-x}\text{Al}_{1-x}\text{Si}_{1+x}\text{O}_4$ for $0 \leq x \leq 1$ in the LAS system by multinuclear NMR spectroscopy.
Luis Sánchez-Muñoz, Isabel Sobrados, Virginia Díez, and Jesús Sanz
- 11) Evidence for an anatectic origin of an LCT type pegmatite: Mt. Mica, Maine.
William B. Simmons and Alexander U. Falster
- 12) Topaz on America's Mountain (Pikes Peak).
Jack Thompson and Kaye Thompson

Hints on the Origin and Evolution of Spodumene Pegmatites in Southeast Ireland

Renata Barros^{1*}, Julian F. Menuge^{1,2} and Thomas Zack³

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Abstract: The Leinster pegmatite belt in SE Ireland occurs within the East Carlow Deformation Zone and comprises subvertical dykes of spodumene and spodumene-free pegmatites that intrude the eastern margin of the ~400 Ma S-type Leinster Granite, minor granitic intrusions and Lower Palaeozoic metasedimentary rocks. To investigate the origin of these pegmatites, previously suggested as residual magma after Leinster Granite extensive crystallization, we used geochemical modelling of *in situ* crystallization and batch melting to examine which process is more likely to be involved in their formation, and Rb-Sr studies to better resolve the age of emplacement of pegmatites and compare initial ⁸⁸Sr/⁸⁷Sr ratios of pegmatite and granodiorite. Results show that extreme concentrations of Li and Rb and depletion in Ba and Sr found in pegmatites cannot be reached by *in situ* crystallization starting with the average granodiorite composition, so it is unlikely that pegmatites represent residual granitic magmas. Batch melting calculations allow granodiorite and pegmatite magmas to have been formed in separate anatexis events from a feldspar-rich source for granodiorite and a feldspar-poor source for pegmatites. Rb-Sr muscovite-plagioclase isochron ages for granodiorite and spodumene pegmatite are indistinguishable, but distinct initial ⁸⁷Sr/⁸⁶Sr ratios of 0.7072±0.0040 for granodiorite and 0.7411±0.0056 for spodumene pegmatite support the hypothesis that pegmatite magmas formed in a separate event.

Introduction

Rare-element pegmatites are well known as sources of various commodities, but the mechanisms to form such unusual rocks and their magmatic origin are still being debated. The studied example in southeast Ireland is the Leinster pegmatite belt, formed by NE-SW meter-scale dykes that occur along the eastern margin of the Tullow Lowlands pluton, the largest within the S-type two-mica Leinster Granite. Dykes occur within the East Carlow Deformation Zone (McArdle and Kennedy 1985) and intrude the Leinster Granite, minor associated granitic intrusions and Lower Palaeozoic schist. Two types of pegmatites are observed: spodumene pegmatite, zoned or unzoned with aplite-rich sections, and spodumene-free pegmatite. They consist of spodumene (only in the first), quartz, albite, Li-muscovite, K-feldspar, spessartine, apatite and accessory minerals, mostly concentrated in the aplitic sections, including beryl, cassiterite, sphalerite and phosphates. Ages of emplacement for both granite and pegmatites are around 400 Ma (O'Connor et al. 1989, O'Connor et al. 1991) and it has been suggested that Li-rich pegmatitic fluids resulted from extreme fractional crystallization of the Leinster Granite (Whitworth and Rankin 1989, O'Connor et al. 1991, Whitworth 1992), even though a separate anatexis origin was not ruled out. We are investigating new samples of the pegmatite belt and country rocks to contribute to this debate.

Analytical approach

Leinster pegmatites and associated rocks rarely outcrop, thus samples were collected from new lithium exploration drilling being carried by International Lithium Corp. As a result of this campaign, an extensive litho-geochemical database and drill core of the entire thickness of several pegmatite dykes are available.

Geochemical modelling Half-core samples of homogeneous rock intervals were used for whole-rock geochemical ICP-MS analysis, carried out by ALS Minerals in Loughrea, Co. Galway, Ireland. Data was used to reconstruct the bulk composition of different rock types that occur in the area through the calculation of concentrations of analyzed elements as a mean of same-rock intervals weighted by core volume, and concentrations of key elements Li, Rb, Ba and Sr were used in geochemical modelling of pegmatites. Pegmatite formation as the final stage of crystallization of the average Leinster Granite's granodiorite was modelled with the equation of *in situ* crystallization proposed by Langmuir (1989):

$$C_L/C_0 = (M_L/M_0)^{(D-1)/[D(1-f)+f]} \quad (1)$$

C_L : concentration of the element in the magma; C_0 : initial concentration of the element in the magma; M_L : mass of the magma; M_0 : initial mass of the magma chamber; f : fraction of magma allocated to the solidification zone which returns to the magma chamber; and D : bulk distribution coefficient.

The hypothesis that pegmatites result from separate partial melts from a (meta)sedimentary source was also tested with the batch melting equation of Shaw (1970):

$$C_L/C_0 = 1/[D_{RS} + F(1 - D_{RS})] \quad (2)$$

In this case, C_L : concentration of the element in the magma; C_0 : concentration of the element in the unmelted source; D_{RS} : bulk partition coefficient of the residual solid; and F : weight fraction of melt produced.

Geochronology Representative samples of granodiorite and spodumene pegmatite were selected for LA-ICPMS *in situ* Rb-Sr dating at the Microgeochemistry laboratory at University of Gothenburg, Sweden. The novel routine, detailed by Zack & Hogmalm (under review), uses reaction gases O_2 or SF_6 that can separate Sr (reactive, mass-shifted) from Rb (non-reactive). By systematically analysing standards with precisely measured Rb/Sr ratios, correction factors can be used so that the measured $^{87}Sr/^{88}Sr$ and $^{85}Rb/^{88}Sr$ ratios are transformed to $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios for determination of isochron ages and initial $^{87}Sr/^{86}Sr$ ratios.

Modelling the origin of pegmatites

Models were calculated using average concentrations of Li, Rb, Sr and Ba in the four rock types and partition coefficients (compiled from Jolliff et al. 1992 and London 2008) for the granitic crystallizing assemblage (*in situ* crystallization) and solid residue (batch melting).

For equation (1), values of C_0 (initial magma) were considered to be the mean trace element concentrations calculated for the Tullow Lowlands pluton's granodiorite. For the fraction M_L/M_0 , values between 0.01 (99% initial magma, start of crystallization) and 0.99 (1% initial magma, end of crystallization) were considered; for f , values between 0.1 (10% liquid returned from solidification zone, representing very rapid crystallization) and 1 (all liquid returns from the solidification zone, representing Rayleigh fractionation) were used. Bulk partition coefficients (D) were calculated considering a crystallizing assemblage of plagioclase (40%), K-feldspar (25%), quartz (25%), biotite (5%) and muscovite (5%).

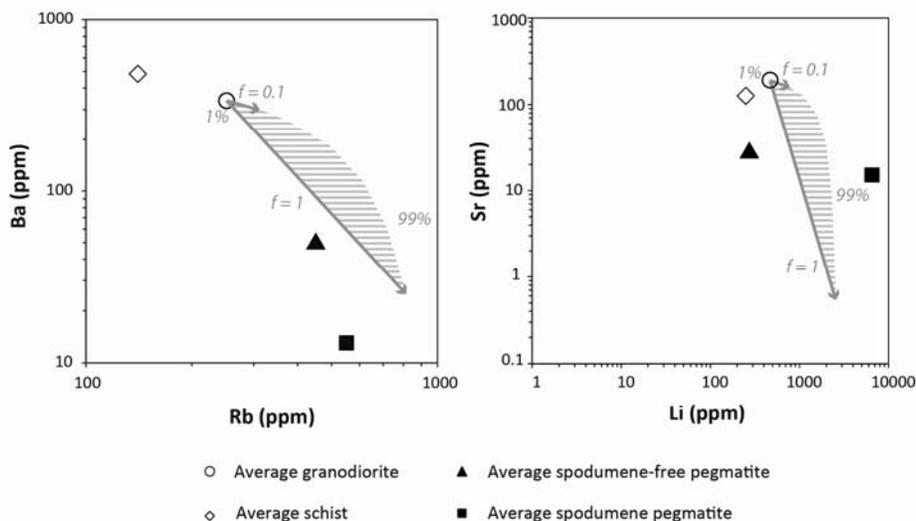


Figure 1. Bivariate plots for *in situ* crystallization modelling with the average Leinster Granite granodiorite as the initial magma. The arrows show the minimum (10%) and maximum (100%) fractions of liquid (f) returned to the main magma body from the solidification zone considered in this system – 100% return is equivalent to Rayleigh fractionation. The hatched areas show the range of values with other values of f between 0.1 and 1. Average composition of the schist is plotted for comparison.

The ranges of possible enrichment and depletion (C_L) of Ba, Sr, Rb and Li, with granodiorite as initial magma, are plotted on Fig. 1. Average concentrations for key elements in pegmatites are not within the ranges of possible

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

concentrations reached by *in situ* crystallization and the maximum limiting Rayleigh fractionation ($f = 1$). Depletion in Ba and enrichment in Li are insufficient to reach the composition of spodumene pegmatites.

Using equation (2), the weighted mean concentrations measured were considered as values of concentration in the generated melts (C_L), allowing calculation of the range of necessary concentrations in the source C_0 to generate these melts. The range of initial concentrations was calculated from 1% melting ($F = 0.01$) to 99% melting ($F = 0.99$). In order to calculate D_{RS} , the source was estimated to be quartz-feldspar-rich sediment, since partial melting of pelitic sediments would result in Li, Rb and Cs being retained in the mica-rich residual solid as partition coefficients are high for these elements (Jolliff et al. 1992 and references therein). The residual solid considered would be composed of quartz, feldspars and Al_2SiO_5 , thus allowing for all mica to be melted.

Possible initial concentrations in sources that can form melts with the compositions of average granodiorite and pegmatites are featured on Fig. 2. Considering a range of 1 to 40% of partial melting to form the three rock types (1 to 10% for pegmatites and 10 to 40% for granodiorite), the lines of initial concentrations converge to a restricted area representing little variation in the source for Rb (50 to 170 ppm), Li (30 to 640 ppm) and Cs (around 5 ppm, not illustrated). For Ba and Sr, initial concentrations converge to restricted areas for pegmatites (30 to 75 ppm Ba, 50 to 90 ppm Sr), but indicate a source more enriched in those elements for granodiorite (450 to 520 ppm Ba, 400 to 530 ppm Sr).

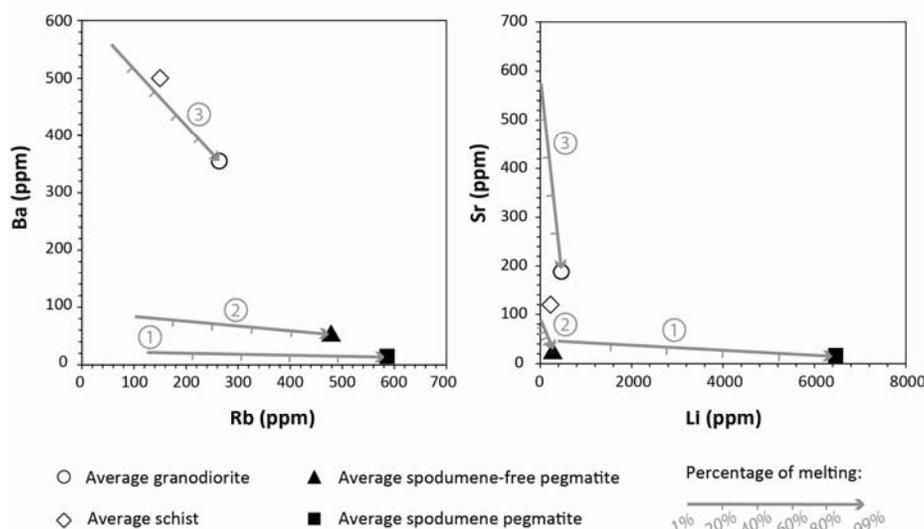


Figure 2. Bivariate plots for partial melting modelling. The arrows show the possible initial concentrations of the magma sources for spodumene pegmatite (lines indicated by the number 1), spodumene-free pegmatite (2) and granodiorite (3) if they underwent 1 to 99% of melting. Average composition of the schist is plotted for comparison.

Rb-Sr studies

A sample of spodumene pegmatite and a sample of granodiorite from a spodumene pegmatite chemical halo (both from Aclare) were chosen for *in situ* Rb-Sr dating. Using the reaction gases O_2 and SF_6 , measurements of ^{85}Rb , ^{88}Sr and mass-shifted ^{87}Sr and ^{88}Sr (to $^{87,88}Sr^{16}O$, $^{87,88}Sr^{19}F$) were carried out in 50 μm spots in muscovite and plagioclase crystals coexisting in equilibrium. Calculated $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios were regressed using Isoplot (Ludwig 2012) with the ^{87}Rb decay constant of $1,3972 \times 10^{-11} a^{-1}$ (Villa et al. 2015). Isochrons obtained yield indistinguishable granodiorite and spodumene pegmatite intrusion ages of ~ 390 Ma but distinct initial $^{87}Sr/^{86}Sr$ values of 0.7411 ± 0.0056 for spodumene pegmatite and 0.7072 ± 0.0040 for granodiorite (Fig. 3).

Implications for pegmatite formation

The chemical evolution of the average Leinster Granite's granodiorite by *in situ* crystallization and limiting Rayleigh fractionation models does not reach the average spodumene and spodumene-free pegmatites composition. A significant change in mobile elements Rb and Li at some stage between generation, ascent and emplacement of pegmatites or contamination by country rocks cannot be ruled out, as even though interaction zones and visible mineralogical haloes are restricted to less than 20 cm, chemical haloes can reach a few meters into granite and schist.

On the other hand, with a narrow range of source rock incompatible element concentrations and reasonable assumptions for degrees of partial melting, it is possible to form melts with the average composition of granodiorite, spodumene-free and spodumene pegmatites. As bulk concentrations of Ba and Sr would strongly depend on the amount of feldspars in these sediments, this variation can be explained by the presence of feldspar-rich and feldspar-poor source rocks, generating granodiorite and pegmatites, respectively.

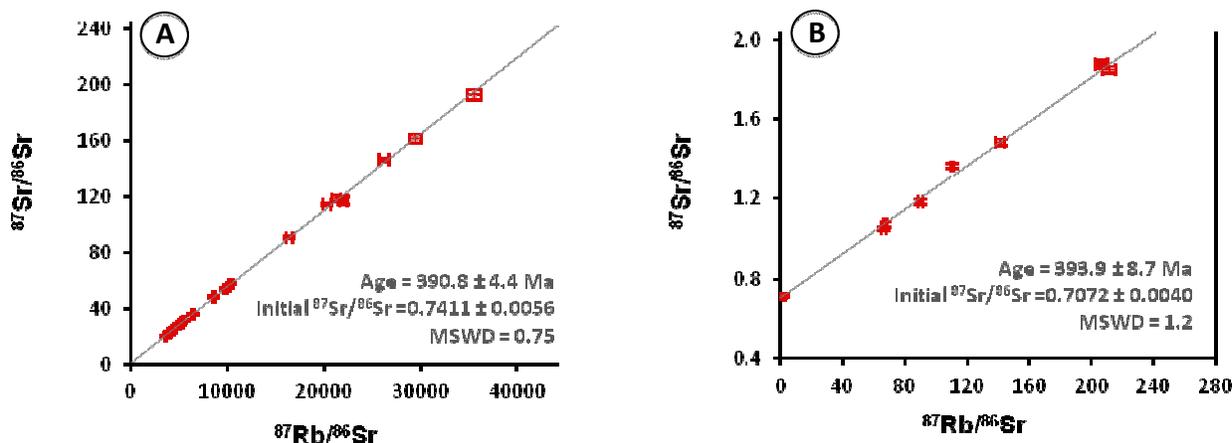


Figure. 3. Rb-Sr isochrons for (A) spodumene pegmatite and (B) granodiorite. Data-point error crosses are 1 σ .

The pegmatite emplacement age of 391 ± 4 Ma (Rb-Sr muscovite-plagioclase isochron), is significantly younger than the Leinster Granite Northern Pluton U-Pb monazite age of 405 ± 2 Ma (O'Connor et al. 1989). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio obtained for granodiorite is within the Leinster Granite batholith range of 0.7046 to 0.7106 (Mohr 1991) and approximates the transition between mantle and crust (0.7045), which could indicate interaction between upper mantle and lower crustal material during anatexis. The higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for spodumene pegmatite suggests a much stronger crustal contribution. This results support the hypothesis of separate events involving anatexis of different source rocks that generated melts with the composition of granodiorite and pegmatites, mobilized and emplaced into the active East Carlow Deformation Zone.

Conclusions and future work

Rare-element pegmatites in southeast Ireland are spatially associated with the S-type Leinster Granite's Tullow Lowlands pluton and their origin has been suggested as residual magma after extensive Leinster Granite crystallization. Geochemical modeling of *in situ* crystallization using the average granodiorite composition as initial magma results in a range of compositions that does not include pegmatites, so it is unlikely that they represent residual granitic magmas. Modelling of batch melting indicates that granodiorite and pegmatite magmas could have been formed in separate events and from chemically different source rocks (feldspar-rich source for granodiorite and feldspar-poor source for pegmatites). Pegmatite and granodiorite emplacement ages around 390 Ma and distinct initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for granodiorite and spodumene pegmatite reinforce the hypothesis that pegmatite magmas formed in a separate, younger event. Further work in geochronology will be carried out to investigate if the pegmatite belt was formed in one or various events, as observed in the Appalachians.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Tectonic Settings of LCT Pegmatites in the Context of the Supercontinent Cycle

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The global supercontinent cycle has been operating at least since the Neoproterozoic. Its timing is revealed by many proxy records, the two best being the age distribution of igneous rocks, and the age distribution of detrital zircons in modern sands. These show remarkably similar, episodic fluctuations through an order of magnitude, with a wavelength of roughly half a billion years. Maxima in the igneous rock population occur at 2700, 1880, 1055, 575,

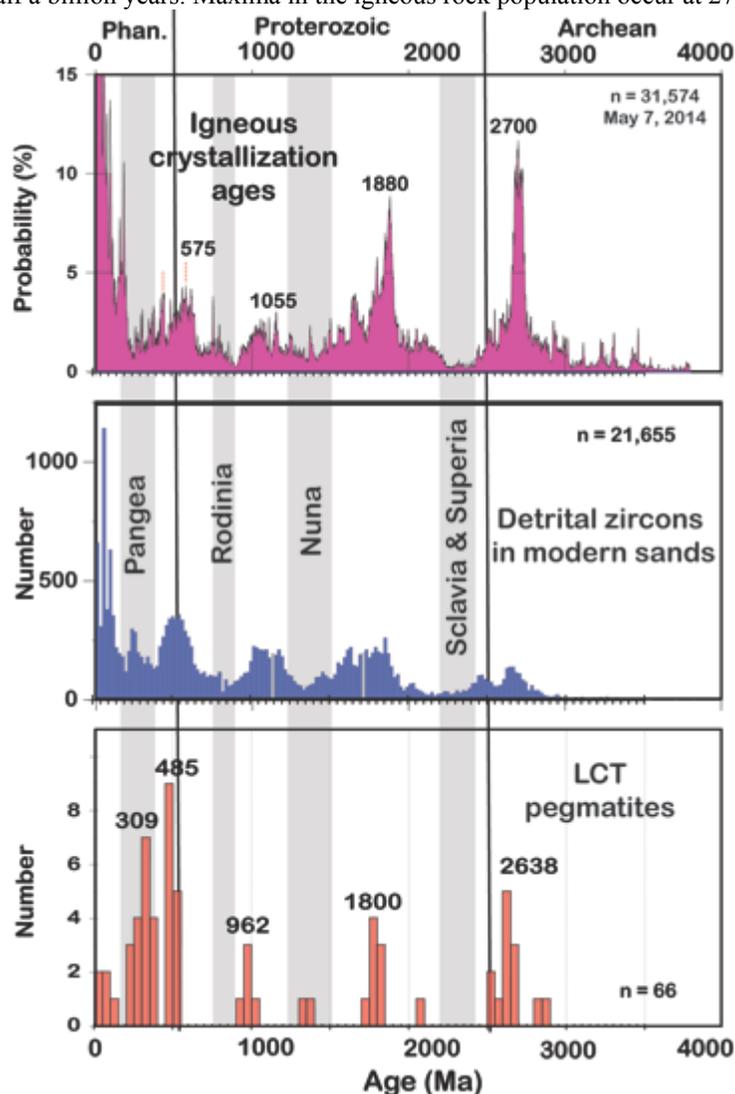


Figure 1. Comparisons among three similar age distributions shown in histogram form. The horizontal axis is time, spanning all but the first 10% of Earth history. (a) Igneous rocks, mainly $^{40}\text{Ar}/^{39}\text{Ar}$ ages in the Mesozoic and Cenozoic, and mainly U-Pb zircon ages in the Precambrian and Paleozoic, courtesy of Bruce Eglington. (b) Detrital zircons from modern sands, gleaned from the unfiltered version of the Voice et al. (2011) database. (c) LCT pegmatites, from McCauley and Bradley (2014).

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
 Colorado School of Mines campus, Golden, Colorado

and 0 Ma (Fig. 1). Except for the youngest maximum, which is an artifact of preservation, the maxima are times of supercontinent assembly and the minima are times of supercontinent tenure. Lithium-cesium-tantalum (LCT) pegmatites have a broadly similar global age distribution, with the most prominent maxima at ca. 2640, 1800, 960, 485, and 310 Ma (Fig. 1). This age distribution clearly links peak times of LCT pegmatite genesis to supercontinent assembly. The fact that LCT age maxima are slightly younger than the corresponding ones in the igneous rock and detrital zircon age distributions is consistent with emplacement of LCT pegmatites late in the local sequence of orogenic events (Černý 1991). Three factors are involved in producing the maxima that mark supercontinent assembly. (1) Global plate flux varies during the supercontinent cycle as plate boundaries are created and destroyed (Bradley 2011). (2) Preservation potential of igneous rocks and zircons is thought to vary through the supercontinent cycle (Cawood et al. 2013); and (3) Most collisions are accompanied by late magmatism, which is a delayed consequence of plate convergence. This effect explains the age distribution of LCT pegmatites.

The detailed tectonic setting of LCTs is potentially important for both pegmatite genesis and for exploration in frontier areas. Specific plate settings and triggering mechanisms have been worked out for very few LCT pegmatites. These could include: ordinary arc processes; over thickening of continental crust during collision or subduction; synorogenic shear heating; slab breakoff during or after collision; slab delamination before, during, or after collision; and late collisional extensional collapse and consequent decompression melting. Many of these mechanisms involve the mantle.

The LCT pegmatites with the best-constrained tectonic setting, on Elba, are also the youngest. The Elba pegmatites were emplaced into the extended hinterland of the Apennine orogen, an Oligocene to late Miocene east-directed arc-continent collision zone (Malinverno and Ryan, 1986), which can be seen as one of many orogenies contributing to the eventual assembly of the next supercontinent after Pangea. The Apennine foreland basin, thrust belt, and orogenic hinterland are a classic example of tectonic belts that migrated in tandem across strike. The country rocks at Elba are part of a thrust stack of continental and oceanic rocks. The pegmatites are spatially and genetically associated with the Monte Capanne pluton, which has a Rb-Sr isochron age of 6.9 Ma (Dini et al. 2002). The pluton and pegmatites have been exhumed from an emplacement depth of ca. 4.5 kilometers along a synmagmatic (Smith et al. 2010) extensional detachment. Extension was a consequence of slab rollback of the lower plate (Malinverno and Ryan 1986) (Fig. 2). Magmatism (mainly crustal melts with a mantle influence) was the consequence of decompression melting (Malinverno and Ryan 1986; Serra et al. 1993). All of this happened in a relatively arid setting as recorded by the widespread latest Miocene evaporites throughout the Mediterranean region (Rouchy and Caruso 2006).

A number of older pegmatite districts are clearly related to collisional orogenesis, but they cannot yet be tied with as much certainty to specific plate-tectonic events. In the Paleoproterozoic Sveconorwegian collisional orogen of Sweden, lepidolite-bearing pegmatites were emplaced after deformation and metamorphism, and just before late-orogenic extensional collapse (Romer and Smeds, 1996). In a recent synthesis of Siberian pegmatites, Zagorsky et al. (2014) related the Ordovician Tastyg and Sutlug pegmatites of the South Sangilen province to a transition from collision to post-collisional extension and strike-slip.

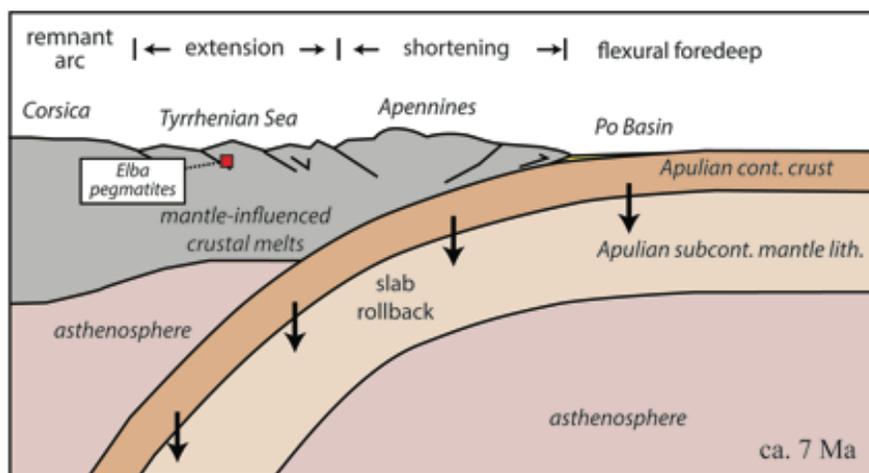


Figure 2. Schematic cross section through Apennines and Tyrrhenian Sea at about 7 Ma (Late Miocene) showing simultaneous foreland thrusting and hinterland extension, and location of the Elba pegmatites when they were emplaced (adapted from Serri et al. 1993).

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Gem-bearing LCT pegmatites of San Diego County, California (Fisher, 2002) are widely held to have formed above a continental-margin subduction zone (Ortega-Rivera, 2003). Although the pegmatites are relatively young, the plate-tectonic record is debatable because of the loss by subduction of vast amounts of seafloor. Most of the pegmatites intruded into plutonic rocks of the Peninsular Ranges Batholith (Symons and others, 2009), which contains multiple intrusive phases dated from ca. 140 to 80 Ma (Ortega-Rivera, 2003). A $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite age of 95.4 ± 0.3 was reported from the Himalaya pegmatite (Snee and Foord, 1991). Tectonic interpretations of events at ca. 95 Ma are problematic (Todd and others, 1999); possibilities include crustal thickening driven by westerly-directed intra-arc shortening (George and Dokka, 1994), crustal thickening because of collision of an outboard arc (Johnson et al. 1999), or lithospheric delamination after collision between the Peninsular Ranges arc and North America (Hildebrand, 2009). The latter two hypotheses, though controversial, open the possibility that the best candidate for a subduction-related LCT pegmatite district is actually collision-related.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Crystallization of the Fisher Quarry Pegmatite, Sagadahoc Co., Maine: Preliminary Insights from Fluid Inclusions

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Abstract: The Fisher quarry is a relatively poorly differentiated, zoned, miarolitic pegmatite belonging to the beryl-columbite Brunswick pegmatite field of southwestern Maine. Fluid inclusion research on graphic and miarolitic quartz from the zoned Fisher pegmatite dike was conducted using microthermometry and Laser Ablation-ICP MS to better understand the temperature regime and the fluid evolution during the sequential crystallization of the pegmatite. Rigorous petrographic examination integrated with cathodoluminescence photography served to identify the very rare occurrences of primary H₂O-CO₂ fluid inclusion assemblages trapped from fluid-undersaturated magmatic stage. Preliminary fluid inclusion results indicate that the wall zone and intermediate graphic granite formed in the range of about 500 to 575 °C at a pressure of 2.5 kbar. Single terminated quartz from miarolitic cavities crystallized from about 300 to 425 °C, with late secondary, aqueous inclusions trapped at a temperature as low as 275 °C.

Introduction and historic perspective

The Fisher Quarry pegmatite, Topsham, southwest ME belongs to the Brunswick beryl-columbite pegmatite field (Wise *et al.* 2012). It has a mixed signature with accessory uraninite and gahnite and miarolitic lepidolite-topaz-hydroxylherderite-beryl with minor elbaite tourmaline and apatite. The Fisher has been mined sporadically for industrial feldspar and mineral collectibles since 1852 to present. Despite its modest enrichments in rare elements and minor gemstone findings, the Fisher pegmatite has attracted mineralogists and petrologists since at least 1909 (Bastin, 1912), perhaps because of its remarkable graphic quartz-feldspar intergrowths (Fig. 1) and miarolitic character, a rare feature for the Brunswick pegmatite field. Wright and Larsen (1909) included samples from the Fisher pegmatite in their pioneer study that proposed the use of quartz as a geologic thermometer.

B



A



Figure 1. Geometric varieties of quartz-feldspar intergrowths from Fisher quarry. A) Medium-grained graphic quartz in K-feldspar. B) Smoky quartz "snowflakes" in plagioclase. Scale in centimeters.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016 Colorado School of Mines campus, Golden, Colorado

A large miarolitic cavity > 3 x 1.5 m wide discovered in 1929, yielded topaz, beryl, hydroxylherderite, gahnite, and microlite collected by the Harvard Museum (Palache 1934). Modern studies of the pegmatites of the Brunswick field focused on their U-Pb monazite age (Tomascak *et al.* 1996), sources of pegmatite melts using Sm-Nd isotope systematics (Tomascak *et al.* 1998), and fractionation trends in comparison to the more differentiated pegmatites from Oxford field, southwestern Maine, using columbite-group mineralogy (Wise *et al.* 2012).

Problem statement

Graphic granite has been interpreted as a consequence of rapid crystallization of a fluid-undersaturated viscous melt subjected to large degree undercooling (150 to 250°C below the liquidus) in which Si and Al have very low diffusivities (London 2009). Our aim is to better understand 1) the conditions that led to the formation of quartz-feldspar intergrowths of unusual geometric varieties during the course of magmatic crystallization and 2) the fluid compositional evolution that led to the topaz-beryl-hydroxylherderite-tourmaline occurrence at the late, miarolitic stage. Various types of graphic quartz-feldspar and subhedral, single terminated quartz from the Harvard pocket were selected for this fluid inclusion study. The samples were collected in 2012 and 2014, when the quarry was reopened, cleaned of debris, and quarried in search for additional pockets by JC Mining.

Regional and local geology

The Fisher pegmatite is part of the Northern segment of the Brunswick pegmatite field intruding the metamorphic rocks in the upper-amphibolite facies named the Falmouth-Brunswick sequence (Hussey and Berry 2002). The nearly NS trending granitic pegmatites and associated small bodies of leucogranite crystallized within a narrow time frame from 274 Ma to 268 Ma (Early Permian; Tomascak *et al.* 1998) whereas the surrounding country rock is 471 ±3 Ma (Middle Ordovician; Hussey and Berry 2002). The granitic pegmatites in this area are rich in beryllium, rare-earths, and niobium. Accessory minerals at Fisher include garnet, gahnite, columbite, several uranium minerals, and Fe-rich columbite (Wise *et al.* 2012) but it stands out for its Li-Be-F rich miarolitic cavities with topaz, lepidolite, muscovite var. schernikite, beryl var. aquamarine and heliodor, pink fluorapatite, and tourmaline var. elbaite, indicolite, and foitite.

The Fisher is a nearly vertical, several hundred meter long dike intruding older migmatites, specifically biotite and amphibolite schists. The contacts with the country rock are sharp, mostly discordant. Most samples included in this study were collected along a 25 m wide, wall to wall W-E traverse through the original Harvard pocket. In this area of the quarry the dike is symmetrically zoned with a 4-5 m thick outer zone dominated by graphically intergrown perthite-quartz and biotite megacrystals of up to 5 m long; and a 10-15 m thick inner zone with more irregularly intergrown quartz-Na-rich plagioclase surrounding a discontinuous 4-5 m thick core dominated by massive quartz-cleavelandite-perthite with coarse beryl and sheet muscovite. With the exception of the miarolitic zone, the Fisher has no tourmaline. About 4 m wide and as much as 10 m deep trenches followed the K-feldspar rich wall zone mined out for pottery in the 1800's and early 1900's. The 2014 exposure suggested that the miarolitic cavities appear to be distributed along two parallel alignments at the border between the Na-rich zone and the core: the original Harvard pocket alignment is about 7 m from the west contact and the newly discovered Black Bear pocket alignment, about 11 m from the east contact.

Methods and summary of results

Twenty doubly-polished, 150 µm thick sections were cut from selected quartz-rich samples for fluid inclusion microthermometry and Laser Ablation ICP-MS. Larger slabs of quartz-feldspar intergrowths were scanned for image analysis. The digital images were processed and analyzed to quantitatively describe the geometry of the intergrowths in comparison with synthetic analogues of known P-T conditions and composition (Sirbescu *et al.* 2015a, b).

The quartz-hosted fluid inclusions in this study were cavities 5 to 80 µm in size occupied by a mixed H₂O-CO₂ fluid (Type 1) or aqueous fluid (Type 2). We focused on fluid inclusion assemblages (FIA's) of primary and pseudosecondary nature because they can reveal the physical and chemical conditions during crystallization of the host mineral from a silicate melt or hydrothermal fluid. Secondary inclusions trapped along fractures in the miarolitic quartz were also investigated to understand the evolution of the pocket fluid. Regular petrographic

microscopy was used to characterize and map the primary and secondary fluid inclusion populations. Cold-cathode cathodoluminescence (CL) photography was used to validate the primary character of the three-dimensional clusters.

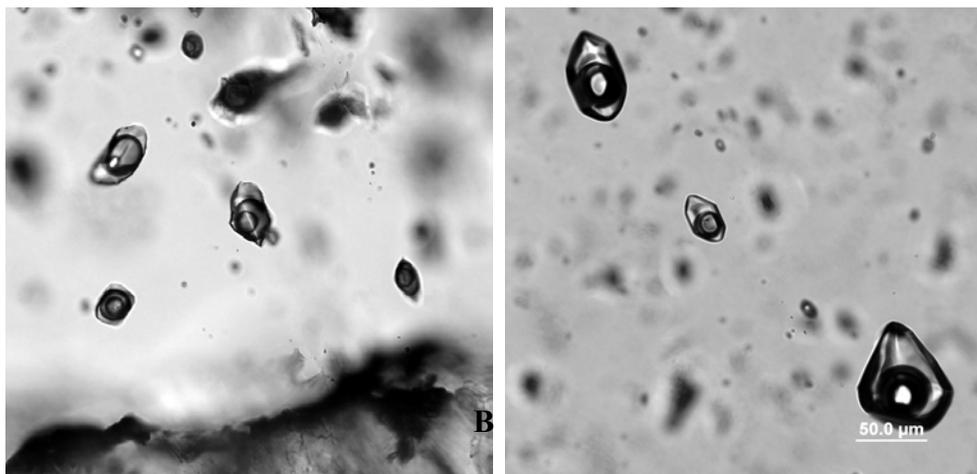


Figure 2. Primary, three phase fluid inclusions of Type 1 - H₂O-CO₂ with low salinity from Fisher Quarry pegmatite, Maine. A) Quartz host is from a “snowflake”, irregularly intergrown quartz-plagioclase sample in the intermediate zone; B) Quartz host is a single terminated crystal from the Harvard pocket, collected by Sirbescu in 2012.

Microthermometric measurements of relevant phase changes including dissolution of chathrate, homogenization of CO₂, and final inclusion homogenization were conducted on a Linkam THMSG 600 heating-freezing stage to determine the major constituents, salinity, and density of fluid inclusions. The pressure-temperature conditions of formation were then calculated based on appropriate equations of state using MacFlincor software. In addition, the detailed chemical composition of FIA's in one selected sample was analyzed using Laser Ablation Ion Coupled Plasma –Mass Spectrometry on an Agilent 7500ce ICP-MS coupled with a Geolas laser ablation system.

Our microthermometric results indicate significant differences between primary FIA's from graphic quartz of various geometries and miarolitic subhedral quartz in terms of frequency, composition, and homogenization behavior. Graphic quartz samples contain extremely rare inclusions of unambiguous primary character that are three-phase Type 1, H₂O-CO₂ mixtures with a relatively high volume fraction of CO₂ (Fig. 2) corresponding to a molar fraction of water $X_{\text{H}_2\text{O}}$ of 0.73 ± 0.12 (N=30 inclusions). In contrast, primary inclusions in miarolitic quartz are quite common and can be both of Type 1 (with a higher $X_{\text{H}_2\text{O}}$ of 0.94 ± 0.01 , N=22) and Type 2, two phase, aqueous inclusions of low salinity ($X_{\text{NaCl}}=0.016 \pm 0.002$, N=21). As expected, the homogenization temperature (not corrected for pressure) is higher in the graphic samples that crystallized from a silicate melt compared to miarolitic samples. T_h in an irregularly shaped quartz-plagioclase intergrowth ranged from 290 to 365°C whereas T_h in a Harvard pocket sample ranged from 273 to 294°C. Secondary aqueous FIA's in homogenized at temperatures ranging from 130 to 207°C.

In spite of the moderate to low salinities of inclusions in the miarolitic quartz, they are quite enriched in elements characteristic for LCT pegmatites. Systematic analysis of primary inclusions trapped in growth zones of a 4x5 cm single terminated quartz revealed that the composition of miarolitic fluid oscillated during growth and contained Li < 1,500 ppm ($Li_{\text{ave}} = 320$ ppm); Na < 24,520 ppm ($Na_{\text{ave}}=5,620$ ppm); K < 1220 ppm ($K_{\text{ave}}=200$ ppm); B < 5,325 ppm ($B_{\text{ave}}= 3860$ ppm); Al < 9,200 ppm ($Al_{\text{ave}}=680$); Cs < 2,470 ppm ($Cs_{\text{ave}} = 440$ ppm); and W < 3.7 ppm ($W_{\text{ave}}=1.3$ ppm). Divalent cations such as Mg, Ca, Mn, and Fe were typically below detection.

Preliminary interpretations and conclusions

The scarcity of primary inclusions in graphic quartz demonstrates that the wall and intermediate zones crystallized in conditions of fluid undersaturation. The rare clusters of primary fluid inclusions were typically found within <200 µm of euhedral edges of graphic quartz. These primary inclusions are interpreted to represent conditions of local fluid saturation reached in the front of crystallization of rapidly growing skeletal crystals. This mechanism of fluid-inclusion trapping has been previously observed in experiments (Sirbescu *et al.* 2015a, b).

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Colorado School of Mines campus, Golden, Colorado

In summary, preliminary fluid inclusion results indicate that the wall-zone and intermediate-zone graphic granite formed at temperatures of about 575 to 500 °C at a pressure of 2.5 kbar estimated from geologic literature (Tomascak *et al.* 1998 and references therein). This corresponds to an undercooling of 140 to 220°C below the liquidus of a hydrous granitic melt. Within analytical error, this range of undercooling matches experimental conditions that produced analogous textures (Sirbescu *et al.* 2015a, b), although additional fluid inclusion data are needed to confirm the observed similarities.

Subhedral quartz from miarolitic cavities crystallized from about 300 to 425 °C and was affected by secondary aqueous fluid at a temperature as low as 275 °C. As temperature decreased from the magmatic to hydrothermal stage, the molar fraction of H₂O increased, possibly because of immiscibility of the CO₂-rich and H₂O-rich fluids. Our systematic study of a pocket-quartz crystal revealed that its crystallization took place mainly from a CO₂-H₂O Type 1 fluid, but, during its growth history, there was an episode when the crystal grew from an aqueous Type 2 fluid. The variation in concentration of the included solutes among the pocket-quartz growth zones may be a consequence of sequential crystallization of various pocket minerals or of the fact that the miarolitic cavities behave as open systems.

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Pegmatite Mineralogy of the Waterloo Quarry, Southern Wisconsin, USA.

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Abstract: Operations in the Michels Materials Waterloo Quarry have exposed pegmatites intruded into Proterozoic metasediments. The pegmatites, weathered moderately to severely, exhibit an evolved mineralogy. Age of the pegmatites may be roughly in accordance with intrusion of the Wolf River Batholith at about 1465 Ma, but the overall peraluminous and evolved chemistry of the pegmatites is inconsistent with the anorogenic, alkalic trend shown by Wolf River magmatism elsewhere in Wisconsin.

The Precambrian basement in southern Wisconsin is largely buried under Paleozoic sedimentary rocks, with the exception of sparse outcrops. Outcrops of Proterozoic quartzite and metapelite occur near Waterloo, Wisconsin, where they are quarried in the Michels Materials Waterloo Quarry for use in railroad ballast and aggregate. The Waterloo quartzite and metapelite are part of the Baraboo Interval metasediments, and were metamorphosed to amphibolite facies at about 1668 ± 23 Ma, during the Mazatzal orogen (Stonier, 2006).

Several pegmatites outcrop in the Waterloo quarry, primarily emplaced in metapelite and less commonly, in quartzite. Most are thin dikes approximately 20-30 cm thick that appear to be randomly oriented in the host quartzite, though one thicker dike up to about 3 meters thickness was recently exposed. All pegmatites initially exposed were highly weathered, with most feldspars and garnets altered to white kaolinite and iron/manganese oxides; other major constituents were lithian muscovite (Li_2O content of up to 0.98 wt %) and quartz. As operations have proceeded deeper, less altered pegmatites have been exposed, with more or less well preserved microcline, albite, spessartine (essentially Ca-free) and sporadic lepidolite (Li_2O up to 2.05 wt %). Kaolinite alteration is probably of Cambrian-Ordovician age, prior to deposition of Paleozoic sediments. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of muscovite from a fresh pegmatite sample has given a good plateau age at 1455 ± 5 Ma (Medaris, L.G., pers. comm. 2006), and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of a muscovite grain from the Waterloo quartz-muscovite-andalusite schist yielded a plateau age of 1452 ± 7 Ma (Medaris et al. 2003), while Aldrich et al. (1959) reported a Rb/Sr date of approximately 1,440 Ma obtained from muscovite from a pegmatite outcropping in a nearby river. These dates are in general accord with regionally widespread Wolf River age magmatism and contact metamorphism (1465 Ma, Medaris et al. 2003) and suggest that the pegmatites may be derived from a Wolf River age intrusion.

Columbite-tantalite group minerals are common but are inconspicuous due to their small grain size, forming prismatic crystals up to about 900×50 μm . Mn enrichment is pronounced and Ta-enrichment is modest to pronounced, with compositions falling into the manganocolumbites and manganotantalite fields; there are two distinct composition trends present in these small dikes, one clustering around a Nb-dominant composition and the other clustered around a Ta-dominant composition. TiO_2 contents range from 0.4 to 0.9 wt. %. Sn, Bi, and Sb were not detected. In less weathered dikes small grains of Bi-rich microlite to approximately 0.4 mm embedded in feldspar. EMP analysis indicates $\text{Bi} > \text{Ca} + \text{Na}$.

Gahnite is common and occurs as small aggregates to approximately 2 mm and as well-formed octahedral crystals to approximately 500 μm . MnO content ranges from 0.4 to 1.1 wt. % and FeO content ranges from 1.5 to 2.9 wt. %. Additional minerals noted include fluorapatite (less than 100 μm in length), goethite (sprays of acicular crystals), ilmenite (crude hexagonal platelets), small grains of a LREE-Ca phosphate (likely monazite or rhabdophane), zircon and a grayite-like mineral. Native Bi forming branching elongated crystals on surfaces of quartz grains is locally common in the highly weathered pegmatite material, and small masses of Bi have been found embedded in quartz grains. The exposed native Bi is commonly replaced by kettnerite and beyerite, as indicated by XRD study, and waylandite is found as small well-formed crystals in open spaces, associated with kettnerite and native Bi.

Small grains of a Th-Si mineral with significant P contents, possibly a thorite-like phase, are uncommon. Grains of this phase from pegmatite #10 show V_2O_5 contents of 1-1.5 wt %. To the authors' knowledge, significant vanadium in such a thorite-like phase has not been previously reported.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Overall, the mineralogy of these pegmatites indicates evolved, peraluminous compositions. The genetic affiliation of these pegmatites remains enigmatic; their apparent peraluminous nature is inconsistent with the anorogenic alkalic Wolf River age magmatism elsewhere in Wisconsin. Perhaps their peraluminous nature is a consequence of the source of their parental melts being significantly different from the sources for the more typical Wolf River alkaline magmatism. As their parental granite is not exposed, nor has it been accessed by drill core or other means, at present nothing can be said about its nature.

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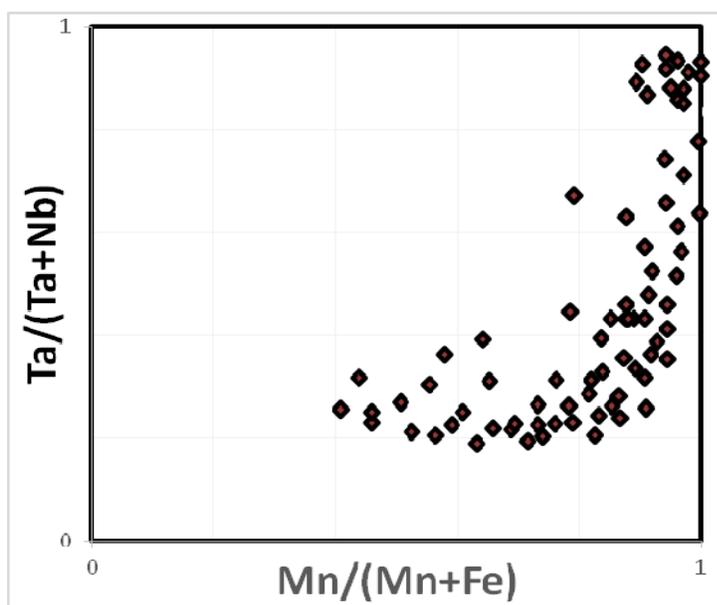


Figure 1. Waterloo Quarry Columbite-Tantalite Quadrilateral



Figure 2. Gahnite, Waterloo Quarry Dike #1. 0.8 mm crystal, D. Behnke photomicrograph.

Vieirópolis Pegmatite Field, Northwest of Paraíba State, Brazil: New Occurrences of Amazonite Pegmatites

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Abstract: The Vieirópolis Pegmatite Field is located in the area surrounding the municipality of Vieirópolis in the state of Paraíba, Brazil, to the west of the Seridó Pegmatite Province, a region known for its unusual variety of pegmatites, which are essentially of the LCT family. This field consists of veins, lenses and dikes of pegmatites injected in NNW-SSE-striking fractures in a which cut Ediacaran monzogranites and syenogranites of the Dona Inês intrusive suite. The emplacement of the latter was controlled by NE-SW-striking, dextral shear zones within the Rio Piranhas terrane of the Rio Grande do Norte Domain. The pegmatites of Vieirópolis are characterized by massive amazonite mineralization of ornamental stone quality, and on a smaller scale, aquamarines as well as considerable concentrations of quartz, biotite and magnetite. The absence of minerals of the LCT family and the presence of minerals such as fluorite and amazonite indicate an affinity with those of the NYF family, registering an increase in the knowledge, from a scientific point of view, concerning pegmatites in the northeast of Brazil.

Introduction

The northeast of Brazil is home to an area of numerous pegmatite occurrences in the states of Paraíba and Rio Grande do Norte. This region was given the name Borborema Pegmatite Province (BPP) by Scorza (1944). It is geologically within the Borborema Province in the context of Rio Grande do Norte Domain. Recent studies, mainly those of geotectonic nature, show that the Borborema Pegmatite Province is distributed throughout the Seridó Folded Belt, for which reason it has been called Seridó Pegmatite Province (SPP) recently (Santos et al. 2014).

The granitic pegmatites of SPP are hosted by supracrustal rocks of Borborema covering an area of approximately 75 x 150 km. More than 750 mineralized pegmatites registered until now, about 80% of those are embedded in garnet-cordierite-biotite-quartz or silimanite-garnet-biotite-quartz-shale of the Seridó Formation. Less than 10% occur in quartzites, metaarcoses and metaconglomerates of the Equador Formation and the rest is embedded in gneisses and skarns of the Jucurutu Formation, late- to post-orogenic granites and more rarely, basement rocks (Da Silva et al. 1995).

The pegmatites of this province belong mainly to the Lithium-Cesium-Tantalum (LCT) family of class and subclass, respectively, rare earth elements or litiniferous, made up of muscovite, quartz and microcline, with varying degrees of albitization. Since the Second World War the SPP has produced large quantities of industrial minerals including feldspar, quartz, and micas, the rare element minerals columbite-tantalite, beryl, and cassiterite and gem-quality spodumene, tourmaline, garnet, euclases among others.

Most recently several clusters of new pegmatite occurrences with economic potential 180 km west of SPP have been identified. In the frame of ongoing projects these occurrences are systematically mapped, sampled and analyzed, including those making up the Vieirópolis Pegmatite Field in the Sertão region of northwest Paraíba (Fig. 1).

The Vieirópolis Pegmatite Field

The Vieirópolis Pegmatite Field is situated in the municipality of Vieirópolis, in the extreme northwest of the state of Paraíba. The basement rocks of this area comprise Paleoproterozoic orthogneisses, migmatites and

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
 Colorado School of Mines campus, Golden, Colorado

amphibolites with a structural NE-SW trend induced by Neoproterozoic (Ediacaran) dextral shearing. These structures controlled the positioning of the intrusive Ediacaran granite suites of Itaporanga and Dona Inês. The granodiorites and monzodiorites of the Serra Branca pluton, which belongs to the Dona Inês Suite, hosts pegmatite dikes and veins of the Vieirópolis Field, which were emplaced along extensional NNW-SSE fractures. These bodies occur in the form of veins, lenses or tabular dikes with the presence of amazonite, albite, quartz, biotite, magnetite, beryl, galena, fluorite and other minerals.

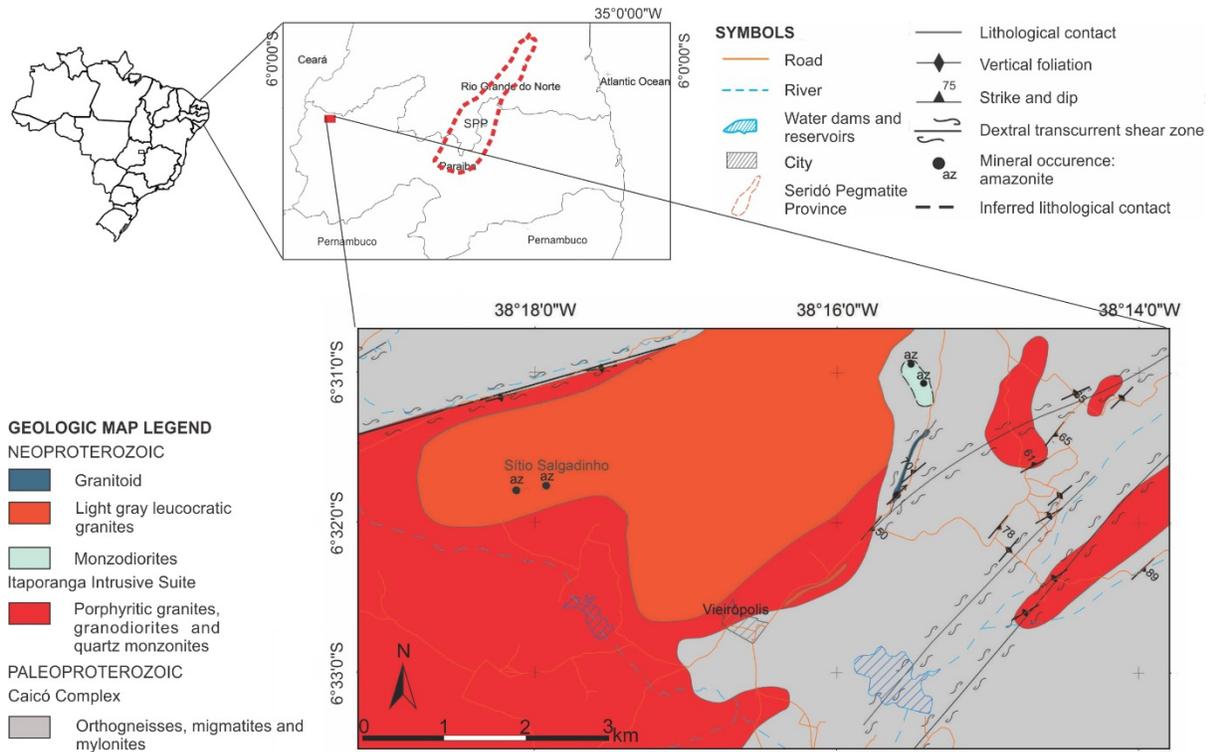


Figure 1. Simplified geological and localization maps of the Vieirópolis Pegmatite Field in the Sertão region of northwest Paraíba.

Amongst the pegmatites identified so far, two bodies with remarkable size and mineralization stand out. The first pegmatite is located to the south of the Serra Branca pluton, named Sítio Salgadinho pegmatite, and occur as a heterogenic dike with the essential minerals laid out in an irregular manner, resulting in a simple but asymmetrical zoning. The outcrops shows a milky quartz core, an area rich in potassic feldspar (pink and amazonite) and an intermediate zone rich in albitic feldspar, blue beryl, smoky quartz, biotite and magnetite.

The mineralization of blue beryl occurs in the quartz of the core and the intermediate zone, presenting gemological quality crystals (aquamarines) and which makes this body unique inside the pegmatite field, and has been, therefore, exploited by collectors of the region in the last years. The second pegmatite is found to the northeast of the Serra Branca pluton and forms of a tabular dike (Fig. 2.). The dike is up to three metres in thickness and several hundred meters long, dipping 45° WSW. This heterogenic body is sectioned into two relatively parallel zones that follow its strike: the lower zone rich in sugary albite and quartz and the upper zone made up of megacrystals of greenish blue amazonite surrounded by breccoid matrix of albite, quartz, biotite, magnetite and accessory minerals such as helvite, fluorite and galena.

From a socio-economic point of view, the mineralization of amazonite represents an important mineral resource in this region and is currently mined by the *Granistone* company for mineral artifacts and ornamental stone for the national and international market.



Figure 2. (A) Mineralization of blue beryl, amazonite and quartz from the Sítio Salgadinho Pegmatite. (B) Transverse section of a WSW-ENE direction in tubular pegmatite mineralized in amazonite, showing zoning. Upper zone is made up mainly of amazonite in brecciid matrix. Lower zone is made up mainly of sugary albite and smoky quartz.

Discussions and Conclusions

Studies of occurrences of amazonite suggest that these are to be found in two main contexts: (i) in granitic pegmatites of the NYF Family (niobium, yttrium, fluorine) and intrusive rocks resulting from anorogenic magmatism, from a period of lower crust tectonism and distension; and (ii) in granitic pegmatites associated to deposits of massive sulfide (e.g. Broken Hill, Australia) (Martin, Vito & Pazzota 2008). The presence of fluorite and amazonitic potassic feldspar and the absence of minerals typical of the LCT family such as spodumene, lepidolite and tantalite-columbite commonly found in the Seridó Pegmatite Province, suggest an NYF affinity for pegmatites mineralized in amazonite, which corresponds to a fundamental increase in knowledge concerning pegmatites in northeast Brazil.

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Mineralogy, geochemistry and geochronology of allanite pegmatites on the KIN property, eastern British Columbia

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Abstract: REE-, Nb-, Mo-bearing NYF-type pegmatites on the KIN property intrude amphibolite-grade rocks of the Neoproterozoic Horsethief Creek Group in the Omineca Belt of the Canadian Cordillera. The Cordillera has traditionally been associated with LCT-type pegmatites, making the presence of NYF-type pegmatites on the KIN property particularly unusual. These pegmatites contain significant amounts of allanite-(Ce), monazite-(Ce), chevkinite-(Ce), aeschynite-(Ce), euxenite-(Y), Nb-rich rutile, ilmenite, amphibole, and fluorapatite within a matrix of plagioclase, Ba-rich feldspar and quartz. U-Pb dating of zircon from the pegmatites yielded a crystallization age of ~79 Ma. Furthermore, geochemical data suggest that the pegmatites formed from an A-type source. Along with the NYF-type pegmatites, (nepheline-) syenites and coarse-grained I-/S-type muscovite granites are located on the property. Geochemical similarities suggest a possible genetic link between the syenites and the pegmatites; however, syenite in the immediate area has been dated to 378 Ma, nearly 300 million years older than the pegmatites. Furthermore, U-Pb dating of zircon from the muscovite granite yielded a crystallization age of ~76 Ma, i.e. 3 Ma younger than the allanite pegmatites. Based on geological, geochemical and geochronological data, we suggest that the allanite pegmatites formed by partial melting of the syenites at ~79 Ma, during the Laramide orogeny. Subsequently, the pegmatites were affected by metamorphism caused by the intrusion of muscovite granite sills, at 76 Ma.

Introduction and geological settings

Deformed REE-, Nb-, Mo-bearing pegmatites were discovered in 2011 on the Trident and KIN properties ca. 95 kilometers northeast of Revelstoke, British Columbia. They are hosted in amphibolite-grade metasedimentary rocks of the Neoproterozoic Horsethief Creek group, and located ca. 12 km SE of the Trident Mountain (nepheline-) syenite, and ca. 3 km E of the closest nepheline syenite outcrop. The pegmatites occur in a ca. 2.5 km long and 100 m wide zone, forming lenses and boudins ca. 0.1-5 meters thick and typically ca. 10-20 m long.

The syenite found in the area is medium- to coarse grained and it is mainly composed of plagioclase, K-feldspar, and amphibole, with minor amounts of nepheline, biotite, titanite, zircon and allanite. Geochemical analyses of the syenite show elevated LREE values with La and Ce values of up to 209 ppm and 328 ppm, respectively (Brown 2012).

Sills of undeformed muscovite granite were discovered in proximity to the pegmatites during our field work in 2014. They are very coarse grained with books of muscovite up to 10 cm in size as well as quartz and feldspar crystals up to 25 cm in size. They are primarily composed of quartz, plagioclase, muscovite and accessory garnet. Subordinate REE mineralization is present in the form of monazite (LREE) and xenotime (HREE). Geochemical data suggest that these granites are peraluminous I/S-type granites (Fig. 1) with high SiO₂ contents (69.2-74.5 wt%).

Pegmatite mineralogy

The pegmatites are irregularly zoned in their textures and mineral contents; four texturally and compositionally distinct zones can be distinguished: (1) amphibole+allanite border zone; (2) albite+biotite+garnet wall zone; (3) intermediate albite+allanite+columbite zone, and (4) the quartz core.

The **amphibole+allanite border zone** contains actinolite and quartz with euhedral allanite-(Ce) crystals up to 2 cm in size. Monazite-(Ce), niobochevkinite, ferrocolumbite, almandine, thorite, and zircon are present in minor amounts. The **feldspar+biotite+garnet wall zone** contains abundant phlogopite and garnet in a matrix of albite, Ba-rich K-feldspar, celsian and quartz. Minor minerals include allanite-(Ce), monazite-(Ce), nioboaeschnite-(Ce), euxenite-(Y), Nb-rich rutile, ilmenite, thorite, and zircon. The allanite composition represents a Ti-rich ferriallanite-allanite-epidote-askagenite solid solution. The **feldspar+allanite+columbite intermediate zone** contains euhedral

ferrocolumbite grains (up to 2 cm) and allanite-(Ce) (up to 10 cm) contained in albite, Ba-rich K-feldspar, celsian and quartz. Fluorapatite, almandine, phlogopite, monazite-(Ce), Nb-rich rutile, REE-bearing epidote, and molybdenite are also present in smaller quantities. The **quartz core** contains minor amounts of actinolite, pyrite, sphalerite, wurtzite, epidote, and spessartine. Frequent monazite breakdown into coronas of apatite and allanite indicate a late-magmatic autometasomatic overprint.

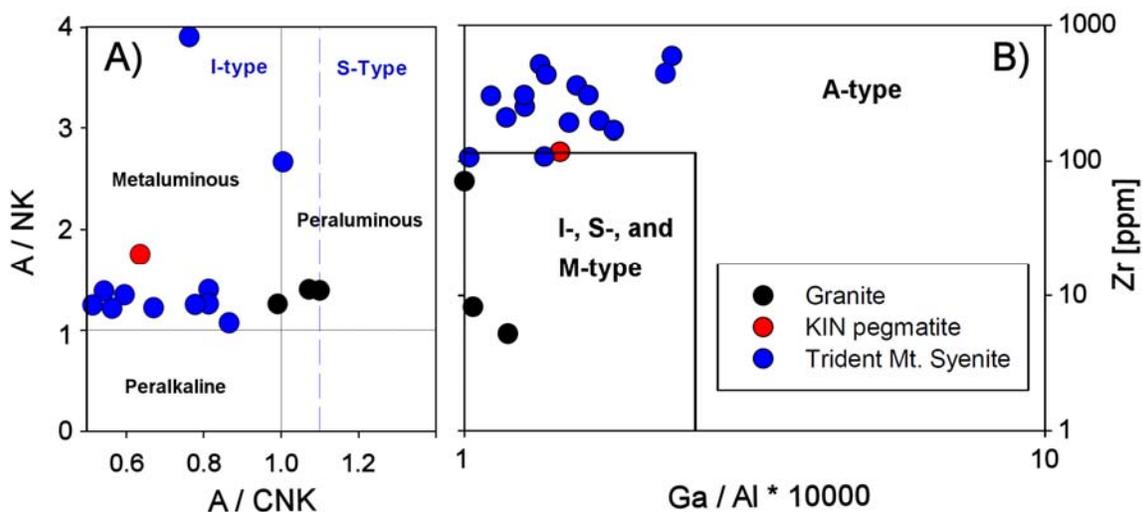


Figure 1. Classification diagrams after (A) Chappel and White (2004), and (B) Whalen et al. (1989), showing the geochemical compositions/characteristics of samples from the muscovite granites, the KIN pegmatite, and the Trident Mtn. syenites).

Geochronology and origin of allanite pegmatites

The KIN property pegmatites have a NYF-family signature with Nb>Ta, and high contents of Ti, Y, Zr, U, Th, F and REE (Černý 1991), as witnessed by their mineralogy. Channel and grab samples from the pegmatites contain high amounts of Nb (up to 2402 ppm; Ta <2 ppm), TREE+Y (up to 17160 ppm), and Th (up to 2544 ppm).

Geochemical evidence suggests the syenite, or an undiscovered, more silicic part of the alkaline intrusive suite, as possible sources for the parental magma of the allanite pegmatites. However, previous work using zircon dating indicates that the syenites intruded at 360 Ma (Millonig et al. 2012) whereas the U-Pb dating of zircon and monazite from the allanite pegmatites provided an age of 79 Ma, and zircons from the undeformed muscovite granite gave U-Pb isotopic age of 76.6 Ma (this study). Based on the geochemical affinity and geochronological constraints, we suggest that the allanite pegmatites formed by partial melting of syenites and their metasedimentary host rocks at approximately 79 Ma. The pegmatites were likely partly metamorphosed during the intrusion of muscovite granite sills at 76 Ma, as suggested by their tectonic position (boudins).

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Amazonite and Smoky Quartz Pegmatites of the Smoky Hawk Trend, Teller County, Colorado

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The Smoky Hawk trend in the Crystal Peak mining district of Teller County, Colorado has produced much of the world's best amazonite and smoky quartz specimens from within some unusual pegmatite structures. Since Glacier Peak Mining (Dorris family) began sporadic exploration for a few days in 2000, it now operates approximately 50 days each season and has been producing numerous pockets of quality smoky quartz and microcline, predominately the variety amazonite. The most noteworthy pocket, which was discovered in 2012, was named the Icon pocket due to its unusual size and quality. This pocket has yielded the largest quality amazonite and smoky quartz plate yet recovered from the district. The Smoky Hawk pegmatite trend consists of multiple pegmatites which have produced an abnormally high percentage of quality amazonite and smoky quartz pockets of fine color. There appears to be structural controls which give rise to the high pocket occurrence. The reason for the deep coloration and high frequency of amazonite occurrence along this trend is yet unknown.

The Smoky Hawk claim is one of approximately 200 unpatented mining claims within the 1,100 square mile Pikes Peak Batholith, which since the 1870s has become historically famous for producing the world's finest amazonite and smoky quartz combination specimens. The Smoky Hawk claim was filed in December of 1998, culminating years of prospecting in the district by Joe Dorris and his family. Eventually a trend of pegmatites was mapped and named the Smoky Hawk trend for this prominent claim. Mechanized exploration of pockets commenced in 2000 with mining commencing in 2003. Exploration has continued within an area of 185 acres now covered by twenty unpatented mining claims. The majority of finds have been located along a narrow trend approximately .9 miles in length by .4 miles wide.

Historic claims along this trend include the former Dry Hole and Jack Rabbit claims (Bartsch and Currier) and the current Two Point claim (Buckner and Stephenson) which have produced significant pockets (e.g. Tree Root Pocket 1997, Bryan Lees). Glacier Peak Mining has produced from this trend through both leased and owned claims since the early 1990s. The most extensive and noteworthy production has centered on the Smoky Hawk claim in a seven-acre area, with notable discoveries being made each year. To date, over 900 pockets have been excavated of which 14 have proven to be major pockets with exceptional specimens. These pockets include the Dragon's Mouth, Legacy, Majestic, Smithsonian, Lucky Monday, Chuck's, and Icon pockets.

The Smoky Hawk trend pegmatites are classified as rare-earth-element (REE) pegmatites of the niobium-yttrium-fluorine (NYF) family (Foord, others). They are noted for their abundance of miarolitic cavities which produce predominately amazonite, smoky quartz, and cleavelandite. This sharply contrasts with other Pikes Peak Batholith pegmatites which contain predominately common microcline in combination with smoky quartz. Other significant macro minerals include zinnwaldite, fluorite, goethite, and hematite. Some of the lesser minerals and micro crystals include bastnäesite, bertrandite, cassiterite, milarite, monazite, phenakite, rutile, xenotime, and zircon. Some macro crystals of topaz, calcite, ferro-columbite, and rare genthelvite have also been recovered. Most, presumably calcite or siderite crystals, have been replaced by goethite and/or hematite.

Pocket occurrence on the Smoky Hawk trend exceeds the frequency of pockets in comparison to other general areas within the district. Pegmatite emplacement along the trend correlates with fracture patterns similar to jointing patterns found within granite. Generally pegmatite emplacement has followed vertical fractures and extended laterally along generally trending horizontal fractures. Step faulting appears to have occurred in several places along the Smoky Hawk trend wherein pocket formation is most prevalent. The majority of pockets, and virtually all of the significant pockets, have occurred in areas where there is pegmatite directional change. In comparison, the more abundant linear pegmatites throughout the district tend to contain widely scattered and infrequent cavities.

The most aesthetic and collectable specimens in the district continue to be amazonite with smoky quartz. Whereas the majority of the batholith generally produces light to medium bluish green amazonite, the Smoky Hawk trend predominately produces deeply colored blue-green amazonite. Approximately ten percent of the amazonite pockets also display a combination of white stripes or white caps, the white caps being microcline. This percentage exceeds the less than one percent district wide (Foord). Additionally, many of the amazonite crystals exhibit bi-coloration in which crystals have a medium teal-blue coloration that grades to a thin outer-coat of bright teal green. The smoky quartz exhibits a more consistent satin luster and very dark to black coloration as compared with the

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

district. There also appears to be a higher tendency to have tapered crystal terminations (some of tessin habit) than elsewhere in the district. Analysis to determine these differences remains to be done.

Amazonite and smoky quartz combination specimen production has increased in the last few years within the district, largely due to the use of mechanized equipment. Miners used mostly picks and shovels during the initial one hundred years. Within the last forty years, they have turned to mechanized equipment, enabling them to go below the former, shallow digs. Glacier Peak Mining generally operates two excavators each season and conducts limited blasting in order to open the deeper lying pegmatites. Mining operations have now extended to depths of sixty feet but average thirty feet or less. Deeper excavations have shown the pattern of linear pegmatites to run parallel with the more shallow pegmatites at approximately fifteen-foot deep intervals. Mining has not extended below the sixty-foot depth because hardrock mining costs exceed the potential results.

Significant production has also increased due to improved laboratory techniques and the abilities of some individuals to piece together ruptured pockets. Although the cleaning and preparation for any given pocket may take a year or longer, better quality specimens which have been completely cleaned of all oxides and overgrowth secondary minerals are now becoming available.

Nevertheless, the higher number of recovered pockets only increases the chance of a quality pocket. The vast majority of pockets remain marginal at best due to secondary mineral over-coatings, extensive rupturing, discoloring oxides, and poor color or quality that no amount of lab work can improve. Based on past production, about one in twelve pockets contains reasonable quality material and one in seventy is high quality.

The Smoky Hawk trend has been largely exploited at this point; however, some structure yet remains in a few limited areas, and new ground has been acquired to the southeast. The greatest hindrance to continued production is not the lack of productive ground, but lies with increased compliance and permitting expenses through the growing number of mining regulations and restrictions and multiple government agencies. Otherwise, the present future for mining additional amazonite and smoky quartz combination specimens appears likely.

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Origin, geochemistry and mineralogy of the post-Penokean LCT-type pegmatites in Florence County, Wisconsin

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The pegmatite field hosting the LCT-type pegmatites in Florence County, Wisconsin (Falster *et al.* 1996) occurs in early Proterozoic metavolcanic and metasedimentary rocks of the Quinnesec formation. The mineralogy of the pegmatite is typical for highly evolved LCT type pegmatites. Texturally, a distinct wall zone with red elbaite right at the contact is most unusual (Fig. 1).

Pegmatites occur in a terrain of amphibolite grade metamorphism and some greenschist metamorphism in the township of Fern in Florence County. Within an area of at least 40 square km, pegmatite of small to moderate size occur. The maximum dimension is 600 m in exposed length and 3.45 m in maximum thickness. Most pegmatites show distinct indications of undercooling and rapid crystallization (comb textures, skeletal quartz/mica intergrowths).

Emplacement of the 600° C pegmatitic melt took place into country rock of 400° C and required 20 days for complete solidification of the pegmatite (Simmons and Webber 2008).

The bulk pegmatite is highly leucocratic with a distinct Mn enrichment and low Fe. Mafic minerals such as biotite are entirely absent in the pegmatite. This is characteristic of melts that are produced from an aluminous protolith (London *et al.* 2001).

Lithium mineralization is typical, essentially every pegmatite contains a quartz-spodumene core and some are rich in amblygonite-montebrazite, lepidolite, lithian muscovite, tourmaline, var. elbaite. Accessory minerals are evolved columbite group species and microlite, fluorapatite, Mn-rich phosphates, beryl, var. morganite, spessartine, helvite, cassiterite, wodginite, zircon, hambergite and very rare rhodizite-londonite. Totally lacking are biotite and schorl.

Granitic rocks exposed to the south and west of the pegmatite field do not correlate well with respect to the bulk chemistry of the pegmatites compared to the bulk chemistry of the country rocks. The content of Al₂O₃ and LILE and HFSE of the granite are lower than the contents of the country rocks. Li, Be and B are substantially higher in the Quinnesec metapelites, whereas HFSE are higher in the Quinnesec metavolcanic than in the granites.

The origin of these pegmatites is likely the result of anatexis of 2 common rock types present in the area and not a result of fraction from the nearby Hoskin Lake granite and other granite bodies. The problem with the granites is a much lower Al₂O₃ content (13.4 wt. %) versus the bulk pegmatite Al₂O₃ content of around 20 wt. %. The country rocks of the Quinnesec formation exposed in the area consists of mafic metavolcanic rocks, felsic metavolcanic rocks and metasedimentary rocks such as quartz muscovite schist and marble. Fig 3 shows a plot of the alkali elements normalized to average shale for the major rock types and the average wall zone present in the area. Figs. 4 and 5 shows spider diagrams for selected elements normalized to average shale. Fig. 6 shows the relative abundance of the light elements Be, Li and B in the same rock types. In all cases, a combination of mafic and felsic metavolcanic and metasediments provide a superior agreement between the pegmatite composition and a mixed source of Quinnesec rock types than do the nearby granite bodies. In particular, the high field strength elements (HFSE) Ta, Nb and Sn are abundant in the widespread titanite in the mafic metavolcanic rocks. Even more convincing is the effect of leaching of titanites in the country rocks where they are close to pegmatites and also a direct correlation of Ta, Nb and Sn abundance in pegmatites with respect to the dominant rock types in contact. Those pegmatites that have invaded into mainly mafic metavolcanic rocks possess the highest amount of Ta, Nb and Sn minerals. Fluorine is abundant in lepidolite, apatite, amblygonite and likely played an important role in sequestering HFSE elements and in mobilizing them from source rocks. Even in the early formed Nb-Ta oxides, a high Ta content is evident (Fig. 2), indicating an already evolved Ta/Nb ratio in the source material which then was even further fractionated, yielding high Ta-tantalite-(Mn) and microlite as well as some tapiolite-(Fe) in the western reaches of the pegmatite field.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Figure 1. Wall zone of the Animikie Red Ace pegmatite with metasedimentary rock in contact and red elbaite comb texture. Length of the elbaites is about 3-4 cm.

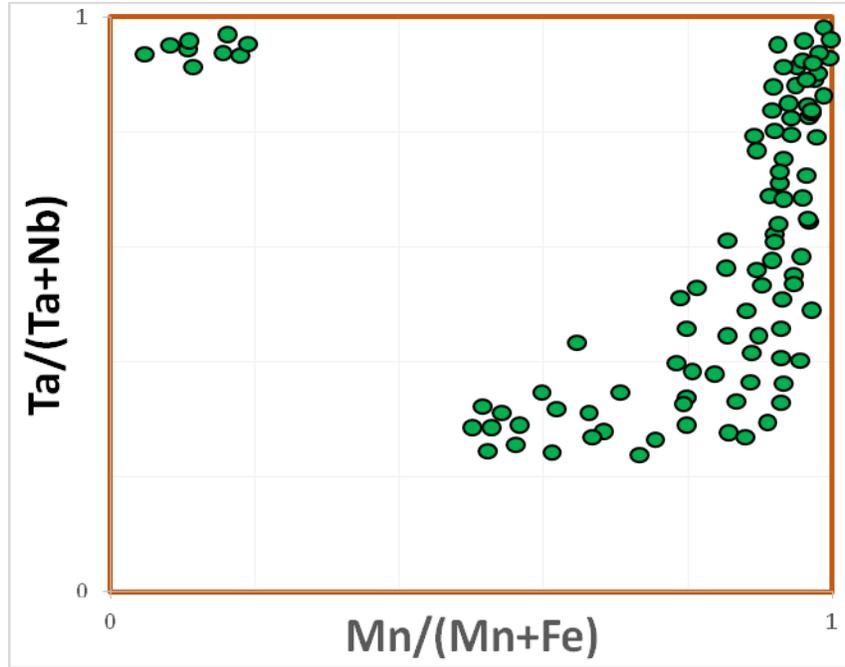


Figure 2: Compositions of columbite group minerals from the Florence Co. pegmatites. WZ: wall zone, OIZ: outer intermediate zone, MIZ: middle intermediate zone, IIZ: inner intermediate zone, CMZ core margin, CZ: core zone, AP: aplite unit, FWLEP: footwall lepidolite, ABREP: albite replacement unit.

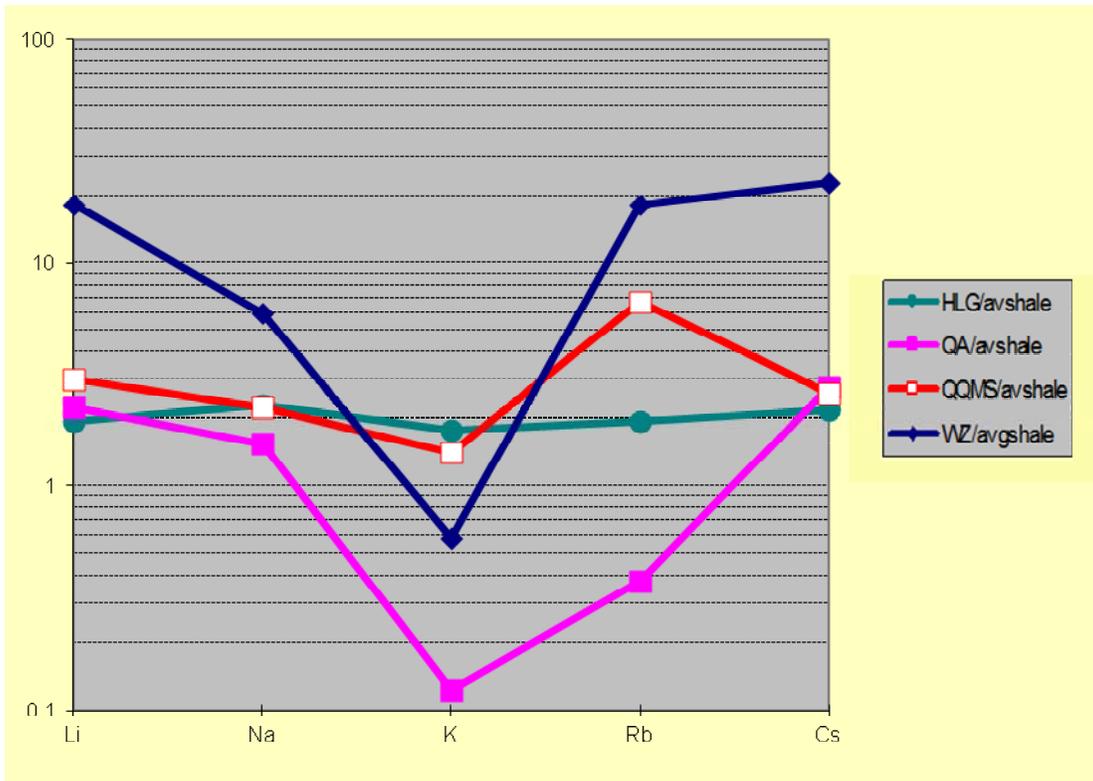


Figure 3: Plot of alkali element abundances, abbreviations as above.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
 Colorado School of Mines campus, Golden, Colorado

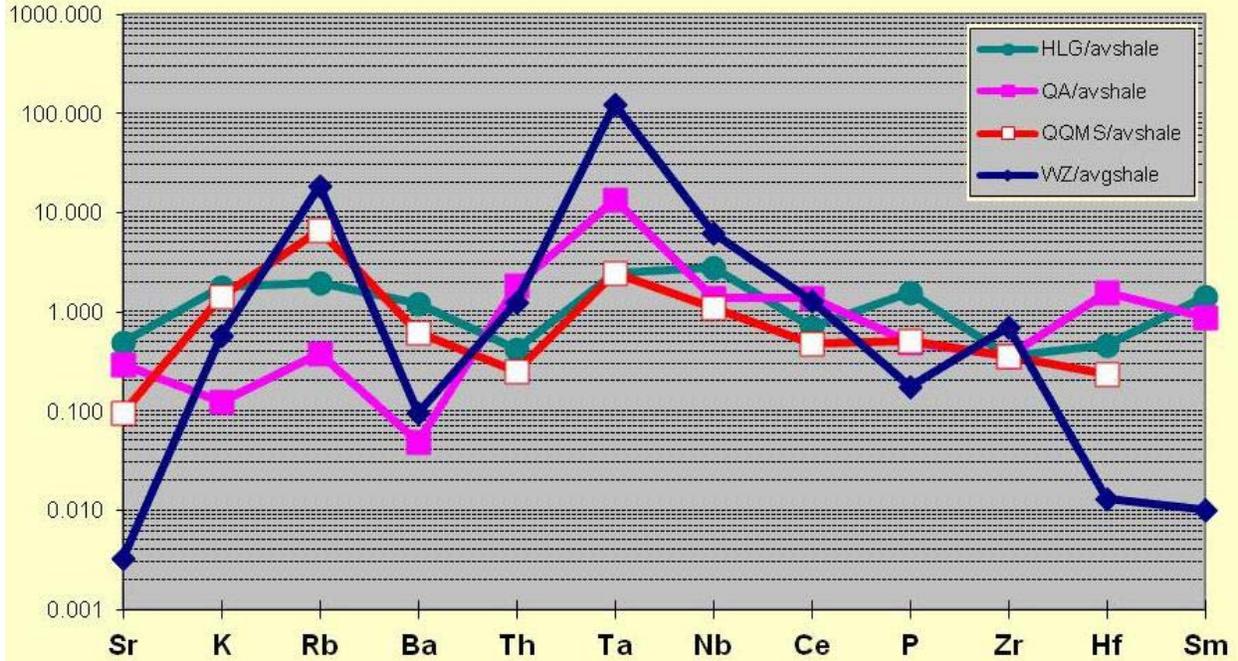


Figure 4: Spider diagram of wholerock samples normalized to average shale: HLG: Hoskin Lake granite, QA: Quinnesec mafic metavolcanics (amphibolite), QQMS: Quinnesec quartz muscovite schist (pelitic metasediments), WZ: pegmatite wall zone.

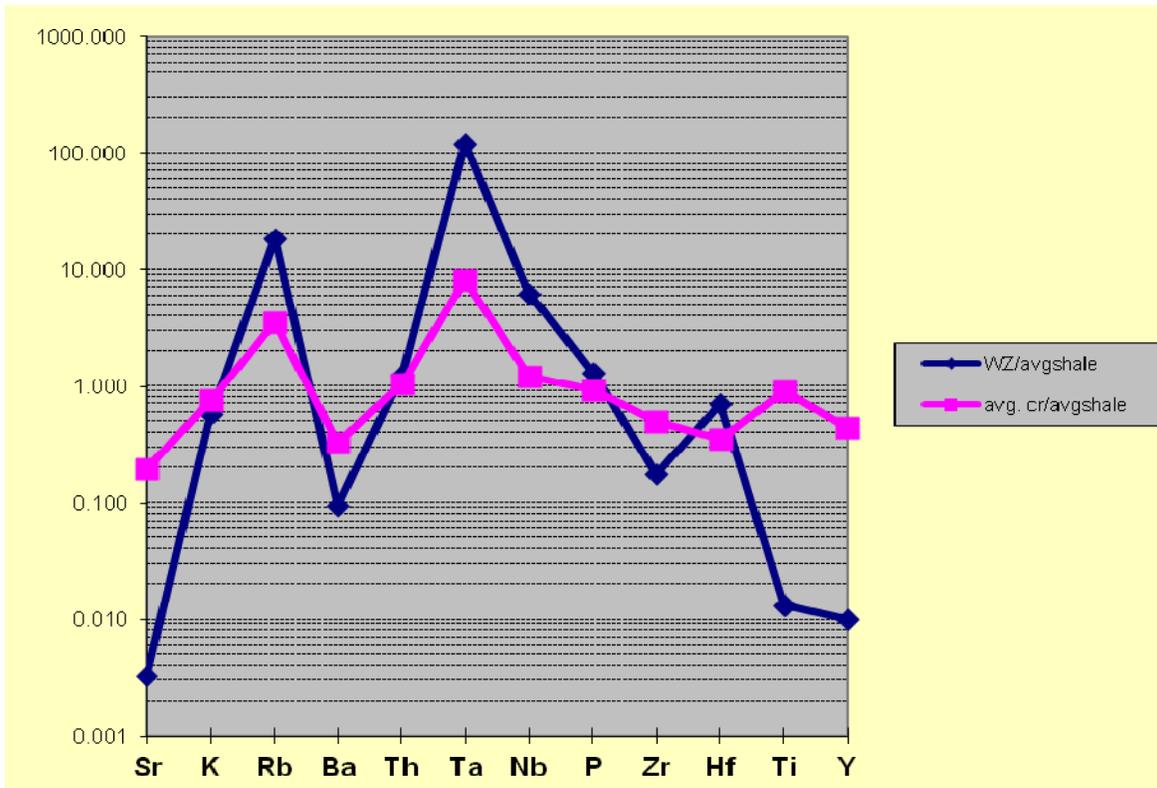


Figure 5: Spider diagram of whole-rock samples normalized to average shale: WZ: pegmatite wall zone, avg. CR: average country rock.

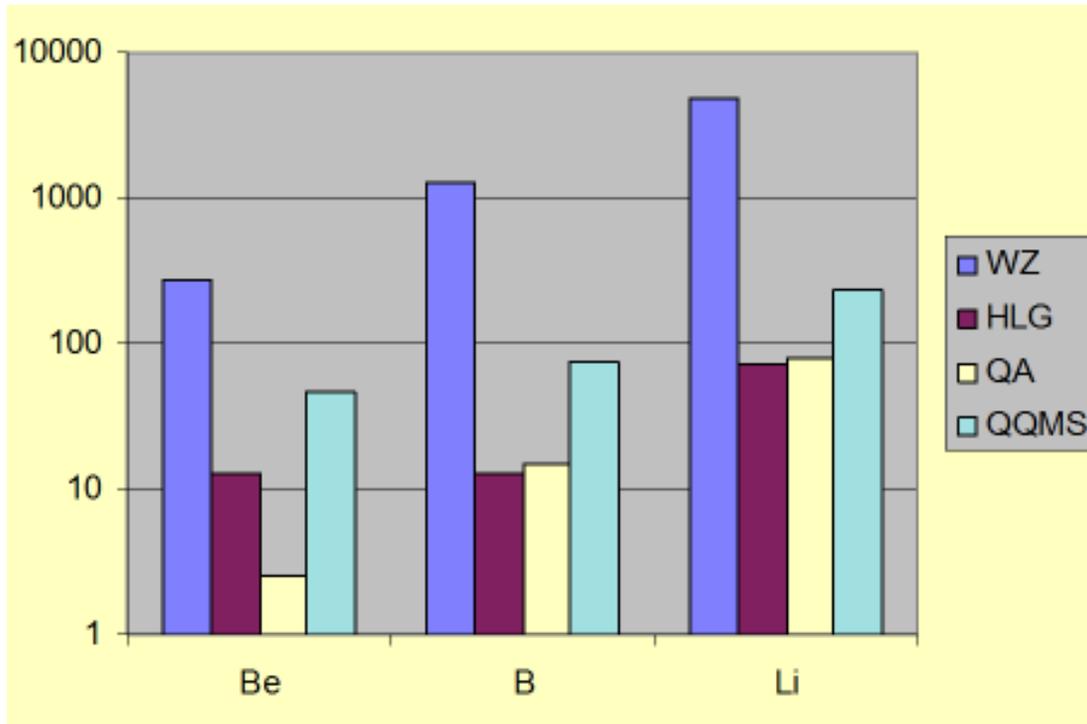


Figure 6: Light element comparison of Wall zone (WZ), Hoskin Lake granite (HLG), Quinnesec metavolcanics, and QQMS (Quinnesec polydeformed metasediments).

A large scale boundary layer texture in the Mt. Mica pegmatite, Paris, Oxford County, Maine.

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The Mt. Mica pegmatite in Paris, Maine, was the site of the first discovery of gem tourmaline in North America. The discovery was made in 1820 and the pegmatite is still mined to this day. Interestingly, throughout its history miners have used the same unidirectional solidification texture (which is a boundary layer) as a zonation indicator to locate gem tourmaline and other rare mineral species occurring in miarolitic cavities in the most interior portions of the dike.

The unidirectional solidification texture, referred to locally as the ‘garnet line’, is a prominent boundary layer feature occurring throughout the pegmatite. It is found just below the core zone, existing between the miarolitic cavity-bearing zone and the footwall contact. Beneath the garnet line is another boundary layer composed of schorl, however, only the mineralogy and textures of the garnet line are discussed here. Both boundary layers are analogous to layers formed by diffusion-controlled oscillatory nucleation and crystallization in the layered aplite units that occur beneath the core zone of the sub horizontal miarolitic-bearing pegmatites in San Diego Co., CA, described by Webber *et al.* (1997, 1999).

The garnet line is composed of euhedral garnet crystals up to 4 cm, ranging from 66.07-38.12% Spss. The garnets host many primary mineral inclusions. In order of abundance these include quartz, mica, tourmaline, zircon, xenotime-(Y), monazite-(Ce), and Fe-bearing pollucite (up to 5.69 wt% Fe₂O₃). The garnets in the garnet line have tourmaline reaction rims around their crystal margins (Figure 1). These are commonly bi-colored (black and blue) and occur near the most chemically enriched regions of the pegmatite. The rim textures are believed to be the result of hydrothermal alteration of the garnet by late stage fluids, similar to the evidence proposed by Buřival and Novák 2015.

We believe that diffusion-controlled oscillatory nucleation and crystallization played an important role in concentrating incompatible elements and fluxes that enriched the garnet layer in rare species (Webber *et al.* 1997, 1999).

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Exploring a topaz-bearing Pikes Peak pegmatite

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The Hunt for Topaz

Rich has spent many years researching and chasing minerals in Colorado's Front Range. Books, maps and stories both old and new have been a constant source of information and inspiration for pursuing new targets. One winter evening Rich was browsing through the "Minerals of Colorado" by Edwin B. Eckel (1997). He turned to his favorite section on topaz and read through the county listings of known topaz locations. Under the El Paso county heading, he was intrigued to read of a brief description of "magnificent pink two inch topaz crystals" found by Edwin Over Jr. somewhere near Cameron's Cone and Crystal Park some sixty years earlier. The information of course was not new and as Rich learned, many other local mineral hunters had attempted to locate the source of the topaz during the intervening decades.

Undeterred, Rich set his sights on finding the original source of the material. Starting in the summer of 2010, Rich spent much of his spare time hiking the hills west of Colorado Springs. Numerous old digs were located that showed amazonite fragments but no confirmed topaz was evident at any of the sites. In the summer of 2012 Rich was contacted by an old friend who had previously hiked the area. Rich mentioned his search for the topaz location and the friend stated that he had found a shard of a pink gem less than a quarter mile from the current search area some forty years prior. What providential timing to hear such details from an old friend!

With renewed excitement the search continued. Mining partner Jean Cowman accompanied Rich on most of his hikes to the area. On one particular hike, Rich found exposed pegmatite material near the top of a ridge and discovered a smoky quartz pocket in the rocks. Jean made it a habit to stay in radio contact and prospect a little further away from Rich in order to search a larger area. (Prospecting right beside Rich can be a little frustrating as he usually sees everything first!) Whenever either partner found anything of interest they would radio the other to check it out. So taking a different route, Jean circled to the valley floor below. Hiking back up the bottom of the valley toward Rich revealed several stringers of white quartz that had eroded down the slopes from above. Near the upper end of the valley, Jean located the largest of these quartz trails of "float" and began to follow the quartz uphill. The trail ended at a relatively small outcrop of white quartz that protruded about 18 inches (46 cm) above the granite scree slope. No quartz crystal faces were evident near the outcrop but the outcrop itself was dissected by a vertical vein-like structure of pink microcline about 18 inches (46 cm) wide. Jean radioed Rich who hiked down to check out the site. Both agreed that it was one of the most unusual structures on the mostly barren slopes of the search area.

Surface digging adjacent to the outcrop revealed large books of biotite mica up to 6 inches (15 cm) in diameter. Several more hiking trips were made to the site to continue digging. Quartz bordering the microcline vein was well fractured along growth lines and was fairly easy to chisel away. This fractured quartz area produced some small doubly terminated tabular crystals of milky quartz. Rich moved several feet to the side of the outcrop and began digging down while Jean continued excavating the fractured quartz. Approximately 18 inches (46 cm) down into the quartz, more tabular doubly terminated quartz crystals were revealed. These crystals appeared to be more translucent and smoky. The small, flat crystals were stacked like pancakes to a depth of about three inches (8 cm) into a small pocket. Below the crystals was a layer of thick tan clay. Removing the clay with skewer sticks revealed no more quartz crystals. Disappointing. The pocket was small, about the size of a grapefruit.

Jean then scraped the bottom of the pocket with skewer sticks to ensure that there were no more quartz crystals. Several needle sharp terminations were found in the bottom of the pocket. Cleaning the crystals revealed that they were not glassy shards of broken quartz but were in fact topaz! The topaz was etched, peachy pink in color, and mostly double terminated in multiple needle-sharp terminations. Crystals were all smaller than $\frac{3}{4}$ inch (2 cm) but did resemble the description of the Over topaz found some 60 years prior.

A second pocket of similar size and material was found about one foot (30 cm) downhill from the first pocket. These weren't nearly the size of the topaz crystals documented from the Over find but were the first topaz found within the search area. The chase was on!

Jean continued excavating the quartz outcrop but no more crystals were found. Digging down just off the edge of the main outcrop, Rich eventually began to find oddly shaped quartz crystals. Most were milky and only a few showed complete terminations. He eventually hit a larger pocket of well terminated mostly clear quartz crystals that appeared to be waterworm or had frosted surfaces. Many crystals were doubly terminated and appeared to be Tessin

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

habit (Carnein, 2013), or tapering in size toward the termination. Some crystals had attachments of minute purple fluorite cubes. Others appeared to be clusters of multiple penetrating crystals. This quartz pocket took many hiking trips to excavate and eventually reached a size of 8 ft x 3 ft x 3 ft (2.5 m x 1 m x 1 m). The sheer size of the pocket was exciting but not a single topaz was found in the pocket.

The small, unusual topaz pockets previously found were inspiration to keep digging. The smaller pockets had a lid of tabular quartz crystals covering a zone containing only clay. Topaz crystals were only found at the bottom of the pocket. What if the much larger quartz pocket discovered by Rich followed the same zoning habit? Could there be topaz located deeper underneath the quartz crystals? There was only one way to find out.

Digging under the floor of the excavated quartz pocket, Rich encountered a horizontal quartz slab. Was this just the floor of the pocket? Persistent thoughts kept encouraging him to explore further. Rich wrestled the slab out of the hole to find some sandy material and another quartz slab below the first one. Rich remembers remarking that “if there’s nothing under this second slab, I’m digging someplace else!” With effort, Rich managed to pry the second slab from the floor of the hole. Immediately under the slab was a pristine topaz crystal! The crystal weighed 1½ lbs (680 g) and was 3 inches (7.8 cm) high.

The area beneath the quartz slabs revealed large quantities of loosely packed golden albite, resembling damp sawdust. Removing handfuls of this flakey damp material revealed more topaz crystals. Many crystals were intact with highly etched prism faces or sides of the crystal. They were a peachy pink in color with multiple needle- sharp terminations. One large specimen that was recovered in two pieces revealed very distinct color zoning where the crystal had broken along the cleavage plane. Some crystals were doubly terminated. The largest incomplete crystal, if repaired, would be at least four lbs (1.81 kg) in weight. Over 60 lbs (27 kg) of topaz were recovered from this pocket in one day.

Of note, not a single quartz crystal was found within the main topaz pocket. Rich then referred to the large quartz crystal pocket located above as “the Halo Pocket” because of its location directly above the topaz pocket. Rich then named the lower topaz pocket “the Tribute Pocket” in honor of Edwin Over Jr. and his collecting partners who had found the original referenced topaz decades before.

Further digging revealed smaller topaz pockets along the side walls in a tan clay. The crystals had less surface etching but were still consistently sherry colored. A few colorless or almost colorless crystals were found. Numerous fissures in the granite surrounding the main pocket also contained topaz, microcline and very well formed zinnwaldite crystals up to 5 inches (13 cm) in length. Small areas of blue clay surrounded topaz crystals further away from the main pocket. Analysis of this clay determined that corrensite and nontronite were present (written communication from Bob Carnein, from a sample submitted to Attard XRD Services, November 19, 2013, sample CARN01). Both above and to the edges of the main Tribute Pocket, the walls consisted of larger quartz faces interspersed with microcline and decomposed microcline. Extracting topaz out of the almost solidified decomposed microcline was difficult. Quartz crystal faces extended for a span of almost 20 ft (6 m) horizontally but were left in place to preserve the integrity of the steeper walls of the pit.

This pocket system has some distinct differences from other known topaz localities within Colorado. The sheer size and quantity of the crystals are larger than most local pegmatites known within the Pikes Peak batholith. Preliminary inquiries suggest that the Tribute Pocket is the largest pocket of topaz and has produced the largest gem quality specimen known from Colorado and possibly from North America. (Large rough pieces of topaz have come from other localities but they were not complete crystals and were very heavily included and fractured.)

Also unusual in comparison with other local pegmatites is the very distinct zoning of the quartz and topaz found in this pocket system. Art Montgomery, in the chapter on topaz in his book “Reminiscences of a Mineralogist” (1997) sheds light on some features of this pocket system. He states that “Topaz with its fluorine is one of the typical late stage minerals associated with complex pegmatites. It tends to be associated with other late stage, well crystallized minerals such as platy cleavelandite variety of albite, smoky quartz, black or transparent tourmaline, beryl, an apatite species, lithium bearing lepidolite and spodumene, and columbite.” Currently identified minerals from the Tribute Pocket system include clear and smoky quartz, albite, microcline, fluorite, zinnwaldite (biotite mica), columbite and niobium. Since lithium bearing minerals described by Montgomery seem to be absent, it is very unlikely that this system would contain tourmaline or associated minerals. It is suspected that beryllium based minerals such as phenakite or beryl crystals could be associated with this system but not yet encountered in the surface zones. Rich has found both phenakite and blue beryl (rare) at other local pegmatites within a one mile (1.6 km) radius of the Tribute Pocket.

Further digging is needed to continue to expose the borders of the pocket system and to determine what lies below the zone occupied by the topaz. Fluids that originally formed the crystalized pockets exposed near the surface could be expected to continue from deeper levels. Current hand digging has only reached a depth of 14 ft (4 m) below the original surface grade. Further study is also needed to confirm details of how this pocket system formed.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

The discovery of the Tribute Pocket has earlier been described by Carnein (2013) and Cowman and Persson (2015).

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Figure 1. Sherry topaz collected by Richard Fretterd and Jean Cowman from their Tribute Pocket. Crystal about 3 inches in height. Offered for sale at the Denver Gem and Mineral Show, September 2013.

The role of pegmatites and acidic fluids for hydrothermal Zr and REE transport in the Strange Lake peralkaline granitic pluton

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Abstract: Strange Lake is mid-Proterozoic peralkaline granitic pluton located at the border between Quebec and Labrador in Canada. It is a world class REE-Zr-Nb mineral deposit host to two potential ore zones (i.e., the B zone and Main zone). This deposit is exceptional because of its notably high proportions of heavy rare earth elements (HREE). The mineralization in the B zone occurs in pegmatite-rich domains, with the pegmatites having characteristics of the NYF family (RE-REE subclass; gadolinite and allanite-monazite subtypes) and miarolitic class (MI-REE subclass; gadolinite-fergusonite type) of the classification scheme from Černý and Ercit (2005). Even though, the initial enrichment of REE, Zr and Nb in the Strange Lake pluton was clearly related to igneous processes, several studies have demonstrated that hydrothermal processes have played a significant role for element mobilization in this system (Salvi and Williams-Jones 2006, and references therein). Furthermore, it was shown that >90 % of the mineralized REE and Zr occurs in hydrothermal minerals with a significant hydrothermal enrichment process (Gysi et al. 2016). In particular, the hydrothermal alteration can be spatially related to the pegmatites, which were the source of saline acidic HF-HCl-bearing fluids that were capable of mobilizing the REE and Zr (Gysi and Williams-Jones 2013). I present here the different alteration types related to these pegmatites by combining field observations at the outcrop and thin section scales with mineral and bulk rock compositions to illustrate the effects of hydrothermal fluid-rock reactions on the mineralogy and chemical mass fluxes associated to this type of peralkaline granitic system. I then use numerical modeling of fluid-rock equilibria to explore the controlling factors for REE and Zr mobilization/mineralization in hydrothermal fluids, and discuss the key factors affecting metal enrichment at Strange Lake.

Field Relations



Figure 1. Drill core of a B zone pegmatite showing the zoning into core (right) and border (left). The white boat-shaped minerals are pseudomorphs after elpidite (Na-zirconosilicate). Modified after Gysi and Williams-Jones (2013).

The B zone consists of numerous flat lying pegmatite sheets forming a mineralized pegmatite spine hosted in the peralkaline granite. The pegmatites are zoned (Fig. 1) into a core enriched in quartz, fluorite and light (L)REE-bearing minerals (i.e., REE fluorocarbonates), and a border at the contact to the granite, enriched in granitic minerals (quartz, arfvedsonite, K-feldspar) and zirconosilicates (i.e., pseudomorphs after elpidite host to Zr and HREE). The

dominant hydrothermal REE-bearing minerals include ferriallanite-(Ce) and gadolinite-group minerals, which occur as mineral replacement, in fractures and hydrothermal veins. The Zr-bearing minerals include three generations of zircons that record different hydrothermal evolution stages (Gysi et al. 2016). The latest zircon generation occurs in the granite and forms spherules intergrown with hydrothermal quartz and fluorite. These zircons have a flat chondrite-normalized REE profile and are LREE enriched compared to typical zircon compositions. This mineral paragenesis is characteristic of a late Ca-F-metasomatic event recording a low temperature acidic alteration related to fluids released from the pegmatites. The pegmatite spine also contains an aegirized (replacement of arfvedsonite) alteration halo restricted to the surrounding granite and border pegmatites. The aegirization and the presence of Ca-zirconosilicate (i.e., gittinsite) pseudomorphs after elpidite in the border pegmatites, indicate a higher temperature alteration stage that was restricted to the vicinity of the pegmatite spine. The high and low temperature acidic alteration events, both indicate, that the pegmatites were the most likely source of these fluids and that autometasomatic reactions overprinted the pegmatites and may be the cause for the observed core and border zoning. The distribution and characteristics of these two alteration events also records a change from a closed to an open fluid-rock reaction system.

Numerical modeling

Numerical simulations were carried out using the program GEM-Selektor (<http://gems.web.psi.ch>) and the MINES thermodynamic database (<http://tdb.mines.edu>) to test different possible fluid-rock interaction scenarios responsible for the transport of REE and Zr associated to these pegmatitic aqueous fluids. Simulations conducted at 150 to 500 °C and 1 kbar indicate that the REE are preferably transported as chloride complexes at low pH and high temperatures, with a fractionation of LREE vs. HREE. Zirconium, on the other hand, is preferably transported at low temperatures as Zr hydroxyfluoride complexes ($ZrF_2(OH)_2^0$ and $ZrF(OH)_3^0$) due to the retrograde solubility of zircon and the requirement of low pH fluids with high F concentrations. The simulations also indicate that the zoning into border and core pegmatites can be achieved by interaction of these acidic saline HF-HCl-bearing fluids with the pegmatites upon cooling. The quartz/fluorite dominated mineralogy in the core pegmatites corresponds to zones of increased fluid-rock reactions, where low pH fluids are stable and creating an ideal pathway for the transport of REE and Zr.

Hydrothermal evolution stage

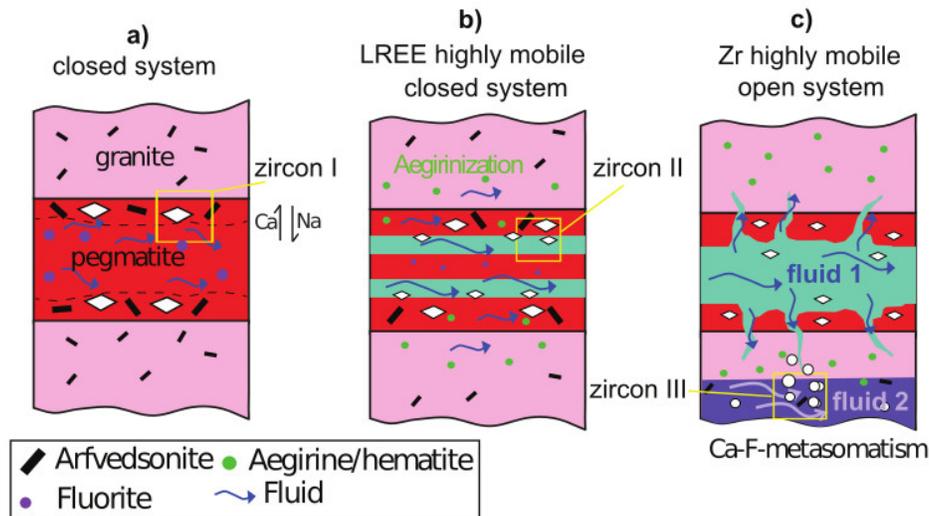


Figure 2. Evolution model of the Strange Lake pegmatite spine (see text for details). Modified after Gysi et al. (2016).

Figure 2 depicts a conceptual model based on an interpretation of field observations and the numerical model. In a first stage (Fig. 2a), the fluids exsolved during the crystallization of the pegmatites reacted at high temperature with the zirconosilicates from the border pegmatites, which led to a pseudomorphic replacement of elpidite (Ca-metasomatism; zircon I). These pseudomorphic reactions led to a Na-Ca exchange and depletion of the pegmatitic fluids in Ca with a corresponding enrichment in Na. In a second stage (Fig. 2b) and upon further crystallization, the

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

high temperature fluids released from the core of the pegmatites reacted in focused zones of increased fluid-rock reactions, which led to a local remobilization of Zr (zircon II) and LREE, and aegirization of the granite adjacent to the pegmatite spine. In a third stage (Fig. 2c), the system cooled down sufficiently for the fluids to become strongly acidic (fluid 1). An opening of the pegmatite system released these fluids to the surrounding granite. These fluids were likely enriched in HF-HCl and had a very low pH (pH <2; see Gysi and Williams-Jones, 2013) to be able to transport significant concentrations of Zr and REE. Mixing with an externally derived meteoric Ca-rich fluid (fluid2), led to the mineralization of zircon spherules (III), fluorite, ferriallanite-(Ce) and gadolinite-group minerals in fractures and veins in the granite and to the formation of a large fluorite breccia observed in the northwest of the B zone. The main factors contributing to the hydrothermal mobilization of REE and Zr, were the formation of a low pH fluid-rich pegmatite subsystem, and a change from closed to open fluid-rock system.

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Using Pearce Discrimination Diagrams to Evaluate the Tectonic Regime for Pegmatite Parent Granite

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The family classification subdivides pegmatites that are derived via fractional crystallization from parental granite into two broad groups based on petrogenetic parameters (Černý and Ercit 2005). These include pegmatites enriched in lithium, cesium, and tantalum (LCT pegmatites) and those enriched in niobium, yttrium + rare-earth-elements (REE), and fluorine (NYF pegmatites). Although most pegmatites can be readily classified using this scheme, a small number do not fall neatly into these families. They include (1) pegmatites that exhibit mineralogical and chemical characteristics of both groups (mixed LCT + NYF pegmatites) and (2) those that lack one of the typical chemical components. Although early work indicated there was a relationship between pegmatite families, granite type and tectonic setting, “significant and widespread exceptions” were noted (Černý and Ercit 2005). Martin and DeVito (2005) suggested there is a strong relationship between pegmatite type and tectonic setting with compressional (orogenic) settings producing LCT pegmatites and extensional (anorogenic) settings producing NYF pegmatites.

A quantitative evaluation of pegmatite whole rock geochemical compositions cannot be measured directly because of the large grain size of pegmatite minerals. Furthermore, internal zonation exhibited by many pegmatites can lead to an incomplete determination of minerals present. For these reasons, published whole rock geochemical analyses of parental granites were used as a proxy for the initial pegmatite composition. An extensive literature search located geochemical data for granite that is parental to sixteen LCT, twenty-four NYF, and three mixed LCT-NYF pegmatites. Although care was taken to choose only granite that is parental to the pegmatites, incorrect parent granite assignment is still a potential source of error. Further complications may arise from using older published data that generally have poor resolution.

Trace element compositions for parental granites were plotted on tectonic discrimination diagrams (Pearce, Harris, and Tindle 1984) (Figures 1a and b). Orogenic granites form in either subduction related volcanic arc (VAG) or continental collision (syn-COLG) settings whereas anorogenic granites form in extensional, within plate (WPG) regimes (Figure 1a). Post-orogenic (post-COLG) granite, which lies within the oval in Figure 1a, can be compositionally identical to syn-COLG, VAG and WPG granite (Pearce 1996).

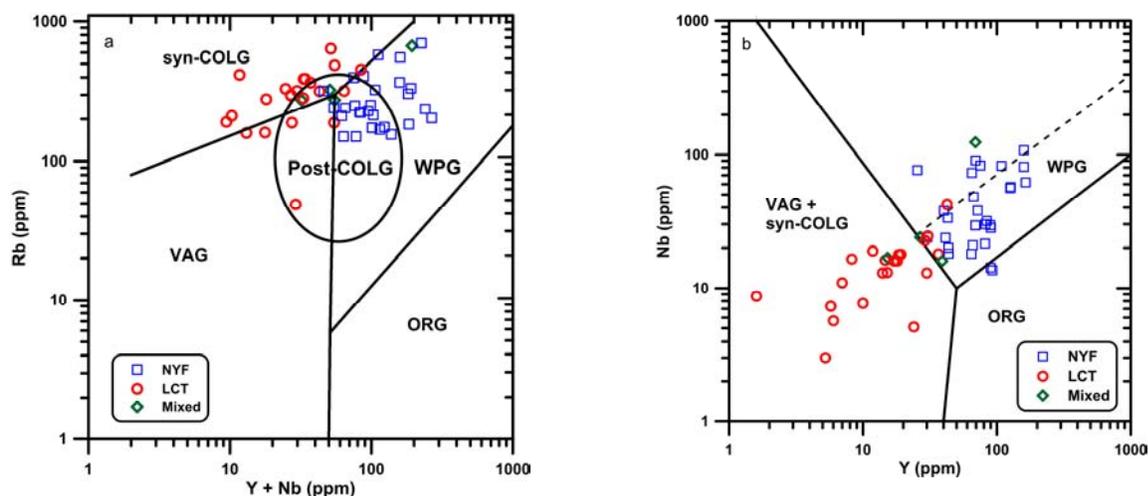


Figure 1. Pearce discrimination diagrams for pegmatite parent granites.

Using data from over 250 locations with known tectonic settings, Förster, Tischendorf, and Trumbull (1997) evaluated the accuracy of the Rb versus Nb+Y diagram to determine tectonic setting and concluded the trace element compositions correlated “to a considerable extent” with tectonic setting but should be used judiciously, also considering the nature of the source rock, especially in complex tectonic settings. It is, however, important to realize

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

the limitations of this type of study, particularly when differentiating orogenic granites (WPG and VAG), which can exhibit similar compositions, and post-orogenic (post-COLG) granites, which compositionally overlap with several of the tectonic fields (Figure 1a). This overlap is attributed to the transitional nature of these granites as they are, at least partially, mantle-derived magmas that have been modified by significant crustal assimilation, thus contain components of both orogenic and anorogenic granites (Pearce, Harris, and Tindle 1984). Furthermore, post-orogenic granites are chemically similar to granite formed in back-arc extensional tectonic regimes, thus, it is possible to have granite with an anorogenic signature derived from a localized zone of extension in a broadly compressional tectonic regime. For this reason, other techniques such as general geology, age dating, or isotopic studies may be required to determine if a pluton is post-orogenic, anorogenic, or results from localized extension in a compressional tectonic setting.

Given the above caveat, it is apparent from these diagrams that orogenic tectonic settings generally host LCT pegmatites whereas extensional tectonic settings, including those that result from localized extension in broadly compressional tectonic regimes, host NYF pegmatites. The geochemical differences in granite from each tectonic setting are reflected in the pegmatite mineralogy. Granite formed in orogenic settings generally has higher abundances of LILE + B, thus the related LCT pegmatites typically contain Li-bearing and Cs-bearing minerals as well as tourmaline group minerals. Granite associated with extensional tectonic settings is typically enriched in REE and HFSE ± F, thus the resulting NYF pegmatites typically have accessory Nb-Ta-Ti oxides, REE-bearing minerals, and in most cases fluorite. These petrogenetic differences hold for the quintessential LCT and NYF pegmatites as well as those that are deficient in one of the typical LCT or NYF components.

Mixed-signature pegmatites that can be attributed to parental granite are rare. Although the locations included in this study all plot within the post-orogenic to anorogenic field suggesting they may have been broadly NYF systems that were contaminated at either the magmatic or hydrothermal stage, other mixed-signature pegmatites suggest a different origin. For example, the broadly LCT pegmatites in the Moldanubian Zone, Czech Republic exhibit an NYF component that is attributed to assimilation of these components in a carbonatite-like marble host rock (Novák, et al. 2012). Clearly there is much to learn about the origin of mixed LCT-NYF pegmatites.

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Rare Earth Element Pegmatites in the South Platte Region of Colorado

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Abstract: The South Platte district of Colorado contains dozens of pegmatites emplaced within the anorogenic 1.08 Ga Pikes Peak Batholith. Three pegmatites have been chosen to study: the McGuire, the White Cloud, and the Wellington Lake pegmatites. Whole rock chemistry and isotopic data and microprobe analyses of REE minerals are used to characterize the composition and zonation of the selected pegmatites. The goal is to discover how these spatially related pegmatites vary petrologically, mineralogically, and connect their genesis to the Pikes Peak Batholith.

Introduction to Selected Pegmatites

The pegmatites in the South Platte district of Colorado are associated with the 1.08 Ga Pikes Peak Batholith. They frequently exhibit enrichment in rare earth elements (REE; Simmons, 1980; Simmons et al. 1987). These include a large population of Nb-Y-F (NYF) type pegmatites. Haynes (1965) proposed that these pegmatites are derived from the last melts of volatile-rich magma from the Pikes Peak Batholith. For this study, we compare the mineralogy and geochemistry of three pegmatites located in the northern-most part of the Pikes Peak Batholith (Fig. 1): the McGuire, the White Cloud, and the Wellington Lake pegmatites. The McGuire and White Cloud pegmatites have been investigated historically, and represent light rare earth element (LREE) and heavy rare earth element (HREE) enriched pegmatites respectively. They are both large volume pegmatites that have been mined for feldspar and quartz. In contrast, the Wellington Lake pegmatite is a much smaller (5m x 5m x 3m in size), that has been recently discovered, in close proximity to the McGuire pegmatite. In order to assess the petrological evolution of the pegmatites and their relationship with the hosting Pikes Peak Batholith we have acquired whole rock analyses, and will continue with Raman, electron microprobe, Raman, isotopic, and fluid inclusion analyses. We intend to determine whether their differences are due to their compositions, formation conditions, or both, for the purpose of understanding the emplacement mechanisms of REE in pegmatites.

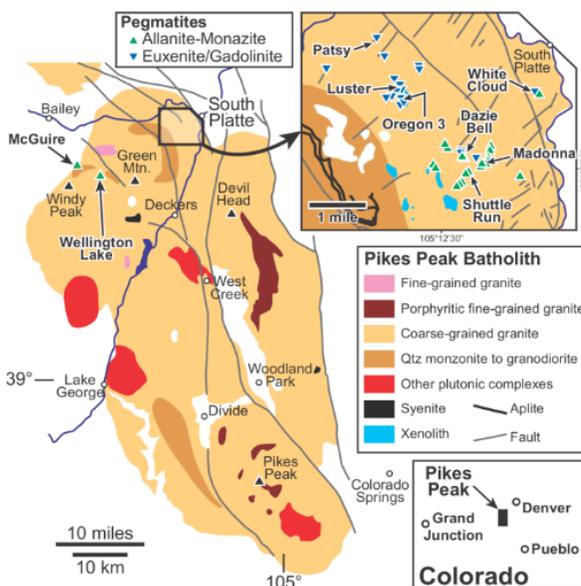


Figure 1. Pikes Peak and South Platte pegmatite district map (upper right; modified from Smith et al. 1999)

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016 Colorado School of Mines campus, Golden, Colorado

The McGuire pegmatite is emplaced at the boundary of a fine grained pink granite (quartz-microcline-perthite) and a gray monzogranite (quartz-plagioclase-perthite-biotite). Its mineralogy is intriguing due to the presence of niobian rutile within a microcline perthite with biotite border facies on the northwest side of the pegmatite (Cerny et al., 1999). It also includes a nodule of blue topaz and fluorite, ~1m x 2m at the surface. It is a large NYF type pegmatite enriched in F, Ti, Nb, LREE, and also contains monazite.

The Wellington Lake pegmatite is depleted in F, Ti, and P despite being located near the McGuire pegmatite (< 2km). It is emplaced within coarse grained syenogranite (quartz-perthite-biotite-microcline) and swiftly but smoothly transitions into the pegmatite. Once in the pegmatite, it displays distinct zonation. As with most pegmatites from the South Platte districts, it exhibits a quartz core with open cavities that contain large (>50 cm) crystals, suggesting growth within miarolitic cavities. The major minerals of the Wellington Lake pegmatite are quartz, microcline-perthite, cleavelandite albite, Fe-oxide, and biotite. Accessory minerals of this pegmatite are columbite, cyrtolite zircon, fluorcerite, and bastnäsite.

Lastly, the White Cloud pegmatite is our HREE enriched choice. Similar to the Wellington Lake pegmatite, it is emplaced in a coarse grain pink syenogranite. And like the McGuire, it was mined for its feldspar and quartz core (fully mined out). The remaining zones of the White Cloud include graphic granite, a transition zone with coarse biotite, and HREE zones containing unique mineral assemblages that are in the process of being analyzed. Thalenite is a key mineral; it sequesters a large concentration of yttrium within the pegmatite. Additional minerals of interest include allanite, synchysite, thorite, yttrifluorite, and xenotime.

Current Whole Rock Analyses

Whole rock analyses have been acquired for many of the zones of these pegmatites. Preliminary investigations reveal a Eu-anomaly for each of the pegmatites, although with varying magnitudes. Thus far, we have focused on host rocks surrounding the pegmatite, and the transition into the pegmatite. In chondrite normalized plots of the whole rock analyses (Figs. 2, 3, 4), it is apparent that there is an enrichment in REEs within the host rock and within the pegmatites. However, this enrichment is not consistent for each zone. For all three pegmatites the graphic granite zones are depleted compared to their host rocks, although slightly enriched compared to chondrites. Within the White Cloud pegmatite's high REE zone, enrichment in REEs can extend above 10,000 times that of a chondrite (with the exception of Eu).

Future Work

Our research will be involving further whole rock chemical and isotopic analyses, use of the electron microprobe on the REE-rich minerals, fluid inclusion analyses to determine pressure and temperature conditions, and Raman spectroscopy of individual minerals. Use of the electron microprobe will be crucial in elemental mapping of the rocks and zonation of minerals. We will use trace elements and isotopic data to find or disprove a link to the Pikes Peak Batholith. Additionally, we will use radiometric dating on zircon and monazite accessory minerals to constrain the ages of the pegmatites to determine their temporal relationship to the batholith. Chemical, isotopic, and P-T variations between the McGuire and the Wellington Lake pegmatites useful in determining why they are dissimilar despite their proximity. Although the Wellington Lake and White Cloud pegmatites have similar immediate host rocks, the pegmatites themselves are different mineralogically and petrologically. Our fundamental interest is to better understand the processes involved in the concentration, transportation, and deposition of REE.

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 Colorado School of Mines campus, Golden, Colorado

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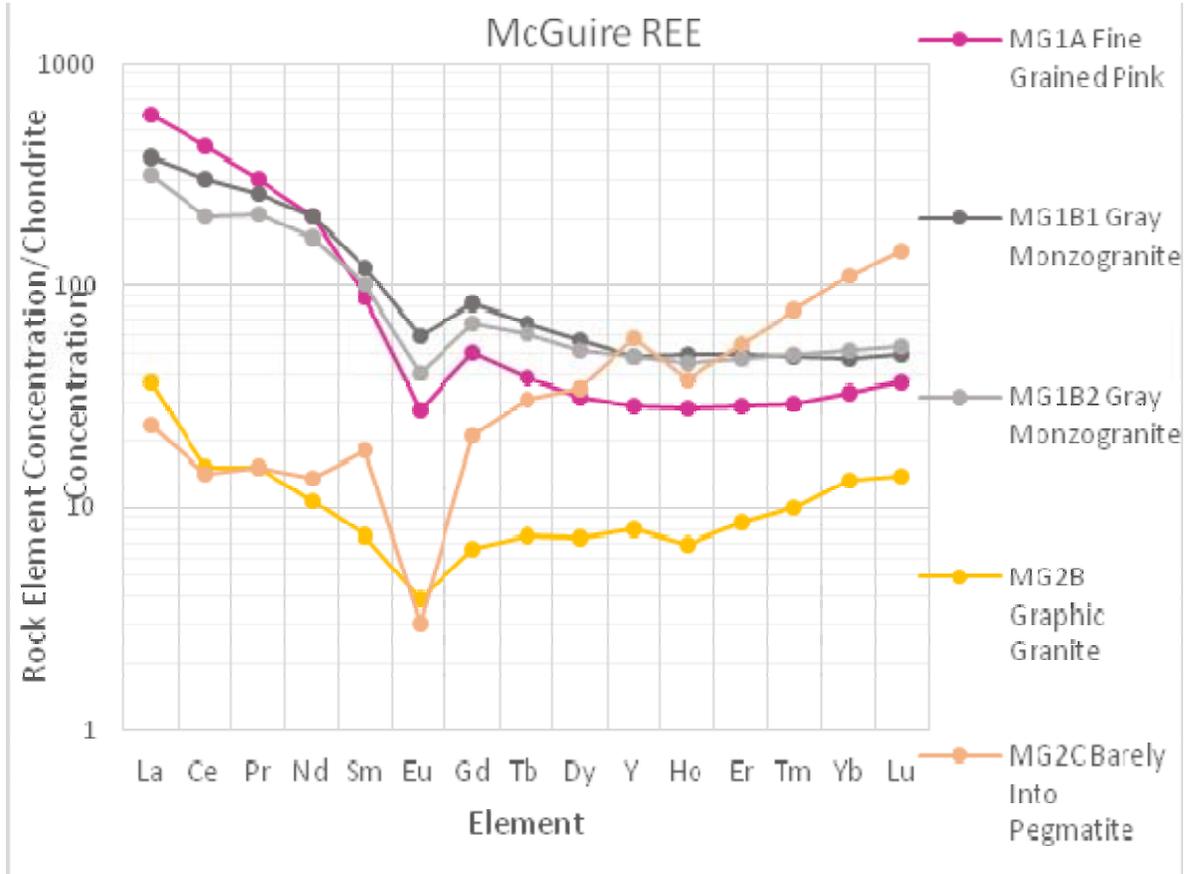


Figure 2. Whole rock analyses, chondrite normalized with McDonough and Sun’s chondrite values. All samples are from the boundary of host rock to the pegmatite, and barely within the pegmatite for McGuire.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
 Colorado School of Mines campus, Golden, Colorado

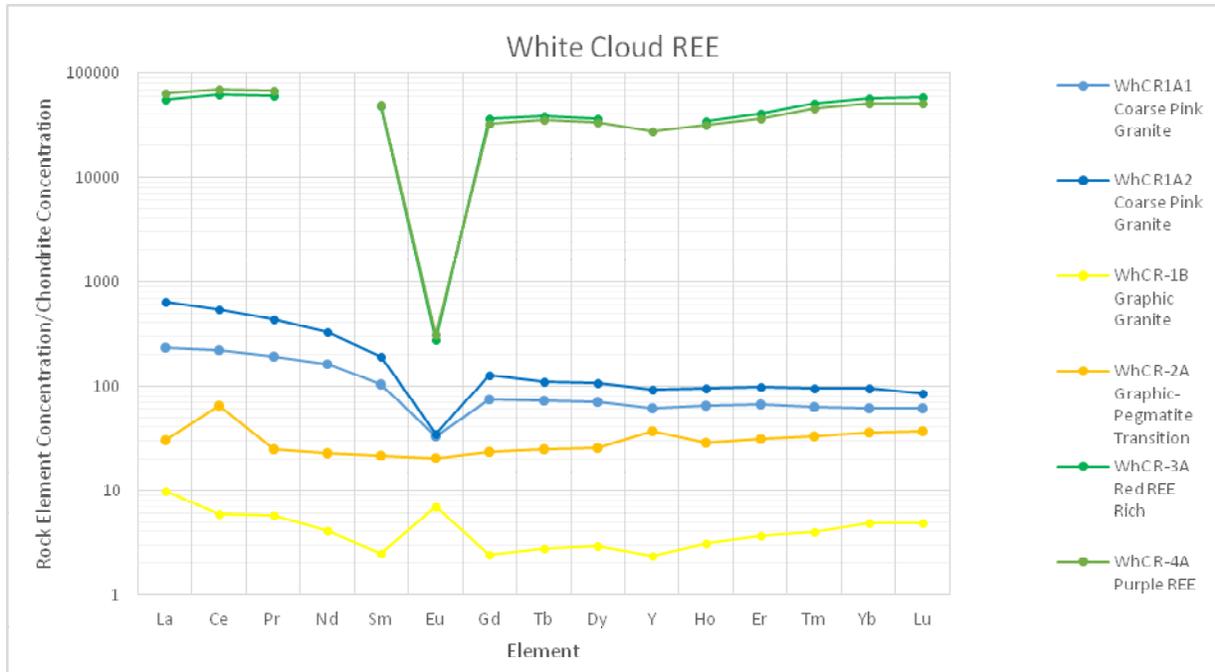


Figure 3: Whole rock analyses, chondrite normalized with McDonough and Sun's chondrite values. Samples are from the closest boundary of host rock to the pegmatite for White Cloud, and the most REE rich zones (WhC R-3A and WhC 4A). The Y content for WhC R-4A was over testing limits, as was the Nd content for WhC R-3A and WhC R-4A.

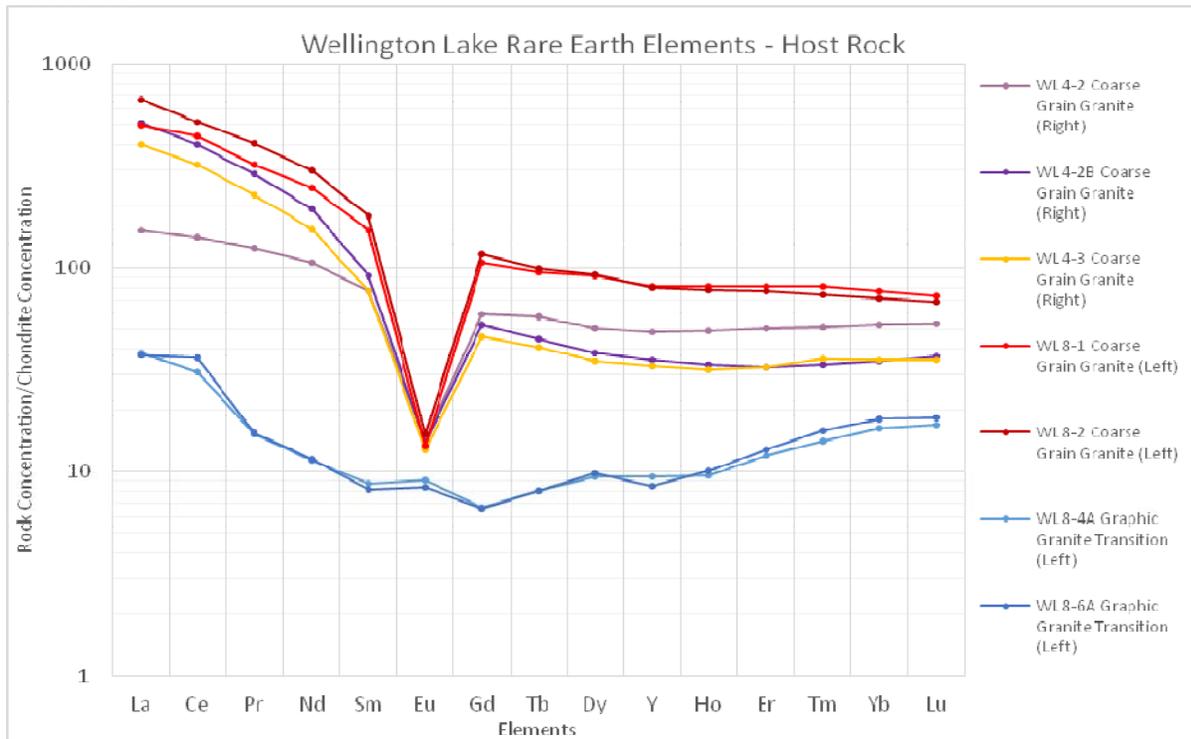


Figure 4: Whole rock analyses, chondrite normalized with McDonough and Sun's chondrite values. Samples are from the closest boundary of host rock to the pegmatite for Wellington Lake, from both sides of the entrance.

Pegmatites of China - A bibliography

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China possesses a diversity of pegmatites that span almost all the known types (class-family) of pegmatites. The English language literature on these pegmatites is minor for various reasons, language difficulties being one reason but certainly not the only one. Since the start of “reform and opening up” of China by Deng Xiaoping in 1978, the situation has been changing almost yearly. Not only has English language but also Chinese language publications on pegmatites, their location, structure, genesis, age, and mineralogy been expanding. Most of this material is legally available to non-Chinese citizens.

The bibliography that is associated with this abstract contains all the published literature that I have been able to locate about Chinese pegmatites and some Chinese minerals without regard to language or publication origin. This material consists of Chinese and non-Chinese publications, sometimes authored by Chinese scientists and sometimes not. These publications are from scientific journal articles, mineral collector hobbyist magazines, books published by state-owned research institutes, masters and doctorate theses, symposium field trip guidebooks, symposium proceedings, and self-published books by Chinese collectors who want to show off their specimens. Most of the compiled literature was created for domestic Chinese audiences, not international.

This material was obtained by various means. The numerous used book stores that typically surround universities sometimes have books of interest. Official Chinese bookstores, some oriented to a general public, some specialized for Chinese scientists will usually have newly published books. Most of the new material can also be purchased online in China. Used scientific books can also be purchased over the internet as can be the hobbyist magazines. Most Chinese journal articles can actually be purchased online for 1/2 RMB (7 cents US) per page and downloaded. The same articles from non-Chinese vendors is significantly more expensive. The documents that are excluded from this list are the reports in the National Geologic Archives of China (NGAC) in Beijing. These reports are only open to those with special permission from the national government since they contain the basic mapped data with detailed maps and associated reports.

What does this material contain? - some basic descriptions of the pegmatite fields in the Altai Mountains, northern Xinjiang (Zou and Li 2006, Luan et al. 1996), a list of all the feldspar and rare-metal pegmatites in the Xinjiang province (Tang et al. 2005), a detailed description of the entire pegmatite field surrounding the Nanping no. 31 pegmatite (Chou and Yang 1985), the muscovite pegmatites of Danba, the unzoned albite-spodumene pegmatites of Ke'erlyn and the Complex LCT pegmatites of Jiajika in the Sichuan Province (Li, Wang, and Fu 2006; Li, Wang, Zhang and Fu 2007), the Qinling Mountains pegmatite fields (Chen, et al. 1993) which stretch across Henan, Shaanxi and Gansu provinces, the pegmatite fields on either side of one of the plutons in the Mufushan batholith, Tongcheng County in Hubei (Huang and Hu 2012) and Pingjiang County in Hunan (Li et al 1994), the miarolitic pegmatites in Inner Mongolia (Wong and Wang 1930; Sun 1933, 1934), the gem pegmatites of Yunnan (Sun et al. 1986, Li 2007), and the NYF pegmatites in Suzhou, Jiangsu (Huang 1949). There are still many more pegmatite fields that have been documented in these and other provinces, so the list above was just to give a feel for what is available in the bibliography.

Since there is little diversity in Han Chinese family names, the citation method capitalizes completely the Pinyin family names and always spelled out where known, the complete given name. In Chinese characters, the names are sufficiently unique and easier to recognize the same author. This fifty-three page, English language bibliography will be released and posted on the internet as a pdf digital file after the symposium on the Friends of Mineralogy, Colorado Chapter website.

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Colorado School of Mines campus, Golden, Colorado

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Experimental Crystallization of the Macusani Obsidian

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The vast majority of experiments aimed at understanding the crystallization of silicate melts, and the consequent formation of igneous rocks, have been conducted by melting finely milled crystalline powders. In those experiments, little or nothing crystallized. Petrologic experimental programs that actually crystallized silicate liquids are very few in number, despite the fact that some of those works have had a significant impact on our understanding of igneous processes (e.g., Fenn, 1977, 1986; Swanson, 1977). We (London et al., 1989) previously published a study of crystallization involving melts derived from the nominally anhydrous Macusani obsidian, a flux- and rare-element rich S-type peraluminous rhyolite from Peru. In the course of subsequent experimentation with other granitic compositions, we noted systematic differences between the crystallization response of powdered glasses versus solid cores. Of the two methods, the use of solid glass cores more closely approximates the crystallization of natural melts. Therefore, we have conducted a new experimental program using solid cores of the Macusani obsidian. In many of these experiments, we added powdered amphibolite at one end of the capsule to simulate a natural environment in which melt is in contact with a host rock with which the melt is not in chemical equilibrium.

In all cases, crystallization commenced with a very fine-grained border zone, followed by a unidirectional wall zone that completely surrounds the melt body. The border and wall zones contain substantially less normative quartz (20-25 wt%) than the bulk composition (35.2 wt). Feldspar compositions are zoned around the wall zone, with comparatively An-rich plagioclase adjacent to the amphibolites versus K-rich feldspar that is prevalent at the opposite end of the melt body. Feldspars at opposite ends of the capsules, however, represent solvus pairs that are close to chemical equilibrium with one another. Thermometry as applied to these solvus pairs yields temperatures that are ~ 10.-20.C higher than the actual run temperatures. This is true whether the experiment was cooled to the run temperature, or heated directly to it, in which case the feldspar temperatures are clearly fictive, higher than the actual temperature at any time. The presence of amphibolite at one end of the capsule serves to trigger the crystallization of ternary sodic plagioclase; that drives the crystallization of K-feldspar, more or less simultaneously, at the opposite end, even at temperatures of crystallization that approach the glassy state for the starting melt. The formation of these paired solvus feldspars requires exceedingly rapid diffusion of alkalis along the entire length of the melt; we have previously described this process as far-field chemical diffusion, which operates over the entire volume of melt and serves to quickly erase chemical gradients caused by crystallization (Morgan et al. 2008; London, 2009).

A second feature of the feldspars is that they exhibit isothermal subsolidus fractional crystallization (London, 2014). In a highly undercooled state, solid solutions like the feldspars undergo an evolution in their compositions that approximately follows their liquidus line of descent. In these experiments, solvus pairs of feldspars actually record a decrease in temperature of crystallization from the margins inward, despite the fact that the feldspars all grew at a single temperature well below the liquidus surface, and indeed well below the crest of the solvus. The apparent cooling history recorded by the feldspars is fictive, except for the last-formed solvus pairs that are usually within 10.-20.C of the actual run temperature.

With a greater extent of crystallization (~ 40-65 vol%), the border zones evolve into a coarse-grained assemblage dominated by K-feldspar with pronounced unidirectional crystallization texture. Graphic feldspar-quartz intergrowths evolve into separate phases, and quartz + mica begins to dominate the crystallization assemblage toward the end. Experiments end their crystallization with nearly pure quartz, as is required by the low modal quartz content of the border and wall zones.

From the outset, a boundary layer liquid develops adjacent to the wall zone that is especially enriched in boron (. 5-8 wt% B₂O₃, with only 0.64 wt% B₂O₃ in the obsidian), as no boron-bearing phases crystallize from the Macusani obsidian. As crystallization proceeds, residual glass compositions become extremely fractionated from the initial composition of the obsidian, reaching 11.95 wt% B₂O₃, 8.42 wt% F, 1.17 wt% P₂O₅, and 0.54 wt% Cs₂O in the most crystallized portions of experiments, which is sufficient to crystallize pollucite as the last phase in one experiment.

Experiments that start with high H₂O contents and those that crystallize extensively develop miarolitic cavities adjacent to the crystallization front, or as larger voids in residual melt pools. Despite the high degree of chemical

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

fractionation attained, and the formation of miarolitic cavities in some experiments, there is no evident reaction with the amphibolite. That is, exsolved vapor remained within the pegmatite body, and none escaped to the surrounding host rock.

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Pegmatites of the Little Three mine, Ramona, San Diego County, California

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Miarolitic granitic pegmatites at the Little Three mine property near Ramona, San Diego County, California (USA) were one of Gene Foord's favorite stomping grounds. That was largely because the miner and owner, Louis B. Spaulding Jr., was so accommodating of visits from scientists, and actually performed work to assist us in collecting material and information.

The pegmatites of the Little Three mine are located within the Ramona pegmatite district, ~ 7.5 km east of Ramona, San Diego County, California (USA) (coordinates +33° 3' 28.44", -116° 47' 31.67"). Spaulding's mine workings are designated as the Main dike, the Spessartine dike, and the Swamp dike. The Main dike contains the thickest section of pegmatite, up to ~ 2.5 meters, and has been a significant source of topaz, elbaite, lepidolite, feldspar, quartz, hambergite, bismuthian stibiotantalite, and boromuscovite from miarolitic cavities. The Spessartine claim, with a maximum thickness of ~ 1.5 meters, lies within the same dike as the Hercules claim to the west; the Spessartine claim has produced much of the finest gem-quality spessartine found anywhere in the world. The Swamp dike is synonymous with workings described as the Spaulding-Hatfield Creek-Sinkankas dikes in Foord et al. (1989). Other small, unnamed pegmatite dikes occur on the property.

Geometry of the dikes. Simpson (1965) represented the pegmatite dikes of the Ramona district as a non-intersecting parallel dike swarm striking N45 ° W with persistent dip of ~ 70 ° to the southwest. As such, each pegmatite represents a single injection of magma. Surface outcrops of the pegmatite dikes are nearly continuous from the claims of the Little Three mine over a strike distance of ~ 1.5 km to the northwest to the ABC and Black Panther mines.

Geologic cross sections presented in Stern et al. (1986) show the Main dike mostly as a subhorizontal body, but with undulations in dip along strike and down dip. Those undulations in the direction of dip form what gem miners refer to as "rolls", which are normally accompanied by thickening of the dike, or "bulge", along either the vertical or horizontal portions of each roll. At the Little Three mine, as in the other gem-bearing pegmatites of San Diego County, the thick "bulges" are mostly subhorizontal in attitude, and these are connected to one another by thinner "rolls" of the dike in the up-dip and down-dip direction. Thus, it is likely that the different attitudes reported by Simpson (1965) and by Stern et al. (1986) represent surface intersections with undulating portions of just a few dikes.

Miarolitic Cavities. In 1976, Spaulding hit what came to be known as the New Spaulding Pocket, so named to distinguish it from prior finds by his father, Louis Spaulding Sr. As illustrated by Stern et al. (1986), the nearly flat-lying New Spaulding pocket was approximately 3 x 3 m and 0.5 m high. In 1991, Spaulding was following a line of small miarolitic pockets (< 1 m in maximum dimension) to the northeast along a steep, up-dip portion of the Main dike above and to the west of the New Spaulding pocket. At the end of that string of cavities, one of us (DL) prospected with a screwdriver into shattered pegmatite to the east, exactly 90° off the strike of the pockets on the steep portion of the pegmatite roll. Digging only 20 cm to the east led to an adjacent and large pocket, dubbed the 1991 London Pocket by Spaulding, that was 4 m in length along the E-W strike, ~ 3 m in width, and 1 m tall at its widest vertical dimension (Fig. 2). The pocket was subhorizontal in dip but conformed to the geometry of the roll, producing a sigmoid shape with its updip termination to the northeast and dipping steeply down-dip to the southwest, toward the New Spaulding pocket below. Within the first hour of mining, the pocket produced large microcline crystals (to 27 kg), flawless smoky quartz crystals (to 9 kg), decimeter-sized dark green tourmaline, cm-scale topaz crystals, and clusters of lepidolite crystals of extraordinary quality. The cavity also contained clear cleavage fragments of hambergite, Be₂BO₃(OH,F).

The Spessartine dike possesses a well-defined pocket line along the centerline of the dike. Miarolitic cavities in the Spessartine dike are rarely more than 20 cm in dimension, but they are common along much of the dike's length. In addition to spessartine, the miarolitic cavities are notable for an abundance of "black" foitite, muscovite, axinite, rare danburite, and even rarer beryl.

Our studies show that the pegmatites possess a bulk composition that matches well the composition of melts that are derived from the anatexis of mica schists. In other respects, however, the pegmatites of the Little Three are

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

unlike those pegmatites (e.g., the LCT family) that arise from aluminous metasediments: the pegmatites contain abundant topaz, are low in cesium, and exceptionally depleted in phosphorus.

Feldspar solvus thermometry records nearly isothermal crystallization at $\sim 450^{\circ}\text{C} \pm 25^{\circ}\text{C}$ for dikes from ~ 1 m (Swamp) to 2.5 m (Main) in thickness. Temperatures recorded by feldspars fall toward the miarolitic center of the thicker Main dike, but increase to $\sim 500^{\circ}\text{C}$ in the thinner Swamp dike. Fluid inclusions within quartz and topaz from miarolitic cavities of the Main dike contain cryolite, arsenides, arsenates, pollucite, and borates including Cs-borate, the latter of which indicates a higher degree of chemical fractionation than is present in the minerals that line the cavities. Extrapolation along isochores based on the homogenization (200° - 225°C) of the low-salinity aqueous fluid (<1 equivalent wt% NaCl) to the temperature of feldspar equilibration (240° - 270°C) within the miarolitic cavity points to hydrostatic entrapment pressures of ~ 50 to 100 MPa, which are unrealistically low. If the isochores are extrapolated to $370^{\circ} \pm 20^{\circ}\text{C}$, the temperatures recorded by feldspars in the pegmatite that surrounds the miarolitic pockets, then the entrapment pressure would be ~ 200 -250 MPa. Formation of the miarolitic cavities at $\sim 370^{\circ}\text{C}$ and 200-250 MPa is plausible, as the cavities contain zeolites; therefore, the feldspars within the pockets have recrystallized (re-equilibrated) to an extent that they no longer preserve their original compositions.

The boron isotope systematics of tourmaline, axinite, danburite, and hambergite are mostly consistent with the crystallization of an H_2O -undersaturated magma body that became vapor saturated toward the end of its crystallization, as the miarolitic cavities manifest. A paucity of host rock alteration indicates that the pegmatites crystallized as essentially closed systems, and their bulk compositions closely approximate those of the melts from which they formed. The pegmatites are, however, sharply zoned. Chemical zonation across the Swamp dike matches the patterns expected from crystallization of undercooled granitic liquids, in which the far-field diffusion of alkalis and local constitutional zone refining of fluxing and incompatible elements contributed to the chemical and textural changes from the margins inward.

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The rise and fall of amazonite

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Eugene Foord (1946–1998) was fascinated not only with mineralogical oddities found in granitic pegmatites, but also with the more mundane rock-forming minerals. In particular, he developed a keen interest in the amazonitic K-feldspar so well displayed in the miarolitic pegmatite dikes of the Pikes Peak area of Colorado. Thus it is very fitting, on the occasion of the second memorial Eugene Foord symposium, to revisit and review the topic of amazonitic feldspar. We will focus on the ultimate destruction of K-feldspar in a granitic pegmatite, very well illustrated in specimens of amazonite because of the color difference between the starting material and the product of its ultimate breakdown.

The mechanism of color generation in amazonite is known to involve a defect caused by the replacement of two K^+ ions by one Pb^{2+} and one vacancy, with ionizing radiation affecting H_2O in the vacant site. In view of the unavailability of sulfur in the system, lead ions are forced to be accommodated in silicates. Lead favors the pegmatite-forming magma until the final stage of its crystallization. Thus it is common to see crystals that are color-zoned, with lead building up toward the rim of the crystal. The K-feldspar structure thus tolerates lead. Furthermore, not all the lead contributes to the generation of color; the feldspar contains active lead and inactive lead, the latter being accommodated according to an “anorthite-like” substitution in which $Pb + Al$ replace $K + Si$, without involvement of a vacant site.

It is important to realize that a crystal of K-feldspar in a typical body of granitic pegmatite is NOT what the magma produced, but rather a pseudomorph of the original feldspar. What is expected to form is a disordered, monoclinic K-feldspar that is completely transparent, *i.e.*, sanidine. There are rare examples of granitic pegmatite in which the original feldspar is retained. Where the primary K-feldspar is lead-bearing, it is of gem quality and mint green. The term “noble amazonite” is used by mineral dealers to describe such transparent sanidine, made popular by discoveries in northern Vietnam. Many samples of noble amazonite contain areas of turbidity, where the conversion to microcline has begun. The conversion to the ordered structure involves H_2O , and the turbidity reflects the presence of pore space, as the ordering reaction involves a reduction in the molar volume of the feldspar.

Sanidine does not remain intact after its appearance. In the presence of a plentiful supply of an aqueous fluid in the cooling pegmatitic environment, sanidine is quickly replaced by a more ordered “monoclinic” K-feldspar, and eventually, very sluggishly, by the triclinic polymorph. The ordering reaction does “clean up” the structure, particularly in Fe^{3+} , which nucleates as hematite particles that color the microcline pink, and it is likely that some of the Pb is lost to the fluid phase during ordering. Such loss may be the reason for blotchiness in the intensity of the blue-green color in some specimens of amazonite. The inversion of the disordered polymorph to microcline is the reason for the well-developed cross-hatched pattern of albite- and pericline-twinning domains. The notorious sluggishness of the reaction means that the temperature of inversion cannot be investigated experimentally. It is considered to be in the range 400° to 450°C. Vestiges of orthoclase are commonly preserved in the microcline.

As the crest of the alkali feldspar solvus is crossed, exsolution sets in. Whereas the early stage of exsolution may well have involved nanoscale diffusion of Na and K, all lamellae that are visible have been subject to “catastrophic” coarsening of the exsolution texture by hydrothermal recrystallization. Thus the coarse “exsolution” lamellae in perthite are only “remotely” a result of exsolution.

After perthite formation, and clearly in the subsolidus realm, it is possible to see a second generation of microcline, accompanied in many cases by blocky albite. Both feldspars are in their field of stability; thus the microcline, which grew epitactically on microcline perthite, is devoid of cross-hatched twins, and devoid of lead. This is the origin of the “white caps” that overgrow perthitic amazonite in the dikes of miarolitic granitic pegmatite of Pikes Peak.

In rare instances, for example in the Keivy pegmatite, Mount Ploskaya, Kola Peninsula, Russia, there is evidence of a late influx of lead-bearing solutions into pre-existing amazonite perthite, leading to enhanced concentrations of Pb. There is also evidence of a localized “soaking” and striking “amazonitization” of the host rocks along the contact with Proterozoic gneissic rocks.

There follows a period of introduction along cracks of coarse albite crystals whose orientation is controlled by the crystallographic orientation of the host crystal. The albite-twinning domains of albite have their twin plane oriented parallel to the albite twins of the microcline host. The replacement is considered to proceed by a rather passive ion-exchange reaction. In some cases, this late albite can be shown to be slightly enriched in Ca compared

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

with the exsolved albite, which suggests that the fluid causing the conversion to albite contains elements picked up outside the pegmatite, in excursions through the country rocks. Minor amounts of quartz and muscovite may well accompany this late albite. Implicit in this conversion of amazonitic microcline to albite is the massive mobilization of the Pb^{2+} ion, whose size precludes its incorporation in the structure of albite.

Excursions of the aqueous fluid beyond the walls of the pegmatite body are to be expected in all major bodies of granitic pegmatite. The cycling of relatively alkaline aqueous fluid through reactive host-rocks provides a mechanism to bring into the pegmatite a host of elements that were not originally in the NYF granitic melt, notably magnesium, calcium, strontium, phosphorus and boron. By this mechanism, one can see the localized development of Pb-dominant tourmaline in narrow cracks, along which the static late fluid could easily interact with the amazonite.

The acid-reflux hypothesis (Martin and De Vito 2014) predicts that the acidity of the aqueous fluid circulating within the body of granitic pegmatite will progressively increase, to the point that the replacement of the microcline + residual orthoclase becomes progressively more aggressive. The result is the appearance of albite with the cleavelandite habit characterized by curving lamellae, associated with muscovite and quartz. The lamellae transect randomly the crystallographic orientation of the precursor. These lamellae of albite grew across the microcline by solution and deposition. External faces of the perthite individuals show clear sign of corrosion and dissolution.

Each body of pegmatite contains evidence of a magmatic stage of crystallization, followed by a stage of open-system hydrothermal soaking involving fluids that have migrated outside the system and re-entered, likely repeatedly. The larger the body, the larger the heat engine, the longer the time needed to shut down the system, and the more important is the second chapter of the pegmatite's history. Gem-bearing pegmatites are those in which the second chapter in the body's evolution is developed exceptionally well.

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Geological Setting and Mineralogy of the LCT Pegmatites of Leinster, Southeast Ireland

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Abstract: Recent mineral exploration has provided an opportunity to examine a swarm of spodumene pegmatite dykes in south Leinster, SE Ireland, to constrain their field relationships, mineralogy and crystallization history through examination of drill core hand samples and thin sections. The subvertical dykes were intruded into granitic, metasedimentary and metavolcanic rocks in an active transtensional zone shortly after emplacement of the nearby Tullow Lowlands pluton of the Leinster granite batholith. Dyke mineralogy and texture are consistent with their classification as albite-spodumene type of the rare element Li class. Their composition and setting are strikingly similar to spodumene pegmatites at Brazil Lake, Nova Scotia, and in the Carolinas.

Introduction

A swarm of spodumene pegmatites was first identified in the 1960s (McArdle 1984) from concentrations of glacially deposited boulders along the eastern margin of the ~400 Ma Leinster granite in SE Ireland. Spodumene is known from most of the length of the batholith, but boulder concentrations suggest that intrusions are concentrated east of the Tullow Lowlands pluton in a ~35 km long belt in the south between the townlands of Coolyhune and Stranakelly (Fig. 1). Starting in 1970, this southern belt has been the subject of eight exploration programs for lithium, including ongoing exploration since 2009 by International Lithium Corp. Drill core has proved the existence of about twenty spodumene pegmatite dykes at five localities.

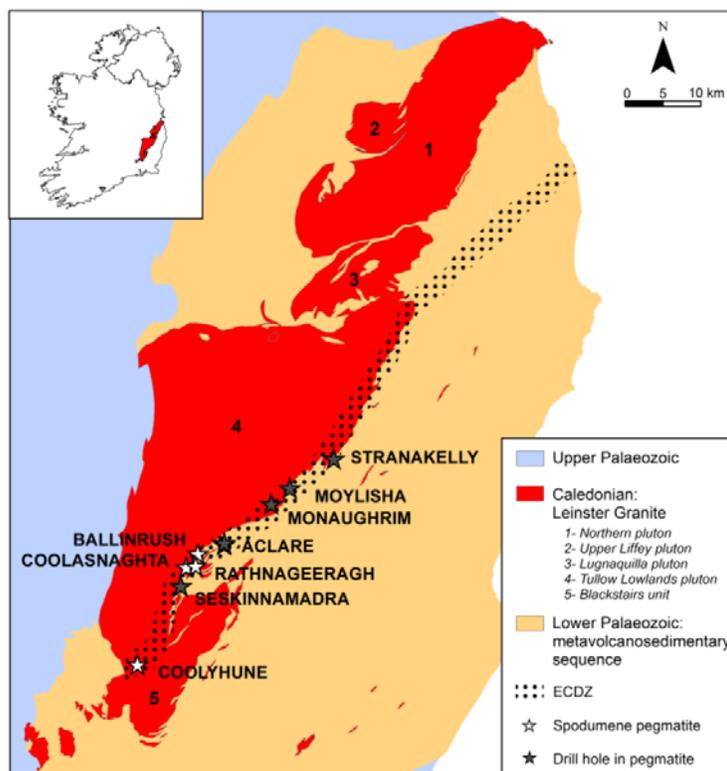


Figure 1. Simplified geological map of southeast Ireland; ECDZ = East Carlow Deformation Zone.

Geological setting

A Cambrian to mid-Ordovician succession of clastic metasedimentary and metavolcanic rocks dominates the geology of south Leinster. The early Ordovician part of this succession, the Maulin Formation, is intruded by both Ordovician and Silurian granite plutons, the latter including the Leinster granite batholith and a number of NE-SW-trending minor granitic intrusions to its east (Fig. 1). Whole-rock Nd isotope data for the Ordovician metasedimentary rocks and the Leinster granite are very similar to the Gander zone of Newfoundland, suggesting that all are founded on Ganderian crust (Menuge et al. 2012). However Precambrian basement in SE Ireland occurs only as the Rosslare Complex, gneissic Neoproterozoic rocks separated from the Lower Palaeozoic succession of SE Ireland by a kilometer wide mylonite shear zone (Chew and Stillman 2009).

The Silurian granitic intrusions are all aligned with the regional steeply dipping D1 NE-SW foliation, which is probably of Acadian age and predates intrusion of the Leinster granite (Chew and Stillman 2009). The Leinster granite comprises several plutons, each of which contains several granite varieties, with two-mica granites predominating. The minor granite intrusions to the east of the batholith are mainly biotite-tonalites and biotite-granodiorites. Along the eastern margin of the Tullow Lowlands pluton and its immediate country rocks, a NE-SW trending zone of D2 sinistral transtension, manifest as dip-slip shear of the D1 regional foliation, is named the East Carlow Deformation Zone (ECDZ) (McArdle and Kennedy 1985). Both plutons and minor granites were intruded during D2 and McArdle (1984) has argued that the minor intrusions predate the Tullow Lowlands pluton. In the aureole of the Tullow Lowlands pluton, the metasedimentary rocks commonly contain porphyroblastic andalusite or staurolite of syn-D2 age (McArdle and Kennedy 1985).

Pegmatite intrusive relationships and mineral composition

Apart from one exposure fortuitously created in 2014 in a drainage ditch in Monaghan, spodumene pegmatite does not outcrop. In five places (Aclare, Seskinnamadra, Stranakelly, Moylisha and Monaghan), spodumene pegmatite dykes decimetres to ~20 metres thick have been discovered by mineral exploration drilling within a kilometre of spodumene pegmatite glacial boulder concentrations. Recent drilling by International Lithium Corp. suggests that spodumene pegmatites have vertical dimensions of order 100 metres (John Harrop, pers. comm. April 2016), strike dimensions of order one kilometre and thickness perpendicular to strike up to at least twenty metres.

Spodumene pegmatite dykes were intruded into a variety of rocks. These include aphyric to sparsely K-feldspar-phyric two mica granites within the eastern margin of the Tullow Lowlands pluton; minor biotite-tonalites and biotite-granodiorites intruding the Maulin Formation; and phyllites, schists and intermediate metavolcanic rocks of the Maulin Formation (McArdle 1984). Most of the spodumene pegmatites have been intruded into the ECDZ and show evidence of syn-intrusive deformation (McArdle and Kennedy 1985). Some deformation took place during pegmatite crystallization, for example the development in fractured spodumene crystals of veinlets that do not penetrate into the surrounding pegmatite (Fig. 2b). Eastern marginal parts of the Tullow Lowlands pluton have a D2 fabric and emplacement has been argued to be syn-ECDZ shearing (McArdle and Kennedy 1985), suggesting that emplacement of spodumene pegmatites closely followed intrusion of the Tullow Lowlands pluton. Barren pegmatites also intrude the Tullow Lowlands pluton and its country rock contacts. Like the spodumene pegmatite dykes, they usually parallel regional D1 foliation in the country rocks, but are more variable within the granite (McArdle 1984). No cross-cutting relationships between barren and spodumene pegmatites have been observed. O'Connor et al. (1991) conducted a whole-rock Rb-Sr dating study of the Tullow Lowlands pluton, minor granitic intrusions, spodumene and barren pegmatites. They obtained a number of isochrons and errorochrons but were unable to convincingly resolve the ~400 Ma ages of these groups of rocks.

External contacts of spodumene pegmatite dykes in phyllites and schists are always parallel to the steeply dipping NE-SW regional foliation. In contrast, spodumene pegmatites intruding the Tullow Lowlands pluton and minor granitic intrusions often strike at a high angle to the contact of the granite and its D1 foliation (McArdle 1984, O'Connor et al. 1991). External contacts are intrusive, not tectonic, and are usually abrupt, as are contacts with apparent rafts of granite within pegmatites. In most cases metasomatism and sometimes veining of the adjacent country rock is visible to the naked eye within centimetres to decimeters of contacts, including occasional development of greisen. In thin section, metasomatic minerals include tourmaline and Li-rich mica; veins are commonly tourmaline-bearing. Limited drill core whole-rock geochemical data suggest that Li metasomatic haloes in phyllitic country rocks may be up to a few metres thick.

Internally, thinner spodumene pegmatite dykes are unzoned but some thicker ones are crudely zoned (Whitworth and Rankin 1989). Where zoned, there is sometimes a thin zone of quartz-feldspar intergrowth at the margins, followed by a thick zone of spodumene pegmatite, in some cases with crystals grown perpendicular to the outer dyke contact and

thickening inwards (Fig. 2a) and finally a thin quartz core. Pegmatitic parts consist of centimeter to decimetre scale crystals of spodumene, albite, muscovite, quartz, spessartine and apatite, rarely K-feldspar and beryl. They have sinuous and sometimes diffuse contacts with aplite that comprises mainly albite, quartz and muscovite, with spessartine, cassiterite, apatite and Mn phosphate. The aplite replaces pegmatitic spodumene and commonly its albite and muscovite crystals are coplanar (Fig. 2c), and sometimes radiating, in planes parallel to country rock foliation. Elsewhere, typically near dyke margins, aplite without a planar fabric replaces slightly resorbed pegmatitic spodumene that has been partially altered to muscovite (Fig. 2d). It appears that the aplitic parts of the dykes crystallized before the coarse-grained parts were fully crystalline, so they likely crystallized from the same parental magma. Columbite-tantalite has been reported from several of the dykes (Steiger and van Knorring 1974), but the distribution of Ta and other rarer metals such as Rb and Cs has yet to be studied in detail. Considering all the lithologies seen, the rocks can be described as LCT pegmatites and can be assigned to the albite–spodumene type of rare-element Li class (Černý and Ercit 2005).

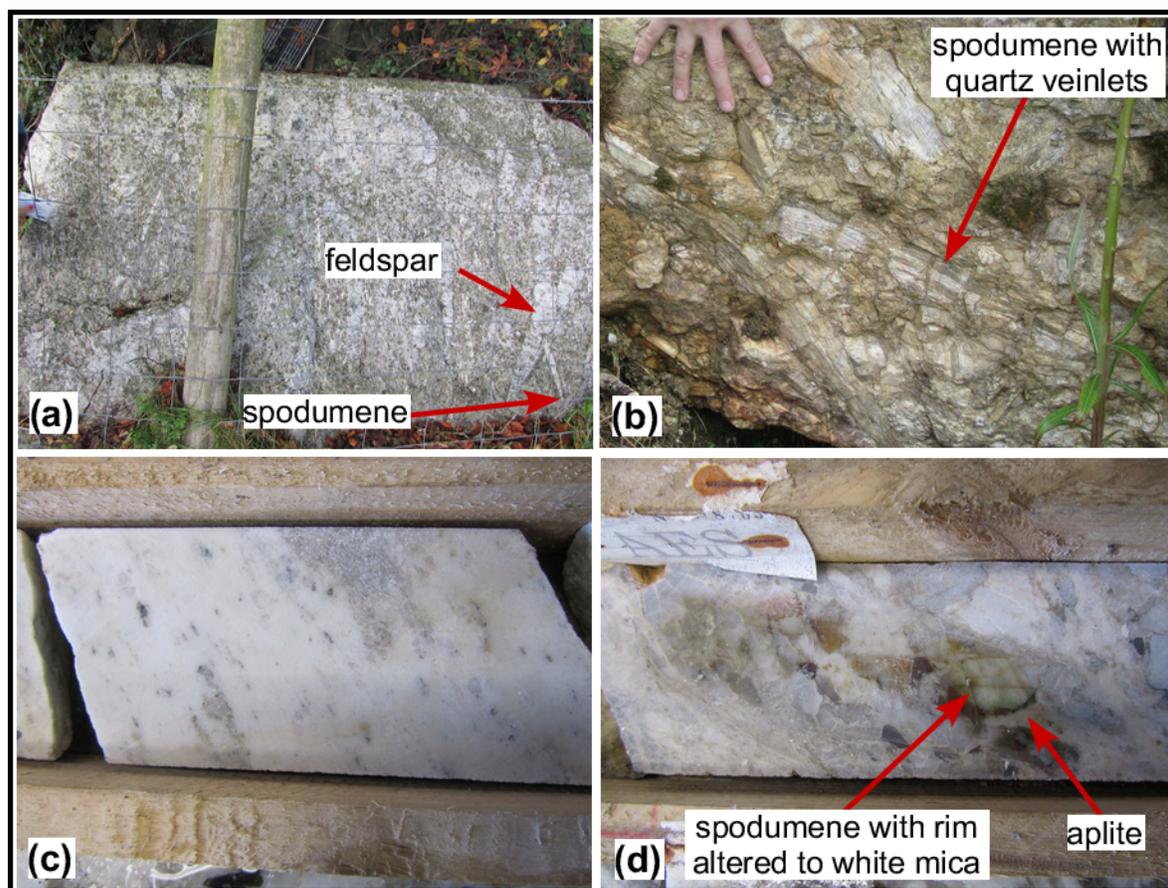


Figure 2. Spodumene pegmatite textures (a) K-feldspar and spodumene crystals thickening from presumed dyke margin (bottom), loose boulder, Monaughrim; (b) spodumene megacrysts deformed and fractured with quartz veins restricted to megacrysts, loose boulder, Aclare House; (c) aplite with foliation defined by albite (white) and aggregates of apatite, white mica and sometimes beryl or Mn phosphate (dark), Aclare House; (d) aplite surrounding a spodumene crystal that has been partly replaced and partly altered to white mica (dark), Aclare House.

Conclusions

A suite of ~400 Ma albite-spodumene LCT pegmatites was intruded penecontemporaneously with granite pluton emplacement into an active sinistral transtensional shear zone along the eastern of margin of the Tullow Lowlands pluton in south Leinster, SE Ireland. Thicker pegmatites are zoned and some display crustal growth perpendicular to dyke margins. In their tectonic setting, immediate country rocks, emplacement environment, mineralogy, internal

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

zoning and other textural features they closely resemble pegmatites of similar age at Brazil Lake, Nova Scotia (Kontak 2006) and somewhat younger pegmatites straddling the North Carolina / South Carolina border such as King's Mountain (Swanson 2012).

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The California Blue Mine: A Recently Discovered Aquamarine Pegmatite in the Mojave Desert

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The California Blue mine is a recently discovered beryllium-fluorine miarolitic pegmatitic granite intrusion located in the Mojave Desert, California. The intrusion is located in San Bernardino County near Yucca Valley and Joshua Tree National Park. The dike is mineralogically fairly simple, being composed predominantly of quartz, perthite and albite with minor to trace beryl, topaz and fluorite. There is minor light and dark micas, especially associated with the cavities. The beryl crystals occur in close association with the cavities, similar to the micas. Gem aquamarine is found within cavities, growing from their walls, perched on terminated quartz or feldspar crystals or as euhedral “floater” crystals. Replacement gem crystals are also found in hexagonal molds in feldspar outside of the miarolitic cavities where they occur as partially etched crystals.

The miarolitic cavities occur centrally within the intrusion as two general types: quartz, perthite and albite and quartz, perthite, albite, white mica, aquamarine +/- topaz. The bimodal nature of pockets is favored by the unique morphology of the dike, which is a tabular body with numerous meter scale sub-verticle apophyses. These apophyses have been injected into the country rock directly from the tabular dike before crystallization. Cavity formed aquamarine occurs as well formed crystals dominantly within the tabular portion of the dike only. The apophyses contain cavities with quartz, microcline and albite. These apophyses appear to have locally channelized late stage acidic fluids, as evidenced by hexagonal voids in albite. These hexagonal voids appear to be beryl crystal molds suggesting late-stage beryl dissolution.

The claim was discovered in 2006 and mined by hand until 2010 when a partnership was formed to mine for aquamarine using large machinery. Currently the claim is being worked intermittently as an open pit style mine and continued specimen production is expected in the future (Hunerlach 2012).

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A review of the 1986 and 1999 Colorado pegmatite symposia

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This 2nd Eugene E. Foord Pegmatite Symposium is dedicated to Dr. Eugene E. Foord, 1946-1998, Colorado mineralogist who was especially well known for his pegmatite studies. An earlier symposium dedicated to him was held in Denver in 1999, "The Eugene E. Foord Memorial Symposium on NYF Granitic Pegmatites". Before this, a first symposium on Colorado Pegmatites took place in Denver in 1986, in which Eugene Foord played a prominent role.

Dr. Eugene Edward Foord (1946 - 1998)

*For his sincere and boundless commitment
to the science of mineralogy*



Eugene Foord, born in Berkeley, CA, earned an A.B. in Geology from Franklin and Marshall College, an M.S. from Rensselaer Polytechnic Institute, and a Ph.D. in mineralogy from Stanford, where he studied with Richard H. Jahns. His doctoral thesis was on the pegmatite-aplite dikes of the Mesa Grande district, San Diego Co., CA. Gene worked as a mineralogist at the U.S. Geological Survey from 1976 until his death in 1988. His geologic and mineralogic studies involved deposits of gold, tin, rare earths, and much more, in addition to pegmatites, and his work took him to China, Pakistan, and Russia as well as many mining and pegmatite districts in the U.S. In the course of Gene's work he was an author or coauthor of the description of some 30 new mineral species, publication of 6 of which was completed posthumously by his colleagues. These minerals are: corderoite (1974), rynersonite (1978), hashemite (1983), minasgeraisite (1986), aheylite (1986), zimbabweite (1986), chestermanite (1988), scrutinyite (1988), grandreefite (1989), pseudorandreefite (1989), laurelite (1989), aravaipaite (1989), boromuscovite (1991), maxwellite (1991), squawcreekite (1991), ferrisurite (1992), parafransoleite (1992), kosnarite (1993), hogtuvaite (1994), mccrillisite (1994), selwynite (1995), artroeite (1995), calcioaravaipaite (1996), meurigite (1996), esperanzaite (1999), simmonsite (1999), kampfite (2001), goldquarryite (2003), nevadaite (2004), and terlinguacreekite (2005); plus the revalidation of planerite (1986). The tin-niobium oxide mineral species foordite was named in his honor by Černý et al. in 1988. Gene played a major role in the collection of data for and writing of the updated version of Minerals of Colorado, an almost 20-year project that culminated in its publication in 1997 (Eckel, 1997). Sadly, Gene died an untimely death in 1998 after a three-year battle against lymphoma (see Modreski, 1998; Simmons and Webber, 1999).

In addition to the E.E. Foord Memorial Symposium held in 1999, the Mineralogical Association of Canada published "Granitic Pegmatites: The Černý-Foord Volume", dedicated jointly to Petr Černý and Gene Foord (Canadian Mineralogist, vol. 36, part 2, 1998, 434 p.).

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Eugene Foord with Eugene B. Rynerson, owner of the San Diego Tourmaline mine, Mesa Grande district, San Diego County, CA. Photo by J.E. Taggart taken during a 1986 I.M.A. field trip.

Colorado Pegmatite Symposium, 1986

The first symposium on pegmatites held in Colorado took place in 1986. "Colorado Pegmatites" was organized by the Colorado Chapter, Friends of Mineralogy, and was held at the Denver Museum of Natural History (now the Denver

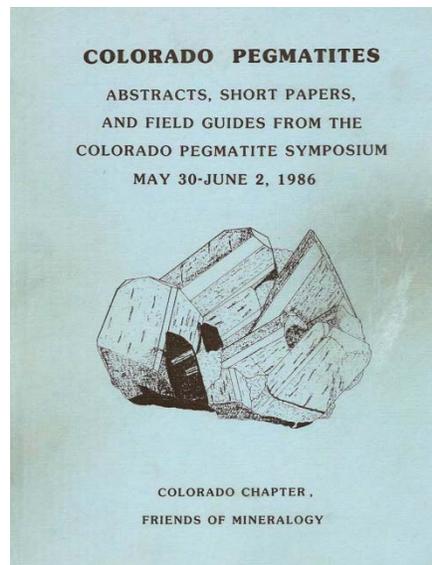
Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016 Colorado School of Mines campus, Golden, Colorado

Museum of Nature and Science). It consisted of two days of lectures, on Friday and Saturday, May 30 and 31, followed by two days of field trips, Sunday and Monday June 1 and 2. After introductions by Jack Murphy (Curator of Geology, DMNH), Barbara Muntyan (President, Colorado Chapter, FM), and Eugene Foord, the first, keynote, talk was presented by Dr. Petr Černý, “Classification of granitic pegmatites”, followed by “The South Platte pegmatite district, revisited”, by Dr. William B. Simmons. There were a total of 32 oral presentations, including talks by Paul Moore, Robert Martin, Reinhard Wobus, Gene Foord, William Nesse, Mark Jacobson, Jack Murphy, Ralph Platte, Al Falster, Robert Hutchinson, Daniel Kile, and Barbara Muntyan. The symposium attendance was almost 200.

Dr. E. William Heinrich, of the University of Michigan, widely known and respected as a premier investigator of Colorado’s pegmatites, was to have attended and would have given a second keynote talk as well as an address at the Friday evening banquet, but he had to cancel his attendance due to health problems. An extended abstract of one of Heinrich’s talks, “Peripatetic Pegmatite Pilgrim’s Progress” did appear in the symposium program booklet. The banquet was held Friday evening at Writer’s Manor Hotel, Denver, with an after-dinner address by Paul Moore on “Minerals and Metals”.

The two field trips were very well attended by almost 100 people on each. The first day’s trip, June 1, visited amazonite-bearing pegmatites in the Lake George area, led by Reinhard Wobus and Gene Foord. The second day’s trip, June 2, led by Mark Jacobson and William Nesse, went to pegmatites, with some preliminary stops in their host metamorphic rocks, in the Crystal Mountain district of Larimer County. A second, “overflow” trip to the Crystal Mountain district was held later in the month for those local-based attendees who could not be accommodated in the original symposium trip.

A volume containing the program, abstracts, and field guide for the symposium, some 160 pages, was printed and distributed at the symposium (Modreski et al., 1986). It proved to be a popular publication, going through several reprinted editions sold by the Colorado Chapter over the subsequent years. The complete volume is now available at no charge as a .pdf file on the Friends of Mineralogy, Colorado Chapter website, at <http://friendsofmineralogycolorado.org/publications/>.



Cover of the 1986 symposium program.

The Eugene E. Foord Memorial Symposium on NYF Granitic Pegmatites, 1999

The second symposium on pegmatites held in Colorado took place in 1999, again held in Ricketson Auditorium at the Denver Museum of Natural History. This was “The Eugene E. Foord Memorial Symposium on NYF Granitic Pegmatites”. The symposium was cosponsored by the Denver Museum of Natural History, The Canadian Mineralogist and Mineralogical Association of Canada, Rochester Mineralogical Symposium, Harvard University Mineralogical Museum, Friends of Mineralogy – Colorado Chapter, The Pegmatite Interest Group (PIGS), and the Friends of Eugene E. Foord. This symposium again consisted of two days of lectures, Saturday and Sunday Sept. 11-12, with a Saturday evening banquet and tribute to Eugene E. Foord, and two days of field trips. After an introduction to the meeting by William B. Simmons, a keynote address was again given by Petr Černý, “The NYF family of granitic pegmatites: simplistic past, fluid present, reformed future”. There were some 27 talks, plus 13 poster papers; other speakers included Victor Zagorsky, Michael Wise, Robert Martin, Federico Pezzotta, Carl Francis, Milan Novak, T. Scott Ercit, Lance Kearns, David London, Daniel Kile, Al Falster, and Karen Webber. As per the title, this symposium was focused on the NYF (niobium-yttrium-fluorine) type of anorogenic granitic pegmatites, of which the pegmatites in the Pikes Peak batholith are a classic example; but the papers given on pegmatites encompassed the entire world. About 50 people took part in the symposium.



Program cover and logo of the 1999 symposium.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Both days of the 1999 symposium field trips went to the Pikes Peak batholith. The first day's trip, Sept. 13, visited pegmatites in the South Platte pegmatite district, including the White Cloud, Luster, and Oregon pegmatites. The second, a half-day trip on Sept. 14, went to examine smoky quartz and amazonite-bearing pegmatites at the PA Claim in the Lake George area.

The abstracts of papers presented at that symposium were distributed in a volume that was a preprint of a special issue of *The Canadian Mineralogist* (vol. 37, part 3, June 1999, pp. 791-863). A separate, 36-page field trip guidebook was printed for the conference (Simmons, Webber, and Falster, 1999).

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Crystallization-induced Field Diffusion as a Driving Force for Pegmatite Zonation

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Deciphering the cause of mineral zonation that is characteristic of complex granitic pegmatites is ultimately a problem of understanding elemental diffusion through magma. The classical approach to determining the diffusivity of component X in silicate liquid is based upon a time-variable series of experiments in which a liquid or solid containing component X is reacted with a liquid containing none (or much less) of that component at a prescribed temperature. The procedure is essentially one of dissolving component X from its reservoir into the initially X-poor composition and then characterizing the time-dependent distance-concentration relationship. There are no known experiments examining the rate of diffusion of a component driven by the crystallization of a solid from liquid. One potential reason for this absence of data is that, at super-solidus temperatures, it is virtually impossible to produce a single coherent nucleation surface from which to measure concentration. Also, if the diffusivity of component X through liquid is as fast as the rate of crystal growth, no gradient will exist in the liquid – only a change in composition with time. Why might the driving mechanism matter? The classical case of diffusion driven by dissolution is effectively a process of “pushing” component X through liquid from a region of surplus, whereas the case of crystallization is one of “pulling” component X through liquid toward a region of depletion. The precipitation of a single crystal from granitic liquid is an incoherent process. Hence, rather than a potentially small positive chemical potential gradient of X produced by dissolution, the removal of X from the boundary layer of melt adjacent to a crystal may produce a nearly infinite negative potential gradient.

Morgan et al. (2008) provided an investigation of alkali diffusion driven by long-range chemical potential gradients among other components in magma, in which ~1 cm-long diffusion couples were comprised of prehydrated haplogranitic compositions that differed only in Al content. Within 16-24 hours, although there was no measurable diffusion of Al or Si, the alkalis re-distributed themselves to completely erase the initial gradients in ASI (=molec. $l/(Na+K+2Ca)$) and Na/Al over the entire diffusion couples; an initially homogeneous K/(K+Na) ratio became uniformly higher in the initially less aluminous end due mostly to the transfer of Na to the opposite end. Measureable changes to the same ratios were produced out to the ends of the diffusion couples in experiments as short as 2-6 hours, making conventional evaluation of diffusivity only possible in experiments of ≤ 2 hr duration. Effective binary diffusion coefficients for the alkalis from the short-duration experiments were ~10-12 m²/s, agreeing with previous investigations from dissolution-type experiments. Those rates, however, were orders of magnitude too slow to account for changes in molecular ratios at the ends of 2-6 hr experiments for which effective alkali diffusivities were more on the order of 10⁻⁸ m²/s. The results demonstrated the operation of a previously unrecognized mechanism of chemical diffusion for alkalis, named *field diffusion*, driven by chemical potential gradients among other components in melt with which the alkalis complex. *Field diffusion* creates coordinated movement of all mobile ions (alkalis in this case) yielding positive ionic currents akin to conveyor belts. Because the movement of all mobile ions in the potential field is coordinated, individual ions can move at the classic (local) rate while yielding effective diffusivity defined by the length of the chemical potential field.

The *field diffusion* of alkalis driven by crystallization was observed in the study of Morgan and London (2005) investigating the partitioning of phosphorus between K-feldspar (Kfs) and haplogranite melt. Results were especially telling for experiments with liquidus undercooling of 200-300°C, which apparently bracketed the glass transition for the composition. In those experiments, after 5-7 days Kfs nucleated only on the outer surfaces of the melt/glass beads. Kfs growth continued until an initial ~20 wt% excess Or component (relative to the minimum composition) was consumed, at which point albite and quartz joined the solid assemblage. Crystallization ceased between 28 and 31 days when the residual melt/glass approached the haplogranite minimum composition. Electron probe transects across the length (6-9 mm) and width (~3 mm) of the products showed that the glasses were compositionally homogeneous at all stages of experiment from 1 to 31 days in duration. Hence, the long-range diffusion of alkalis kept pace with crystallization even when it occurred at temperature below the glass transition. The field diffusion of alkalis is presently the only mechanism that explains the long-range transport required to produce the zoning of alkali aluminosilicates observed in complex granitic pegmatites. The rock fabrics of these bodies, especially in the outer oriented zones, indicate sequential inward growth from widely-spaced nucleation centers starting at the margins of the bodies. Because chemical potential fields for alkali exchange are established between crystallization centers of different alkali

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

aluminosilicates (e.g., sodic plagioclase, potassium feldspar, spodumene/petalite, pollucite), nucleation and growth of one such species initiates an ionic current of its principal alkali cation toward the center of growth and a counter-flow of other alkalis in the opposite direction, necessitated by charge balance on Al in melt. This enables growth of a phase bearing a different alkali in another location and, hence, permits the great variability in zonal assemblages observed in granitic pegmatites including the common juxtaposition of zones that are compositional complements with respect to the granitic bulk composition (e.g., sodic hanging wall versus potassic footwall, and vice versa). Moreover, Al diffuses through melt roughly an order of magnitude faster than Si (e.g., Mungall 2002). Hence, the formation of aluminosilicates on separate growth fronts slowly enriches the intervening liquid in Si, helping to explain the common separation of zones enriched in different alkalis by nearly pure quartz cores.

Although *field diffusion* was originally defined for alkalis and certainly is most important for them, there is no reason why it cannot apply to other cations in melt if they are effectively mobile. Therefore, it is more appropriate to assess the field diffusion of Si or Al in melts that are strongly depolymerized by the presence of fluxing components such as H₂O, B, and F. London (2009) reported experiments dissolving silica from quartz into B- and F-enriched peralkaline liquid resembling compositions observed as melt inclusions in evolved granitic pegmatites and as boundary layer liquids adjacent to crystallization fronts in experiments with weakly-fluxed granitic liquids. The results demonstrated both that the local diffusion of Si was greatly increased relative to simple haplogranite melts, and that field diffusion driven by crystallization would yield effective diffusivities many orders of magnitude faster because they scale to the distance between crystallization centers. Mineralogical evidence refutes the origin of pegmatites from magmas with such highly-fluxed bulk compositions, but experimental evidence shows that thin boundary layers of such composition adjacent to feldspar-quartz-dominated crystallization fronts are a natural consequence of rapid crystallization. Local mobility by *field diffusion* within such boundary layers lies at the heart of the inward coarsening of crystals and graphic intergrowths in complex pegmatites (London 2009).

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Can pluton-related and pluton-unrelated granitic pegmatites be distinguished by their chemistry?

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Abstract: Precise isotopic dating demonstrates that there is an increasing number of rare element pegmatite fields that are not related to pluton-sized granitic intrusions. These pegmatites are hosted in amphibolite facies rocks and formed directly by anatexis and small-scale differentiation. They have Niobium-Yttrium-Fluorine (NYF), Lithium-Cesium-Tantalum (LCT) or mixed but incomplete NYF-LCT pegmatite family characteristics. The abundance of Nb, Y, F, Li, Cs and/or Ta in some anatectic pegmatites indicates that the enrichment also can be achieved via small-scale differentiation if the source rock provides the necessary starting concentration of these elements in the anatectic melt. Thus, rare-element-enriched anatectic pegmatites can hardly be discriminated chemically from pluton-related pegmatites. Observations suggest that the pegmatites derived from anatectic melts could be considered as NYLC (Julianna and Tørdal pegmatites), NYC (Evje-Iveland pegmatites with albite zones) or NY (Evje-Iveland pegmatites without albite zones) if one follows the Černý's (1991) family nomenclature style. The formation of large swarms of rare element pegmatites by anatexis and small-scale differentiation requires a reconsidering of existing pegmatite classifications and of models for pegmatite melt formation. In addition, these findings are fundamental for assessing the economic potential of pegmatite occurrences.

The classical model of pegmatite formation implies that the bulk of pegmatite bodies encountered worldwide are not of anatectic origin, but are derived by fractionation of pluton-size batches of felsic magma (Černý 1991, Martin and De Vito 2005, London 2008). That is definitely true for the majority of intra-plutonic miarolitic pegmatites, pegmatite dykes and stockscheider-type pegmatites. Only some chemically primitive granitic pegmatites, also known as abyssal, barren, or ceramic pegmatites, are occasionally considered to have formed directly by anatexis as a result of regional high-grade metamorphism, especially if there is no spatially related granite pluton exposed (Jahns and Burnham 1969, Simmons et al. 1996, Ercit 1999). However, owing to the fact of the increasing availability of precise formation ages of granitic pegmatites and spatially related granite plutons, it becomes obvious that there may be significant time gaps (>20 Ma) between granite intrusions and adjacent fields of pegmatites of the Niobium-Yttrium-Fluorine (NYF) and Lithium-Cesium-Tantalum (LCT) families as well (Romer and Smeds 1996, Beurlen et al. 2014, Müller et al. 2015a). In addition, for a number of large pegmatite fields there are no exposed granite intrusions, thus leaving the discussion open whether there are hidden granite plutons at depth or not. The close genetic relationship between the endogenic processes of regional metamorphism and formation of granitic pegmatites during evolution of orogenic belts, which has been demonstrated for a number of areas worldwide, has been used to link periods of particularly important pegmatite formation to the supercontinent cycle and to link changes in predominant pegmatite types through time with systematic changes in orogenic style (e.g., McCauley and Bradley, 2014). The formation of pluton-unrelated pegmatite fields is associated with orogenic events. These findings have revitalized the controversial discussions (1) on the igneous (pluton-related) or anatectic (pluton-unrelated) origin of rare element pegmatites in some provinces, (2) the causes of regional chemical and mineralogical gradients in pegmatite fields, (3) the use of such gradients for genetic interpretations, and (4) the implications of these observations on the classification of pegmatites. This discussion is not only fundamental for the understanding of the genesis of pegmatites but also for assessing the economic potential of pegmatite occurrences.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
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In a genetic context, LCT pegmatites are generally considered to be members of orogenic (calc-alkaline) suites that formed in a subduction setting. In contrast, NYF pegmatites are affiliated with anorogenic suites that formed in an extensional setting involving magmas containing crust and mantle components (Martin and De Vito 2005). Rare element pegmatites that have been identified to be formed independently of pluton-sized granite intrusions exhibit commonly mixed NYF-LCT but also typical LCT or NYF characteristics. Examples are the Sveconorwegian Evje-Iveland and Tørdal pegmatite field in Norway (Müller et al. 2015b), the Julianna pegmatites in the Sowie Mts. massif in Poland (Piecicka et al. 2015) and Mount Mica pegmatite in Maine, USA (Simmons et al. 1996, Simmons et al. 2013). The anatectic mixed NYF-LCT pegmatites show a very strong internal mineralogy and chemical zoning commonly with a “barren” biotite-magnetite-bearing wall zone, a muscovite-rare-element bearing intermediate zone with NYF affinity and a quartz core. The intermediate and core zones are superimposed with albite replacement zones of LCT affinity. Thus, the family classification (NYF versus LCT) is not applicable in these cases because the composition of the pegmatite melt depends entirely on the type of melted host rock (which can be a wide range of different types of metamorphic rocks) and not on differentiation via pluton-sized intrusions of melt-characterizing S- or A-type signature. Despite exhibiting NYF and LCT features, the anatectic mixed NYF-LCT pegmatites can be poor in F- and Ta-bearing minerals compared to the classical pluton-related NYF and LCT pegmatites. The abundance of Nb, Y, F, Li, Cs and/or Ta in some anatectic pegmatites indicates that the enrichment also can be achieved via small-scale differentiation if the source rock provides the necessary starting concentration of these elements in the anatectic melt. Those rare elements that are preferentially hosted in minerals that control anhydrous melting (e.g., muscovite, biotite) may strongly partition into the melt when their original hosts become consumed. Observations suggest that the pegmatites derived from anatectic melts could be considered as NYLC (Julianna and Tørdal pegmatites), NYC (Evje-Iveland pegmatites with albite zones) or NY (Evje-Iveland pegmatites without albite zones) if one follows the Černý’s (1991) family nomenclature style.

In addition, the identification of pluton-unrelated rare element pegmatites introduces the following issues: (1) The spatial coincidence and even chemical similarities between pegmatite fields and adjacent granite intrusions does not imply straightforwardly a genetic relationship. Large swarms of rare element pegmatites can be formed directly via anatexis, which requires a reconsideration of existing models for pegmatite melt formation. (2) The regional chemical zoning of anatectic pegmatite fields, as for instance the rare element pegmatites of the Sveconorwegian orogen, is linked to large scale tectonic structures and units rather than to granite intrusions.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
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Primary (magmatic?) and hydrothermal milarite-group minerals from the Velká skála pegmatite, Písek pegmatite district, Czech Republic

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Abstract: Four paragenetically, morphologically and compositionally distinct milarite-group minerals were recognized in the intragranitic NYF pegmatite Velká skála near Písek, Czech Republic. They crystallized from magmatic to hydrothermal stage in the sequence: milarite I → Sc-rich milarite II → REE-rich milarite to agakhanovite-(Y) and "agakhanovite-(Ce)" III → milarite IV. Early milarite I is likely the only primary (magmatic?) milarite from granitic pegmatites. Electron microprobe and LA-ICP-MS data revealed continuous evolution of tetrad effect from M-type to W-type pattern followed by evolution of Eu anomaly from strong positive to strong negative.

Milarite group includes framework silicates with the general formula $A_2 B_2 C D T_2 T_1 T_2 O_{30}$ (H_2O) where $A = Ca, Na, Y, REE, Sc$; $B = \square, Na, K, Ca$; $C = K$; $D = \square$; $T_2 = Be, Li, B, Al$; $T_1 = Si$ (Hawthorne et al. 2014). Several distinct textural and compositional types of milarites were discovered in the Velká skála pegmatite described first in late 1890ies (Vrba 1894, Ježek and Krejčí 1919). Simply zoned, subvertical pegmatite dike, up to ~1 m thick, is enclosed in quartz melasyenite and its mineral assemblage includes: $Pl+Kfs+Qz+Ab\square Bt$ + accessory titanite, pyrite, fluorapatite, allanite-(Ce), zircon and cheralite; no primary muscovite was found. Feldspars are P-poor (≤ 0.08 wt.% P_2O_5) and biotite shows Fe~Mg.

Milarite-group mineral were examined using electron microprobe and LA-ICP-MS. Homogeneous milarite I, close to the ideal formula $Ca_2K(Be_2Al)Si_{12}O_{30}$ (H_2O), forms pale yellowish, subhedral, elongated grains, up to 2.5 cm long, enclosed in coarse-grained $Ab+Qz$ unit and locally in part developed into small pockets. Prismatic subparallel aggregates of white to grayish milarite II, up to 1 cm long, typically occur in small pockets lined with $Ab+Qz+Kfs+REE$ -minerals (Fig. 1); inner part of individual elongated crystals are enriched in Sc (≤ 0.17 apfu). Very rare milarite III forms short prismatic crystals, up to 0.2 mm long, and overgrowths, up to 20 μm thick, on milarite II (Fig. 1). It is highly heterogeneous with complex oscillatory zoning reflecting variable Y (≤ 0.51 apfu), and REE (≤ 0.45 apfu), and in general its evolution respects following trend: milarite → agakhanovite-(Y) → Ce>Y "agakhanovite"-(Ce). Late milarite IV, close to the ideal formula $Ca_2K(Be_2Al)Si_{12}O_{30}$ (H_2O), occurs in fractures cutting fine-grained aplitic rock as colorless prismatic crystals, ≤ 2 mm long and locally forms irregular elongated aggregates (≤ 0.5 mm) adjacent to perthites in K-feldspar. It associates with Sc-rich allanite-(Ce), monazite-(Ce), LREE,Ca-Nb-Ti phases, titanite and Mg-rich chlorite. The general compositional trend in milarites is characterized by simplified evolution (I) $Al+Ca \rightarrow$ (II) $Be+Sc \rightarrow$ (III) $Be+Y,REE \rightarrow$ (IV) $Al+Ca$ expressed by the exchange vectors: (1) ${}^B Na + {}^{T2} Be = {}^B \square + {}^{T2} Al$, (2) ${}^A (Sc) + {}^{T2} Be = {}^A Ca + {}^{T2} Al$, (3) ${}^A (Y,REE) + {}^{T2} Be = {}^A Ca + {}^{T2} Al$ and (4) ${}^A Ca + {}^{T2} Al = {}^A (Y,REE) + {}^{T2} Be$. Milarite I to III are characterized by M-type tetrad effect, milarite IV exhibits continuous decreasing of M-type tetrad effect through none-tetrad pattern to W-type tetrad pattern. These changes are followed by evolution of Eu anomaly from strong positive to strong negative.

The Velká skála locality is the only granitic pegmatite containing several distinct textural-paragenetic types of milarite starting from a magmatic stage with milarite I, which substitutes beryl or gadolinite as a Be-dominant primary mineral in the pegmatite, to several hydrothermal stages with milarite II and hydrothermal milarite III developed in pockets and with late milarite IV on fractures, the most common paragenetic type of milarite in granitic pegmatites. The mineral assemblages of the Velká skála pegmatite imply alkaline conditions with low activity of B, P and F typical for most F-poor NYF pegmatites such as some pegmatites enclosed in melasyenites of the Třebíč pluton, Czech Republic (Škoda et al. 2006, Novák et al. 2011) generated by similar melasyenite. Similarities in chemical composition (Be and Y+REE) in milarite to agakhanovite-(Y) $(YCa)_2K(BeAl_2)Si_{12}O_{30}$ (H_2O) and in gadolinite $(Y,Ca)_2FeBe_2(SiO_4)_2O$ indicate that the Velká skála pegmatite may be related to the REL-REE gadolinite-type pegmatites and to MI-REE gadolinite-fergusonite pegmatites (Černý and Ercit 2005), although these pegmatites

show generally higher degree of fractionation indicated by further common Y,REE-minerals. Milarite became further primary Be-rich dominant mineral in the NYF pegmatites along with gadolinite (Černý and Ercit 2005) and beryl; however, because the pegmatite classifications (e.g., Černý and Ercit 2005, Černý et al. 2012) cannot comprise all variations in mineral composition of such extremely variable rocks – granitic pegmatites; the Velká skála pegmatite with milarite as a sole primary mineral of Be does not require a definition of new specific (sub) type.

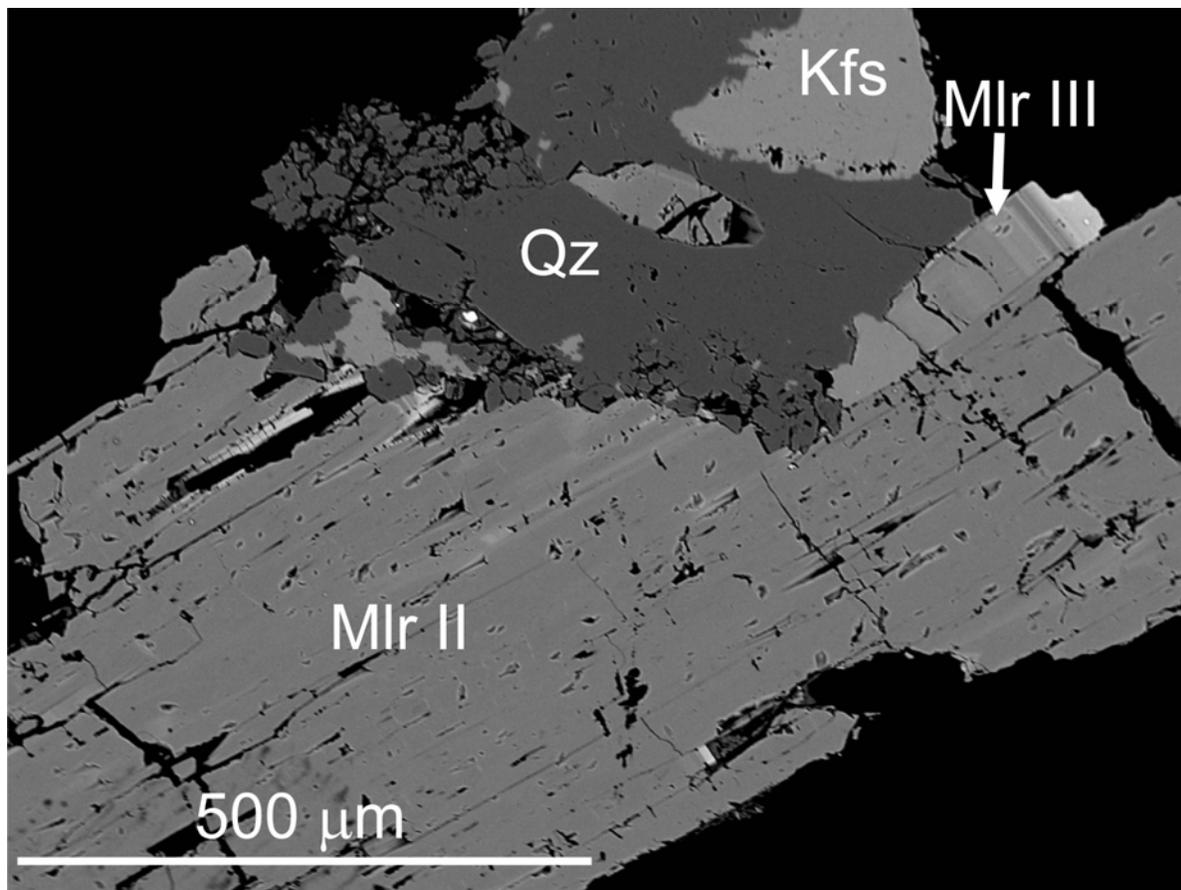


Figure 1. BSE image of the milarite II and III and associated minerals. Mlr-milarite, Qz-quartz, Kfs-K-feldspar.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Unusual REE and rare element minerals from pegmatites and alkaline granites: thalenite and brannockite from the Golden Horn Batholith, Washington, and South Platte Pegmatite district, Colorado (USA)

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Abstract: The rare minerals and brannockite (ideally $\text{KLi}_3\text{Sn}_2\text{Si}_{12}\text{O}_{30}$) and thalenite (ideally $\text{Y}_3\text{Si}_3\text{O}_{10}\text{F}$) are described from new localities in the alkaline granite of the Golden Horn batholith. They are compared with their respective occurrences in pegmatites at Kings Mountain, North Carolina and White Cloud, Colorado, respectively, based on detailed crystal chemical analyses.

Introduction

Here we investigate the crystal chemistry of the rare milarite group mineral brannockite and the REE silicate thalenite, which we recently identified in the alkaline granite of the Golden Horn Batholith, North Cascade Mountains, Washington State, USA, as the first joint occurrence of these two mineral in the same geological setting.

For brannockite this represents the first description of this mineral from outside its type locality in the Foote Mine, Kings Mountain, North Carolina. We provide a chemical and structural analysis and comparison of brannockite from these two different geological settings. In addition, we studied the relationship of trace element composition between brannockite, sogdinate and zektzerite from the Washington Pass locality. These results add to the understanding of the complex crystal-chemical and structural relationships within the milarite-group minerals.

Furthermore, we investigate the crystal chemistry of thalenite, also from a new occurrence in the Golden Horn Batholith, with a focus on chemical composition and structure in comparison with the results from other localities. In particular, we perform a detailed re-analysis of thalenite from the White Cloud pegmatite, South Platte District, Colorado. In the context of the recent redefinition and question about the F and OH substitution we perform Raman spectroscopy for the identification of the crystal OH groups.

Geologic settings

The *Golden Horn Batholith* is a shallow peralkaline granitic intrusion of Eocene age (47-50 Ma) in the crystalline core of the North Cascades Mountains in Washington State, USA. There are four phases of granite intrusions in the batholith. These phases range from a peralkaline arfvedsonite granite, a less alkaline transitional “border granite”, and two different types of biotite granites (Boggs 1984). The granites are unusually rich in otherwise rare, REE minerals and in particular Zr-bearing silicate minerals. A wide range of REE minerals have been noted in the Golden Horn batholith, primarily rare earth carbonate members of the bastnasite and synchysite groups, allanite, beta-fergusonite, calciohilairite, chevkinite, euxenite, gadolinite, gagarinite, kainosite, okanoganite, and the pyrochlore group. These species are rarely to commonly found disseminated throughout the rock in small miarolitic cavities.

The *South Platte* pegmatite district, Colorado, at the northern end of the 1.08 Ga ‘A-Type’ (anorogenic) Pikes Peak Batholith, has long been known for its large number of pegmatites, with many exhibiting unusual rare earth element (REE) enrichment with of the Nb-Y-F (NYF) type. The White Cloud pegmatite exhibits a mineralogy distinct from most South Platte pegmatites, with abundant fluorite and silicate minerals enriched in Y and REE, with few oxides, except hematite. It is well zoned with quartz, perthite, biotite, and fluorite of variable Y content and albitization of microcline and perthite. Primary REE silicates of allanite, gadolinite, fergusonite, ‘cyrtolite’ zircon

are generally rich in Y and HREE yet depleted in Ce and La. Later stage, thought to be replacement of fluorite, are yttrifluorite, synchysite-(Y), and fluocerite-(Ce), bastnasite replacement of gadolinite, albitization of microcline and perthite, and Fe-oxide and clay replacement of biotite.

The *Foote Mine*, located in the tin-spodumene belt of North and South Carolina, is one of several Li-bearing granite pegmatites (quartz-microcline-spodumene pegmatite) of Mississippian age (~340 Ma), intruded into the Cherryville quartz monzonite, schist, and amphibolite. The pegmatite is generally unzoned, and characterized by the absence of primary hydrous phases. It consists predominantly of primary microcline, quartz, and spodumene (~20%) with accessory amounts of beryl, Mn-bearing fluorapatite, triphylite (LiFePO₄), and cassiterite.

Brannockite

Brannockite is a milarite-group mineral. The milarite-group minerals have the general formula A₂B₂CD[(T₂)₃(T₁)₁₂O₃₀](H₂O)_x and space group *P6/mcc*, the crystal structure of brannockite has been recreated in fig. 1 (A). Many of the more than 25 species have only been discovered in the last few decades. The structure consists of [Si₁₂O₃₀] 6-membered double rings that are linked by tetrahedrally coordinated cations at the T₂-site, and octahedrally coordinated cations at the A site. Stacking in the *c*-direction forms the C-site with 12-coordinated cations between the double rings.

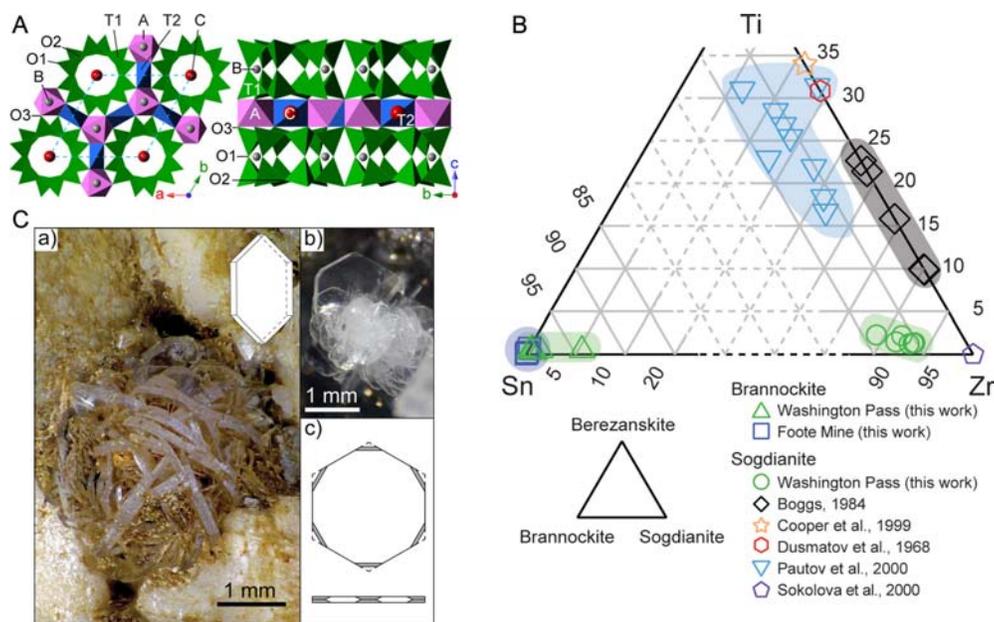


Figure 1. (A) shows the crystal structure of brannockite in two crystallographic orientations (a). A ternary diagram (B) comparing data from this study and literature in the brannockite (Sn), sogdianite (Zr), and berezanskite (Ti) compositional field. (C) depicts Brannockite cluster on microcline from Liberty Bell/Washington Pass, Golden Horn Batholith, Washington, USA, with schematic drawing of idealized hexagonal morphology (inset). Distinct crystal habit of brannockite from the type locality Foote Mine, Kings Mountain, North Carolina (b), with idealized crystal drawing (c). (Raschke et al. 2015).

Of the known Li-bearing milarite-group minerals. Brannockite, ideally KSn₂Li₃Si₁₂O₃₀, was described by White *et al.* (1973) from Li-Sn rich pegmatites of the Foote Mine, Kings Mountain, North Carolina, USA, and its structure refined by Armbruster and Oberhänsli (1988). Closely related to brannockite, are the corresponding Zr end-member sogdianite KLi₃Zr₂[Si₁₂O₃₀] and the Ti end-member berezanskite KLi₃Ti₂[Si₁₂O₃₀]. The relationship of the end members can be seen in the ternary diagram in fig. 1 (B) with percentages of end member elements along each edge. Coupled substitution of Sn⁴⁺ in brannockite with 3+ cations and associated occupancy of the vacant B-site with Na⁺ leads to sugilite K(Na,□)₂(Fe³⁺,Mn³⁺,Al³⁺)₂Li₃[Si₁₂O₃₀] (Armbruster and Oberhänsli, 1988). Darapiosite K(Na,K,□)₂(Mn²⁺,Zr³⁺,Y³⁺)₂(Li,Zn,Fe²⁺)₃[Si₁₂O₃₀] in end-member composition with Zn₂Li in T₂-site is charge

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

balancing the divalent A-site with two Na⁺ on the B-site (Raschke et al. 2015, and references therein). Similar relationship applies to dusmatovite K(□, Na, K)₂(Mn²⁺, Zr³⁺, Y³⁺)₂(Zn, Li)₃[Si₁₂O₃₀].

Brannockite has previously only been described from the type locality at the Foote Mine (White *et al.*, 1973). A second locality of the milarite-group mineral brannockite (ideally KLi₃Sn₂Si₁₂O₃₀) has been discovered at Liberty Bell/Washington Pass in the alkaline granite of the Golden Horn Batholith, Okanogan County, Washington, USA as sub-millimeter euhedral bladed clear crystals in a single miarolitic cavity in a biotite granite as seen in Fig. 1 (C inset a, b). We find that the Washington Pass brannockite shows micro-scale compositional zoning involving tetravalent A-site Sn⁴⁺, Zr⁴⁺, Ti⁴⁺, and Hf⁴⁺ substitution and the coupled substitution ^A(X⁴⁺) + ^B□ ↔ ^A(Fe/Al)³⁺ + ^B(Na,K)⁺ (Raschke et al. 2015). In contrast, brannockite analyzed from the type locality in the late hydrothermal zone of the Li-Sn-rich pegmatite of the Foote Mine, Kings Mountain, North Carolina, USA exhibits near end-member composition with only minor Na⁺, Al³⁺, and Ti⁴⁺. Single crystal X-ray diffraction of Washington Pass brannockite confirms the space group *P6/mcc* with unit-cell parameters *a* = 10.014(2) Å, *c* = 14.268(5) Å, and *V* = 1239.16(8) Å³. Washington Pass brannockite co-exists with its Zr-analogues, both the milarite-group sogdianite and the related tualite-group mineral zektzerite. Selected samples of both minerals show Sn as minor elements. The sogdianite contains unusually low Na and Ti compared to most other localities and has near end-member composition. The results emphasize the high compatibility of the milarite structure with different heterovalent cations, associated with the cation size dependent coupled distortion of the octahedral A and tetrahedral T2 sites.

Thalenite

Thalenite (ideally Y₃Si₃O₁₀F), a monoclinic rare-earth-element (REE) silicate was first described by Benedicks (1898, 1900), from Österby granite pegmatite, Dalarna, Sweden, and named in honor of T. R. Thalén (1827-1905), a French physicist (French: thalénite). It has subsequently been identified in only 10 other localities worldwide, primarily in niobium-yttrium-fluorine (NYF) granitic pegmatites, and some other igneous suites.

Despite the range of studies from several localities, many questions about this mineral remain open. The necessary geochemical environment for its formation is poorly constrained. Thalenite is generally rare, but where it occurs it is often abundant, and often associated with fergusonite ((Y,REE)NbO₄), gadolinite ((Y,REE)₂FeBe₂Si₂O₁₀), cyrtolite ((Zr,U,Th,Hf)SiO₄), and magnetite (Fe₃O₄). Yet it often does not occur, even in pegmatites with high abundance of REE elements including Y and F, which suggests that in typical prevalent pegmatite conditions and chemical environments, thalenite does not seem to form.

Furthermore, important details about its crystal chemistry have remained elusive. Thalenite has previously been defined as the OH-analogue of fluorthalenite-(Y). However, a reexamination of the type material has only recently revealed that not only the type material in fact exhibits a dominance of F over OH, but also thalenite from several other localities (Škoda *et al.*, 2015). The type material thus corresponds to a species earlier defined as fluorthalénite-(Y). Thalenite has thus been redefined by IMA in 2014 (IMA 14-D) as a F-dominant species with ideal composition Y₃Si₃O₁₀F and given the name thalénite-(Y) as it has historical priority.

At the Golden Horn, thalenite was found in a talus boulder of mostly peralkaline arfvedsonite granite of varied texture, ranging from medium grained arfvedsonite granite, with abundant miarolitic cavities, to a finer grained granite tending towards a graphic granite texture with annite becoming the dominant dark mineral over arfvedsonite. Within the miarolitic cavities, which range up to 2 cm diameters, Thalenite is found as rare crystals up to about 2 mm in size as clusters or occasionally as smaller single crystals as shown in Fig. 2 (A inset a and b).

In the White Cloud as studied for comparison, thalenite occurs in the quartz-perthite-fluorite zone (Fig. 2 B), in a number of irregular up to meter size fluorite-rich pods immediately adjacent the quartz-microcline core zone. Thalenite-(Y) occurs both in yttrifluorite, as well as associated with quartz and feldspar (Adams and Sharp 1972, Wayne 1986). The thalenite rock texture varies from dense, dull-gray decimeter sized aggregates of nodular texture with yttrifluorite, gadolinite, bastnasite, synchysite, allanite, thorite and zircon, to larger areas in which irregular 'sea island' textured yttrifluorite is associated with the aforementioned REE minerals with minor blebs and veinlets of thalenite (Adams & Sharp 1972, Raschke et. al., 2016 and references therein).

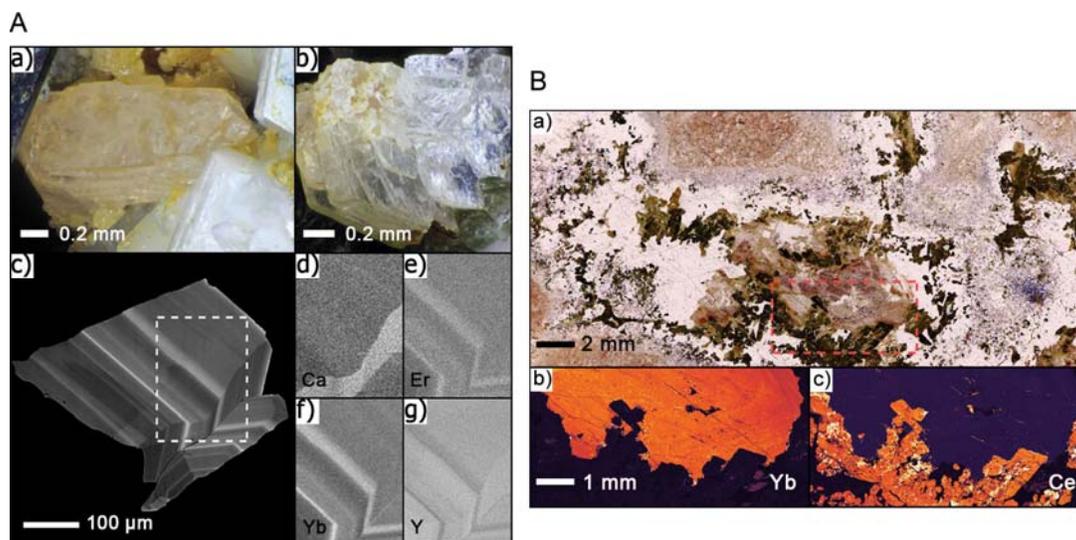


Figure 2. (A) Thalinite (a,b) from miaorolitic cavities from the Golden Horn Batholith, Washington, USA. Backscattered-electron image (c) of thalinite with distinct oscillatory zoning. The dashed box in (c) corresponds to the elemental maps of Ca (d), Er (e), Yb (f), and Y (g). A distinct Ca band runs semi-perpendicular to the REE zoning. (B) White Cloud thalinite rock thin section (plane light), with gadolinite (pale green), allanite (dark brown/green), fluorite (colorless), and thalinite (pink). Yb map (b) highlights anhedral mostly homogeneous thalinite crystal. Ce map emphasizes adjacent gadolinite in brownish-green and allanite in darker green. (Raschke et al. 2016).

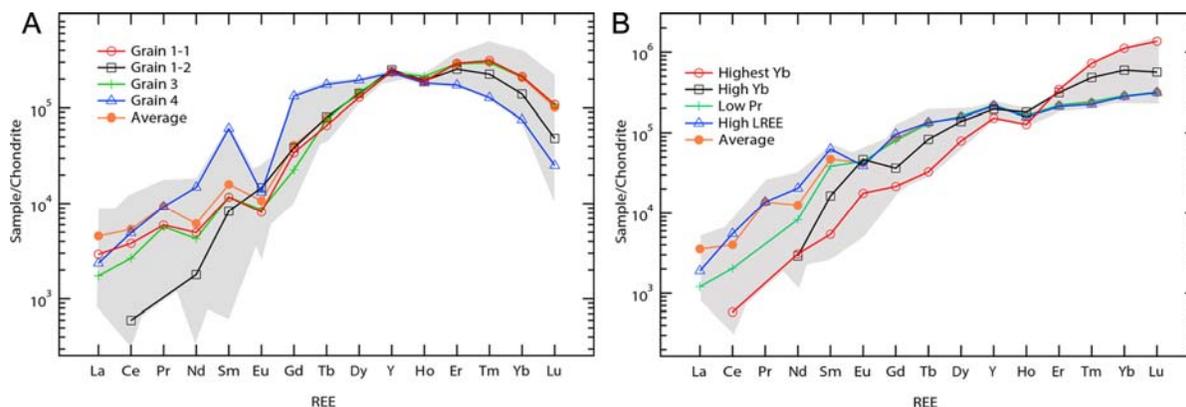


Figure 3. (A) Chondrite normalization for the range of REE analyses for Golden Horn thalinite with a characteristic depletion of HREE. Two characteristic chondrite patterns were found in grain 1, one with high levels of HREE and one with low LREE, labeled grain 1-1 and grain 1-2, respectively. (B) Chondrite normalization for White Cloud thalinite. The anomalously high and highest Yb content is in very localized region of secondary thalinite only. Note the HREE to MREE and LREE anti-correlation. (Raschke et al. 2016).

We analyzed crystal structure and mineral chemistry of thalinite (ideally $Y_3Si_3O_{10}F$) by electron microprobe analysis, X-ray diffraction, and micro-Raman spectroscopy comparing thalinite from the White Cloud pegmatite in Colorado, USA with thalinite from a new locality in the alkaline granite of the Golden Horn Batholith, Okanogan County, Washington State, USA (Raschke et al. 2016). The Golden Horn thalinite exhibits distinct HREE vs. LREE variational growth zoning (Fig. 3 A), with cross cutting Ca-enriched domains, with an average formula $(Y_{2.14}Yb_{0.20}Dy_{0.13}Er_{0.13}Gd_{0.06}Ca_{0.03}Lu_{0.03}Ho_{0.03}Sm_{0.03}Tm_{0.02}Nd_{0.02}Tb_{0.02}Eu_{0.01}Ce_{0.01}Fe_{0.01})_{\Sigma 2.87}Si_{3.11}O_{10}F$. The White Cloud thalinite occurs in two distinct anhedral and botryoidal crystal habits with similar average formula $(Y_{2.17}Yb_{0.17}Dy_{0.14}Er_{0.12}Gd_{0.06}Ca_{0.03}Ho_{0.03}Sm_{0.03}Lu_{0.03}Nd_{0.02}Tm_{0.02}Tb_{0.02}Eu_{0.01}Ce_{0.01}Fe_{0.01})_{\Sigma 2.87}Si_{3.10}O_{10}F$, including a minor amount of secondary thalinite unusually enriched in Yb (Fig. 3 B). Single-crystal X-ray analysis and structure refinement show a correlation of unit cell volume with electron site occupation of the three distinct REE sites, in

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

agreement with microprobe REE analysis. Chondrite normalization shows increasing enrichment of HREE with Z and absence of Eu anomaly in White Cloud thalenite, in contrast to Golden Horn thalenite with depletion of HREE and Eu-anomaly. The results suggest hydrothermal formation of the Golden Horn thalenite compared to primary magmatic origin in the White Cloud pegmatite.

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Mineralogy and petrology of a new REE pegmatite near Wellington Lake, in relation to the South Platte Pegmatite district, Colorado (USA)

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Abstract: A new lenticular (ca. 5x8x3 meters) zoned REE pegmatite in the NW of the Pikes Peak batholith near the South Platte pegmatite district is described based on compositional whole rock, comprehensive mineral assemblage and electron microprobe, and fluid inclusion analyses.

Introduction

The South Platte pegmatite district, Colorado, at the northern end of the 1.08 Ga 'A-Type' (anorogenic) Pikes Peak Batholith, has long been known for its large number of pegmatites, with many exhibiting unusual rare earth element (REE) enrichment (Simmons 1980; Simmons et al. 1987). These pegmatites represent globally significant examples of the Nb-Y-F (NYF) type. The northern and central part of the South Platte District contains large, well-zoned heavy REE-rich pegmatites, whereas the southern and western pegmatites of the district are generally light REE-dominant and more variable in size (<1 m to >15m diameter). From early studies, the South Platte pegmatites are generally thought to result from a late-stage, volatile-rich mobile magma in the mesozone of the Pikes Peak batholiths (Haynes 1965). However, with only limited recent work (Smith 1999) the specific origin and formation of the pegmatites have still remained unclear, specifically whether the South Platte REE rich pegmatites are the result of an extreme fractionation concentrating REE in late stage, or whether the parent magma has already been REE rich.

Here we present a detailed petrographic and mineralogical analysis of a yet undescribed REE pegmatite near Wellington Lake, situated on the north-western periphery of the South Platte district (Fig. 1), as the basis for a detailed analysis and modeling to address the origin and pegmatite formation in the South Platte.

Petrology

The Wellington Lake pegmatite is a steeply dipping, lenticular body hosted in coarse to medium-grained pink syenogranite of the Pikes Peak Batholith. A main upper concentrically zoned body measures ~5m x ~8m x ~3m, with a lower body extending to unknown depth. The pegmatite has a sharp boundary to the host granite with a narrow graphic granite transition into a coarse zone of microcline-perthite, 'cleavelandite' albite, biotite, and Fe-oxides. It contains a major quartz core with large, open cavities hosting euhedral multi-generation quartz crystals to >50 cm in size. Accessory minerals include fluorite, bastnäsite, columbite, 'cyrtolite' zircon, and minor secondary U/Th species. Notable is the absence of fluorite or phosphate minerals (monazite) in the pegmatite body.

Thin sections were analyzed from samples across the transition from granite into the pegmatite, and different representative zones of the pegmatite itself. The host granite consists of quartz, perthite microcline, Fe-rich mica (fennite), plagioclase, zircon, with minor fluorite, and monazite. It is typical for the pink Pikes Peak granite (PPG) of the potassic series with 74% SiO₂ (Smith et al. 1999). Within few cm distance the granitic texture starts to exhibit oriented quartz, followed by a decrease in biotite, and developing graphic intergrowth of perthitic microcline with quartz. Perthitic microcline is more abundant than plagioclase, which itself is not graphically intergrown with the quartz. Within 10-15 cm from the granite the quartz-microcline perthite becomes coarser, with macroscopic intergrowth, and the disappearance of plagioclase and biotite. That pegmatite wall zone, of 20-70 cm width is characterized by large both pink albite crystals (in hand samples similar to pink microcline) and white cleavelandite albite, with interspersed biotite, and little quartz. It is then followed by a sharp contact to the mostly monomineralic quartz core, which consists of a skeleton of large intergrown quartz, with open space loosely filled with euhedral milky and smoky quartz crystals, minor hematite, albite, and clay.

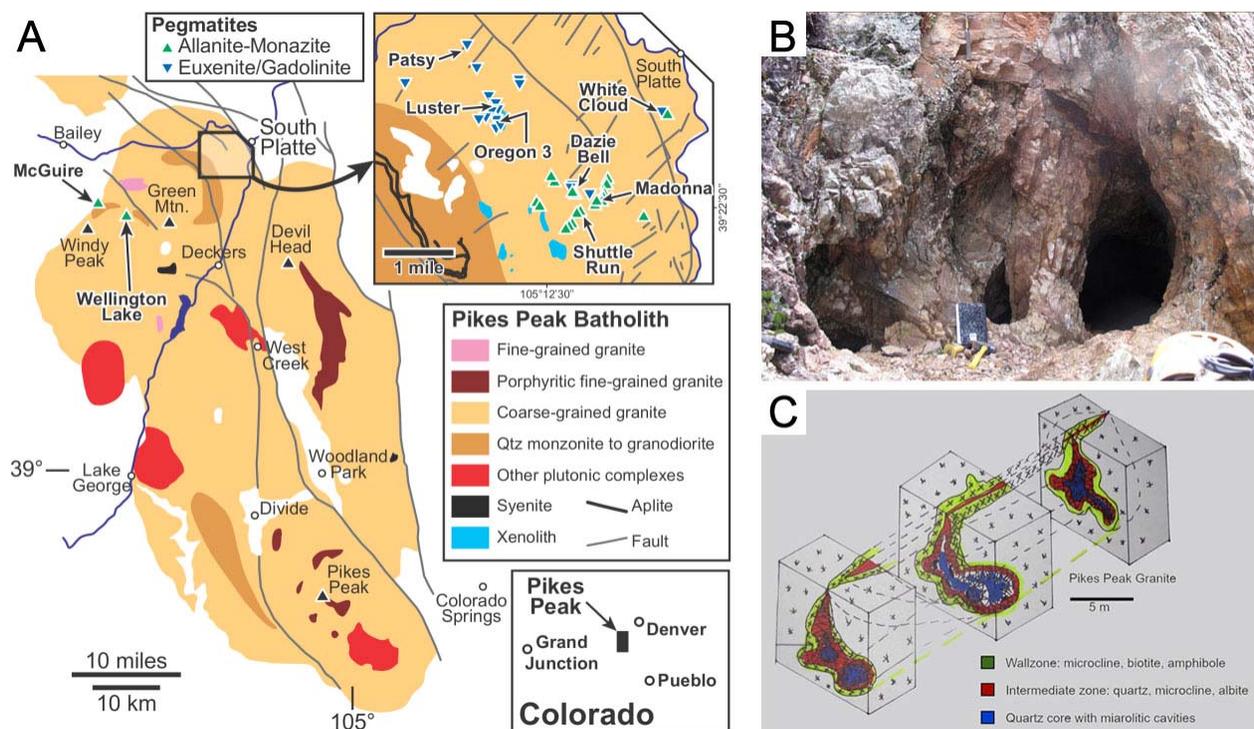


Figure 1: A) Pikes Peak batholith (Colorado, USA) with Wellington Lake pegmatite relative to South Platte pegmatite district and other major pegmatites (after Smith et al. 1999). B) Outcrop photo of Wellington Lake pegmatite with cross sectional view showing the distinct miarolitic quartz core. C) Corresponding three dimensional schematic with the three major pegmatite zones.

We performed a systematic series of whole rock analyses following the transect from the granite host rock through the pegmatite contact and into the different zones of the pegmatite. As shown in Fig. 2 for the granite (WL19, WL 4-1) the HREE rich pattern as characteristic for the pink Pikes Peak granite is observed yet with an in part (WL19) even lower LREE/HREE (normalized) ratio of 2:1 compared to 3:1 in Smith (1999). A strong negative Eu-anomaly is developed with the exception of a narrow zone at the pegmatite granite contact (WL 4-4, WL 4-5), which we attribute to plagioclase formation offsetting the Eu-anomaly. With increasing coarseness (WL 5-1, WL 5-5) the REE content decreases, yet exhibits a similar REE pattern compared to the host granite, with a lower La vs. Ce in contrast to the host granite. Inside the pegmatite a pronounced relative HREE enrichment is observed for microcline and albite. This HREE enrichment is most notably for the Fe-rich breccia developed in different pocket areas in the pegmatite.

Mineralogy

In the following we describe a series of REE and rare element minerals found in the pegmatite. Columbite is found in both well formed up to several cm-sized crystals in albite/microcline and associated with biotite. In the biotite it is associated with different secondary uranium minerals that occur as coating and thin fracture fillings. Nodules of zircon and thorite, in contact and as solid solution are found associated with the biotite up to 5 cm in size, locally with inclusions of 10's micron size cassiterite. The zircon-thorite is also found locally on the surface of large euhedral quartz crystals in etch pits, suggesting their late stage formation.

Most notable for the pegmatite are well-developed tabular crystals of fluocerite $[(Ce,La)F_3]$ which are overgrown by bastnäsite $[(Ce,La)[CO_3]F]$ as shown in Fig. 3A. Ca. 30 crystals of variable sizes ranging from < 1 cm to 4 cm were found in a matrix of brecciated Fe-oxides with albite and associated with euhedral quartz crystals filling a large (80 cm x 50 cm x 40 cm) miarolitic pocket at the roof of the quartz core in contact with the pocket walls in part quartz core and albite from the wall zone.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
 Colorado School of Mines campus, Golden, Colorado

Historically, a similar crystal habit was first described from the Pikes Peak batholith (Stove mountain area) by Allan and Comstock (1880) and termed as ‘tysonite’. Recent detailed crystallographic and high resolution TEM analysis revealed an epitaxial growth along the crystallographic c-axis because of the hexagonal symmetry with close lattice match (Müller et al. 2011).

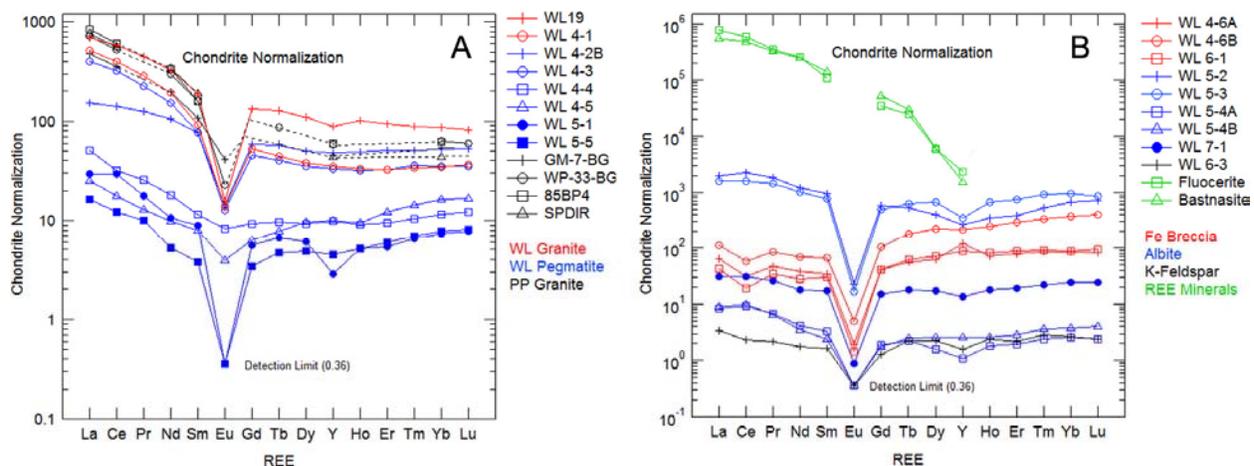


Figure 2: Whole rock analysis of host granite, and within the pegmatite of samples of albite and microcline, a hematite-breccia, and fluocerite and bastnsite from a miarolitic pocket filling (for details see text). GM-7-BG, WP-33-BG, 85BP4, SPDIR from Smith et al., 1999.

We have performed a detailed electron microprobe and crystallographic analysis of the fluocerite/bastnäsite crystals, which have not previously been reported from the South Platte district. Microprobe and whole mineral analysis (Fig. 2) highlights the LREE selectivity of these minerals. From polarization resolved micro-Raman spectroscopy and symmetry selection rule analysis we confirmed the parallel alignment of the crystallographic c-axes of the fluocerite core and bastnäsite overgrowth (Fig. 3B).

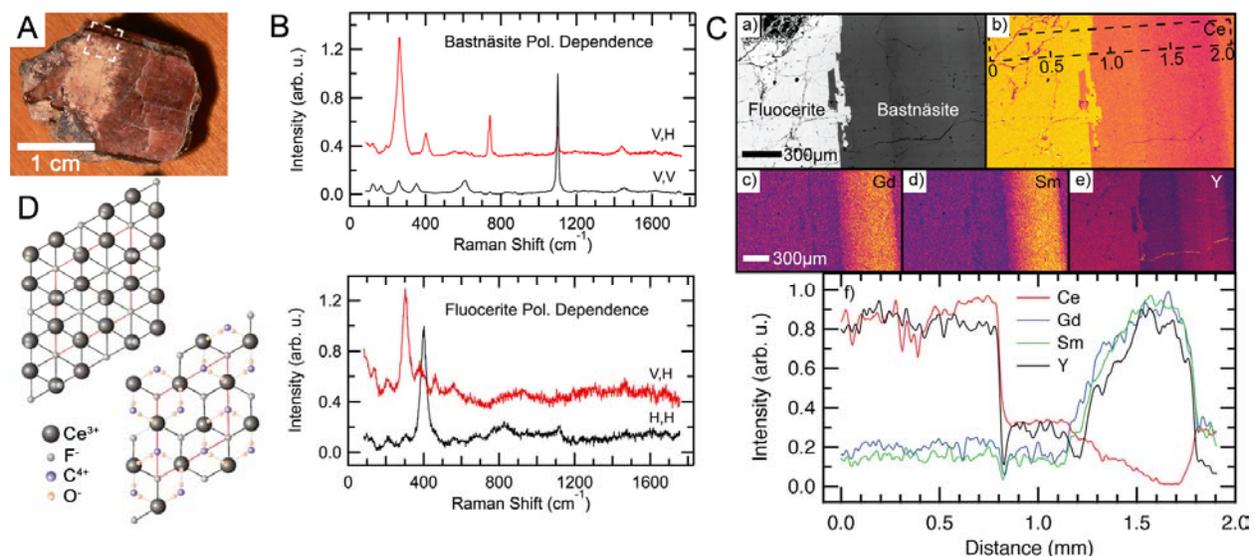


Figure 3: (a) Backscattered electron image of fluocerite-bastnasite interface in zoned crystal from Wellington Lake pegmatite. (b-e) Microprobe X-ray element maps near the interface for (b) Ce. (c) Gd, (d) Sm and (e). (f) shows X-ray intensity (arbitrary units) from microprobe X-ray maps of the same REE variation across area scaled in (b). (D) Shows the lattice structure of fluocerite on top and bastnäsite on the bottom shown from the c-axis (after Müller et al., 2011).

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016 Colorado School of Mines campus, Golden, Colorado

Electron microprobe analyses (Fig. 3C) shows a chemical quite homogeneous composition for the fluocerite core with empirical formula $(La_{0.26}Ce_{0.49}Pr_{0.04}Nd_{0.15}Sm_{0.02}Gd_{0.01}HREE_{0.01})F_3$. In contrast the bastnäsite overgrowth is zoned with respect to REE and exhibits linear bands of enrichment in Nd, Sm, Gd, & Y perpendicular to the c-axis (Fig. 3C). For the bastnäsite a empirical formula of $La_{0.20}Ce_{0.44}Pr_{0.05}Nd_{0.21}Sm_{0.04}Gd_{0.03}HREE_{0.02}CO_3F$ is derived. The bastnäsite is generally depleted in light REE and enriched in medium REE compared to the fluocerite. No other REE minerals have been found in the pegmatite.

Fluid inclusions

Fluid inclusions in pegmatite core-zone quartz of different generations were analyzed by micro-thermometry. Inclusions are abundant, both secondary along fractures, and with a random or growth parallel distribution which suggests a primary origin. Four different types of inclusions could be identified. Common to all is the absence of a low eutectic point which precludes the presence of CaCl in the solutions. The majority of inclusions are liquid-rich of intermediate salinities between 10 and 16 wt. % NaCl equivalent, and homogenize between 119 and 196 °C. Their eutectic point close to -21 °C suggests that the source solution was H₂O-NaCl. A slightly lower eutectic point of some inclusions suggests additional cations in solution, possibly K⁺. In addition minor vapor-liquid inclusions with 30-40% vapor, and only observed in one sample, homogenize at 340 - 362 °C with salinities of 3 - 6 wt. % NaCl. In addition, few halite bearing fluid inclusions, with salinity around 28 wt. % NaCl, and liquid-rich CO₂ fluid inclusions were identified. The results suggest the presence of at least two types of fluids in the Wellington Lake pegmatite, a H₂O-NaCl and a H₂O-CO₂ fluid, with no evidence of boiling. The higher temperature fluid inclusions might represent a distinctly earlier fluid of higher temperature as suggested by Simmons and Heinrich (1980).

In contrast to the Oregon No. 3 pegmatite of the South Platte district (Gagnon 2004) with both Na+K+Sr+Ba and Na+K+Sr+Ba+Ca solutions, the majority of inclusions in the Wellington lake pegmatite were trapped from solutions of the NaCl-H₂O ± KCl type and are of lower salinity compared to the ones in the Oregon No. 3. Fluid inclusions of low salinity and distinct compositions including the content of REE, Y, Th, and U were identified in fluorite of the Oregon No. 3, while fluorite is not present at the Wellington Lake pegmatite.

Also, in contrast to the McGuire pegmatite, a nearby (< 2km) large NYF pegmatite enriched in F, Ti, Nb, and containing fluorite and monazite, the Wellington Lake pegmatite is smaller and poor in F, Ti, and P.

The transition of fluocerite to bastnäsite growth suggests an increase in pH and/or decrease in F/CO₃²⁻ activity ratio (William-Jones 1992). The REE zonation seen in the bastnäsite may involve selective complexation of certain REE with CO₃²⁻. With many of the euhedral smoky quartz crystals exhibiting strong dissolution-reprecipitation growth features and abundant 2-phase (liquid and vapor) inclusions this suggests a hydrothermal fluid may have been associated with this pegmatite. This fluid may have also affected the growth and REE zonation of the fluocerite/bastnäsite crystals, which appear to be paragenetically late.

In summary, our preliminary results of the Wellington Lake pegmatite suggest this pegmatite to be an interesting study object to test proposed earlier and develop new hypotheses of pegmatite petrogenesis in the Pikes Peak Batholith. Further stable isotope work and thermodynamics modeling is in process.

Acknowledgements

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Raman and Rayleigh Scattering Microscopy: Applications in Alkali Feldspars for the Characterization of Pegmatites

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Abstract: Microtextures from Na/K exsolution and twin microstructures from Si/Al ordering and recrystallization of alkali (K-rich) feldspars have been traditionally studied by means of optical microscopy, secondary electrons and back-scattered electrons in scanning electron microscopy and transmission electron microscopy. Three examples of microtextures and microstructures resolved by Scanning Rayleigh/Raman scattering spectroscopic microscopy will be presented, including: i) an exsolution pattern by nucleation and growth in feldspar from a pegmatite of the Rabb Park in New México (USA) resolved by Raman microscopy; ii) an incipient exsolution pattern by spinodal decomposition in a feldspar from a pegmatite in Sri Lanka with blue iridescence, using Rayleigh microscopy; and iii) a tartan pattern of Albite and Pericline twinning in feldspar from a pegmatite in Kola Peninsula (Russia), using Raman microscopy. New information is now available from these spectroscopic images.

Experimental setup

Four elements are needed Raman and Rayleigh scattering spectroscopic microscopy, including a laser light illumination, an optical microscope on an active vibration isolation system, a diffraction grating with a CCD detector, and a computer to control measurements and detectors, the Z- and X-Y stages and data acquisition and analysis (Figure 1).

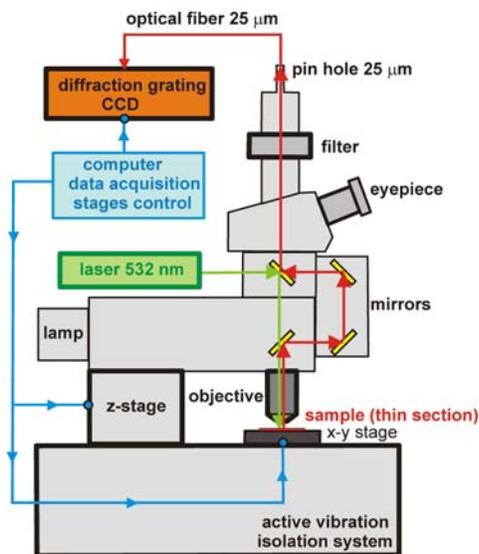


Figure 1. Raman and Rayleigh scattering spectroscopic microscopy equipment arrangement.

The equipment (Witec Alpha300 RAS) consist of a Zeiss microscope with a Nd:YAG laser light with $\lambda = 532$ nm wavelength for Raman spectroscopy (Dieing et al. 2010). Scanning Rayleigh scattering images were recorded using a modified confocal Raman microscope. The laser beam is focused perpendicular to the sample surface by a 100X objective (N.A. 0,95). The specimens were mounted on a piezo-driven microscope scanning stage, which allows steps of 3 nm in the X-Y plane and 1.0 nm in the Z plane. Images were performed in areas of several microns of the sample surface by laser light scanning step by step. The reflected laser light at each point was collected

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

through the same objective, driven along the microscope column and without any filter was conducted using a 25 μm in diameter multimode optical fiber to a very sensitive CCD detector which measures the intensity of Rayleigh scattering at every step. The very small diameter of the optical fiber acts as pinhole and guarantees the confocality of the system.

Light scattering by matter can be inelastic (i.e., Raman scattering) when frequency shifts are detected between the incident and the scattered light, or elastic (i.e., Rayleigh scattering) if no frequency shift occur. Raman scattering results from molecular interactions and it was useless for imaging resolution of the spinodal patterns, because it is necessary the existence of spectral differences between the two separated phases to make possible the image formation. Thus, this feature is absent at the very early stages of spinodal decomposition. However, Rayleigh scattering is structurally specific with high sensitivity to small changes in refraction index and density and it was extremely useful to show early and intermediate spinodal patterns. This technique was useful because the refraction index and density are higher in Na-feldspar than in K-feldspar, involving a higher intensity of scattered light from the Na-rich component than for the K-rich component of the modulation.

The specimens from Sri Lanka used in this study were a blue moonstone and a white moonstone. Additionally, a specimen of alkali feldspar from Rabb Park (NM, USA) was studied along (001) and (010) planes in polished and etched surfaces, in order to compare the resolution capabilities of Raman and Rayleigh imaging techniques. Specimen ZAG is perthitic K-rich feldspars from Kola Peninsula (Sánchez-Muñoz et al. 2012) used to visualize twin patterns. Quantitative chemical analysis for Si, Al, Na, K and Ca of the specimen used in the figures were performed by electron micro-probe analysis (EMPA), using a point-counting technique with a Jeol Superprobe JXA-8900M. The chemical compositions can be expressed as $\text{Or}_x\text{Ab}_y\text{An}_z$ ($x+y+z=100$) with Or, Ab and An expressing the molar content of KAlSi_3O_8 , $\text{NaAlSi}_3\text{O}_8$ and $\text{CaAl}_2\text{Si}_2\text{O}_8$ components in the solid solution, as an average of five analyses per specimen.

Table 1. EPMA bulk chemical compositions

Samples	SiO_2	Al_2O_3	Na_2O	CaO	K_2O	$\text{Or}_x\text{Ab}_y\text{An}_z$
Sri Lanka moonstone (Fig. 1)	65.18	18.62	4.71	0.22	10.01	$\text{Or}_{57.7}\text{Ab}_{41.2}\text{An}_{1.1}$
Rabb Park feldspar (Fig. 2)	65.98	19.21	4.44	0.15	10.53	$\text{Or}_{60.5}\text{Ab}_{38.8}\text{An}_{0.7}$
ZAG feldspar (Fig. 3)	66.91	19.00	2.25	0.00	13.59	$\text{Or}_{85}\text{Ab}_{15}$

Exsolution by spinodal decomposition

Alkali feldspars from southeastern Sri Lanka with schiller effect (moonstone) occur in pegmatites hosted in granulite-facies metamorphic rocks (Harder 1992). The phase separation phenomenon took place at very slow cooling rate and high confining pressure, but in a very dry geological setting, a kind of geological conditions at which spinodal decomposition is common (Abart et al. 2009). Different crystal orientations were observed with easy sample preparation at, having up to $\lambda/20$ of maximum spatial resolution in the X-Y plane (Boustany et al. 2010). Based on the reflectance variations on the sample surfaces, two different light scattering statistics in scanning experiments were found: a bimodal distribution and a Gaussian distribution. Each type of light statistics is correlated with well defined spinodal patterns as follow. The first type of statistics involves a sharp bimodal distribution of scattered light (continuous line in Fig. 2a). Bimodal scattering results from stripe patterns where Na- and K-rich domains alternate very regularly, shown in red and purple color in the (110) plane (Fig.2b) and in the (010) plane. The bimodal distribution (continuous line) with two well defined maxima corresponds with images in which phase separation domains in purple and red color are separated by narrow regions of intermediate composition. The Gaussian distribution (discontinuous line) has a single maximum close to the origin, and it corresponds with images in which the areas of green color are dominant. The second type of statistics appears only in the (110) and (100) planes and consists of regions with a broad Gaussian distribution in the intensity of the elastic scattered light (discontinuous line in Fig. 2a). Gaussian scattering corresponds to parts of the crystal where unmixing cannot be detected (green color in Fig. 2a) which always are spatially related to regions with incipient unmixing formed by island and labyrinthine patterns of Na- and K-rich domains of red and purple color respectively, as shown in Fig. 2b. It is important to note that the periodic stripe pattern is very different of the typical non-periodic host-guest microtextural relationship found when exsolution of alkali feldspars occurs by nucleation and growth, where sharp and strait phase boundaries along (-601) planes exist (Smith and Brown 1988). Spinodal patterns cannot be resolved by Raman imaging as only one type of spectrum was obtained throughout the surfaces. Two orthogonal systems of chemical waves are derived from the periodicity and orientations of these patterns, which must be controlled by

symmetry constraints during phase separation (Sánchez-Muñoz et al. 2016). It suggests that long-range chemical waves (as far-from-equilibrium effects) are independent of structural detail at the local scale but are constrained by the overall monoclinic $2/m$ symmetry of the crystal, as anticipated by McConnell (1971).

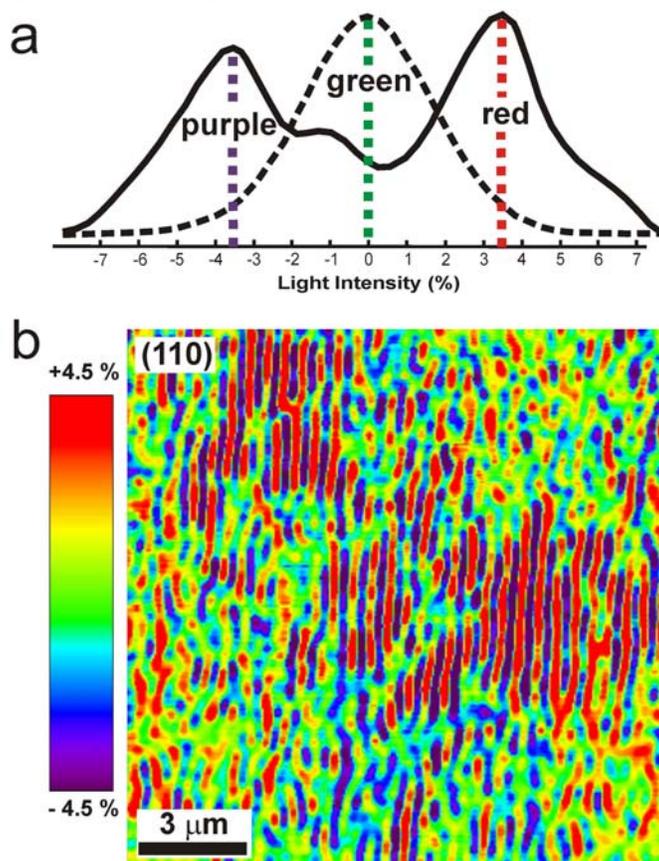


Figure 2. Scanning Rayleigh scattering spectroscopic microscopy of the Sri Lanka moonstone. a) The statistic distribution of the elastic light scattering experiments follows two different distributions: Gaussian and bimodal. b) In the (110) plane both statistics coexist side by side and correspond with stripe patterns and labyrinth-island patterns of unmixed domains, respectively. The qualitative color scale in the image varies between +4.5 and -4.5 % of relative intensity of the laser scattered light. The density for compositional end-members in alkali feldspars ranges from 2.613 gr/cm³ in Na-feldspar to 2.557 in K-feldspar while Refractive Index for the Na-feldspars (1.527, 1.535 and 1.536) are higher than for K-feldspars (1.519, 1.524 and 1.523). Thus, Na-rich domains are visualized in red color, whereas K-rich domains are seen in purple color.

Exsolution by nucleation and growth

Granite pegmatites of the Rabb Park complex are preserved with volcanic and shallow subvolcanic rocks because the plutonic development was arrested (O'Brien 1986). Thus, the exsolution phenomenon took place on cooling at a relatively fast cooling rate, at very low confining pressure, and in a water-rich environment. Microtextures are extremely regular throughout the feldspar crystals. Coherent cryptoperthitic intergrowths shows a clear host-guest microtextural relationship, formed by high-albite lamellae of ~ 50 nm wide inside a monoclinic sanidine matrix or lamellae of ~ 100 nm wide, in contact by the (-601) plane (Keffer and Brown 1978). Opaque feldspar crystals without schiller effect can also be found in the intermediate zone of some of the subvolcanic pegmatites. In this case however, they are much coarser and the intergrowth has semi-coherent character, although the host-guest relationship, the mutual orientation and the film shape of the Na-rich feldspar do not change in comparison with moonstones (Fig. 3a and 3b) or other film perthites of granitic pegmatites.

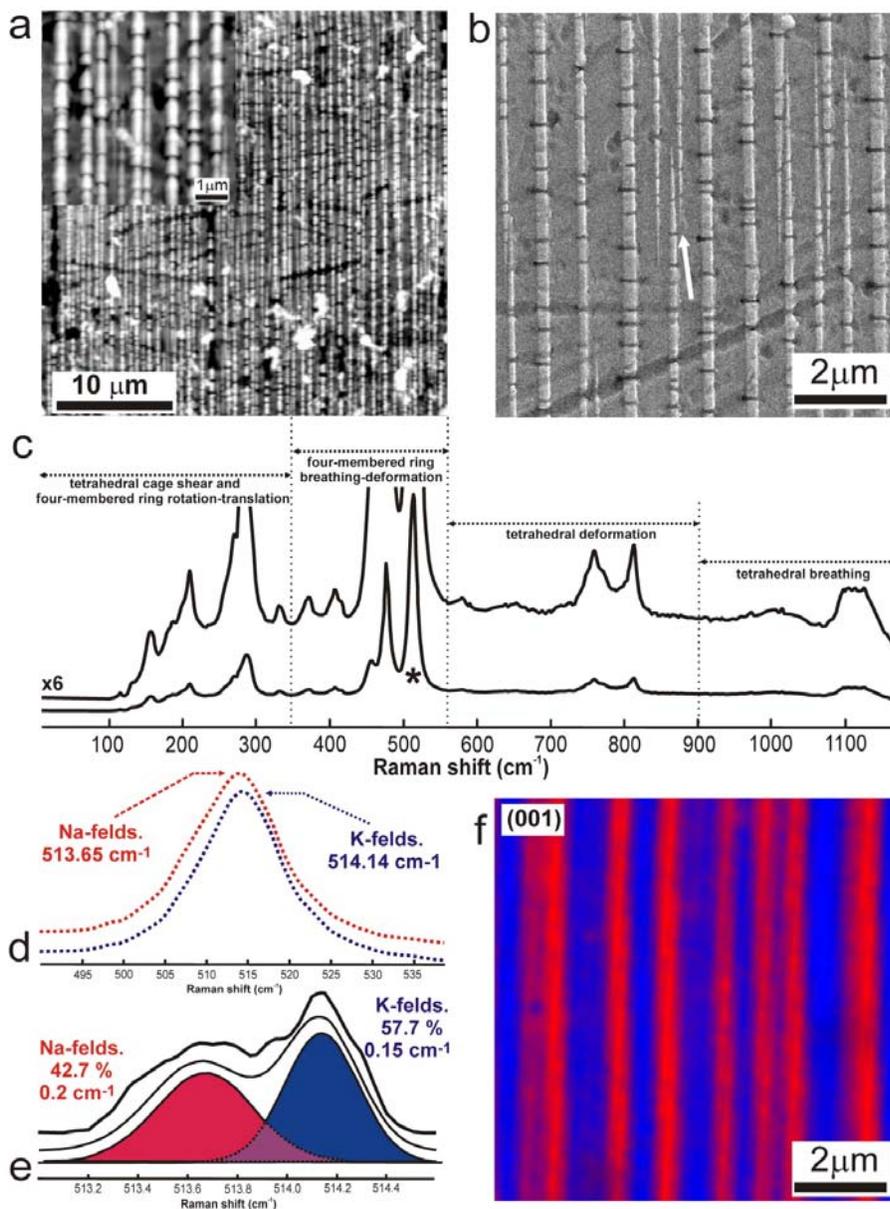


Figure 3. Scanning Raman scattering spectroscopic microscopy of the Rabb park perthite (in f) in comparison with the same microtexture resolved by AFM (in a) and FESEM (in b) techniques. The Raman image was constructed by using the 513-514 cm^{-1} band, that is slightly different in the two feldspars (in d). The statistics of the peak position in the Raman spectra is shown in e) that allows the quantification of the two phases in the image. c) Raman spectra on (001) plane at the same orientation than in the images and * to show the 513-514 cm^{-1} band, see McKeown (2005).

The Na-rich films are extremely thin, long and strait, and they are continuous for tens of microns in (001) and (010) planes. The thickness of the Na-rich films show a maximum value of about 550 nm but it decrease very gradually up to disappear laterally (i.e., following the direction of growth) to form needle tips in (001) and (010) sections. The distribution of the films in the matrix is clearly non-periodic, with alternation of wide and thin films without a constant value of separation between films of totally different thickness. When two growing films approaches one to each other (arrow in Fig. 2b), thinning without coalescence is observed, and shape changes (like lamellar splitting or wavy distortions) are never observed. Another difference between moonstone and opaque crystals is the existence of dislocation pairs in the later, revealed by etch pits, which are regularly distributed along the interphase between the

two separated phases. Thus, the appearance of edge dislocations involves a transition from initially coherent to semi-coherent interfaces as the exsolution phenomenon progresses, without additional changes neither in shape nor orientation. Figure 3 exhibits the Raman scattering technique to build up a Raman image of the phase separation microtexture on (001) plane in the Rabb Park perthite. It was extremely useful to visualize nucleation and growth exsolution patterns, as the spectra of the K-rich and the Na-rich phases can be easily distinguished to build up Raman images. The Raman shifts of the two phases indicate that exsolution is incipient and the compositions of the coexisting alkali feldspars are close to each other, an information that has not been obtained by other techniques.

Tartan twinning in microcline

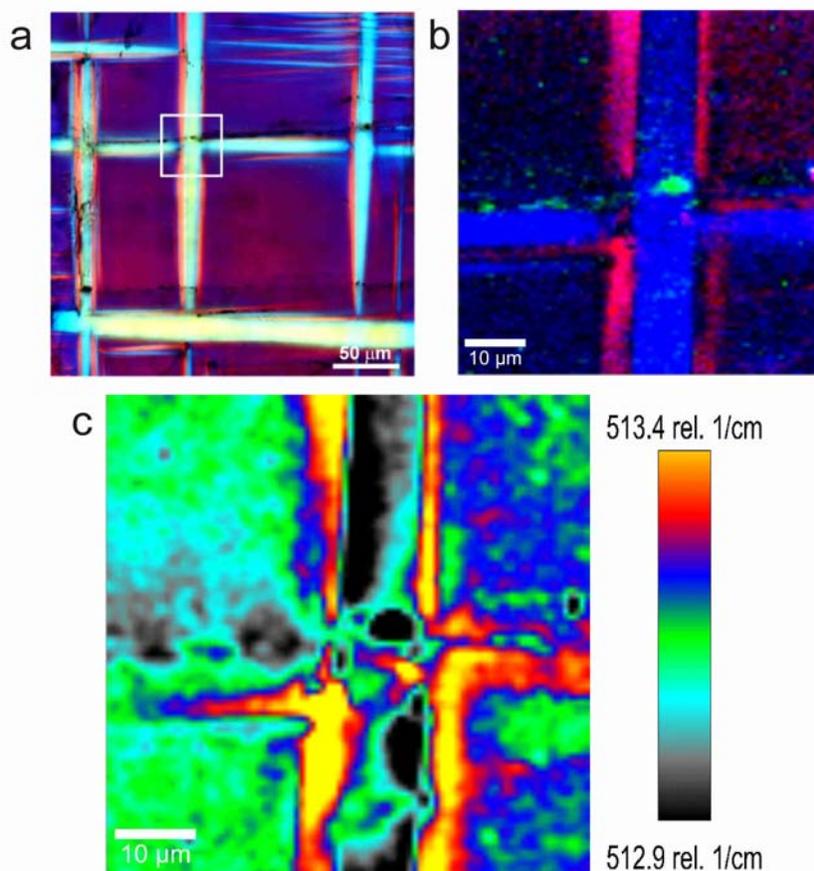


Figure 4. Recrystallization twinning of microcline from Ploskaya pegmatite in Kola Peninsula (Russia) with a tartan pattern. a) Optical micrograph in the (001) section using transmitted light and crosses polarizers close to the parallel crossovers as well as “serrated” and/or distorted boundaries, needle twins with tips at distorted twin boundaries (suggesting this interface is the nucleating point), as well as the coalescence of A and P twins with the same sign to form right angle twins. The position of the band at 280-285 cm^{-1} can be used to monitor the local degree of order, as disordered K-feldspars have this band at 280.5 cm^{-1} whereas in ordered K-feldspars appears at 285 cm^{-1} . Figure 4b constructed with the relative intensity of the Raman peak at 285 cm^{-1} and thus different microcline twins can be recorded in the Raman images that reproduce the optical image. However, elastic strained domains can also be visualized with the band at 513 cm^{-1} as shown in Fig. 4c, implying that left and right handed twins have opposite distortions.

The NYF pegmatites from anorogenic environments typically have K-rich feldspars with tartan and parquet twin patterns. They consist of regular frameworks of large, thin and sharp twin lamellae with needle tips of low microcline, leaving microcline with diffuse twinning in quadrilateral shape. Low microcline twins form directly from recrystallization units and thus no intermediate products are detected between precursor and twins. Figure 4a is a red plate image of very well preserved tartan microcline. The more typical features are the coexistence of four

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

twin orientations, $A\pm$ twins with $\delta = \pm 18^\circ$ and $P\pm$ twins with $\delta = \pm 21^\circ$, forming positive or negative interference effects at position, with a red plate. Albite $A\pm$ twins are in the N-S direction whereas the Pericline $P\pm$ twins are in the E-W direction, zig-zag irrational twins on the top of the image. The twin crossover (white square) was studied by Raman imaging as in the image of b) that was build up with the relative intensity of the 285 cm^{-1} band. in c) the band at 513 cm^{-1} was used to visualize a map of elastic strain, being different in the left- and right handed twins.

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Local Structure of Beryl Group Minerals from Multinuclear NMR Spectroscopy

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Abstract: Five specimens of beryl and alkali-rich beryl with different alkali contents and one specimen of pezzottaite have been studied by ²⁹Si, ⁹Be, ²⁷Al, ²³Na, ¹³³Cs, ⁷Li and ¹H MAS NMR spectra at 9.4 T, to find structural relationships between these minerals. We have found that the structure alkali-rich beryl is intermediate between the structures of alkali-poor beryl and pezzottaite. In addition, the NMR data of these structures are not fully consistent with available lattice models from reciprocal-space techniques. The ¹H spectra indicate that protons are as OH groups instead of water molecules as it is commonly assumed in the beryl group minerals.

Introduction

Beryl $\text{Be}_3\text{Al}_2\text{Si}_6\text{O}_{18}$ (*P6/mcc*) and pezzottaite $\text{Cs}(\text{Be}_2\text{Li})\text{Al}_2\text{Si}_6\text{O}_{18}$ (*R-3c* or *R3c*) are classified as two species of the beryl group of minerals with $\text{R X}_3 \text{Y}_2 (\text{T}_6\text{O}_{18}) \cdot \text{pH}_2\text{O}$ as general formula. NMR has shown that the beryl structure can incorporate a high content of alkali atoms in solid solution (Sherriff et al. 1991) with a chemical composition between these two end members. Here we study the local structure alkali-poor beryl, alkali-rich beryl and pezzottaite to correlate the structural features along the series, by means of magic-angle spinning nuclear magnetic resonance (MAS NMR) spectroscopy, leading to ²⁹Si, ⁹Be, ²⁷Al, ¹³³Cs, ⁷Li and ¹H spectra at 9.4 T (Figure 1 and 2).

Result and discussion

The local structure of beryl ($\text{Li}_2\text{O}+\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{Cs}_2\text{O} < 1.0$ % wt) from MAS NMR is different from the *P6/mcc* model from X-ray diffraction (XRD), first resolved by Bragg and West (1926). Reciprocal-space techniques describe the crystal structure with six-membered rings of one tetrahedral site for Si atoms, rings that are linked with one tetrahedral site for Be atoms and one octahedral site for Al atoms. Thus, beryl is classified as a cyclosilicate Q^2 structure. However, the ²⁹Si spectra suggest a tectosilicate Q^4 structure with chemical shift values at -103 ppm. The ⁹Be spectra are consistent with two tetrahedral sites, separated by 1-2 ppm, instead of one site from the XRD model. The ²⁷Al NMR spectra show a single octahedral site for Al atoms with isotropic chemical shift close to 0 ppm, as in the XRD model. The ¹H spectrum shows a wide band at 1.5 ppm and a small signal at 4.7 ppm. These results suggest a Si-Be order-disorder phenomenon in the beryl mineral species having a framework-type crystal structure.

The local structure of alkali-rich beryl with $\text{Li}_2\text{O}+\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{Cs}_2\text{O}$ between 1.0 and 6.0 % wt is different from that of alkali-poor beryl. The ²⁹Si spectra become wide between -98 and -106 ppm, indicating Si disorder in more than a single tetrahedral position. The ⁹Be spectra are very asymmetric and also consistent with two tetrahedral sites. The ²⁷Al spectra are similar to that of alkali-poor beryl in a single octahedral site. A single site is found in the ¹³³Cs spectrum with a maximum at -15.3 ppm. In the ⁷Li spectra two signals appear, at 0.8 ppm a major resonance from Li atoms in tetrahedral sites and at -1.6 ppm a minor signal from Li in the channels. The ¹H spectrum has two major resonances with maxima at 1.2 and 2.3 ppm and a minor one at 4.6 ppm. These result suggest that the Si-Be disorder phenomenon increases with the incorporation of alkali atoms in the structure. The term vorobyevite, used for high-alkali beryl ($\text{Li}_2\text{O}+\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{Cs}_2\text{O} \sim 10.6$ % wt), has a similar average structure to that of beryl *P6/mcc* (Yakubovich et al. 2009). Thus, alkali-rich beryl has an intermediate structure between alkali-poor beryl and pezzottaite.

The local structure of pezzottaite (Lauris et al. 2003, Liu Shan Gi et al. 2008, Yakubovich et al. 2009, Gatta et al. 2012) with $\text{Li}_2\text{O}+\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{Cs}_2\text{O} \sim 18.0$ % wt is very different from that of the previous ones. The ²⁹Si spectrum shows three maxima at -99.2, -100.4 and -102.2 ppm. The ⁹Be spectrum is consistent with a single tetrahedral site

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

for beryllium atoms. The ^{27}Al spectrum has a wide signal indicating more than one octahedral site, but no tetrahedral occupancy. The ^{133}Cs indicates two sites from two well separated peaks at 15.2 and -52.2 ppm, and a minor signal at -46.1 ppm. The ^7Li spectrum shows a signal consistent with three sites, two tetrahedral sites at very close chemical shifts and a minor signal related with a small amount of lithium located in the channels along the c -axis. In the ^1H spectrum four signals were recorded, two major bands at 2.5 and 3.8 ppm, and two minor resonances at 1.2 and 4.9 ppm. These data are not fully consistent with the R-3c model (Yakubovich et al. 2009, Gatta et al. 2012), neither with the $R3c$ model (Liu Shan Gi et al. 2008).

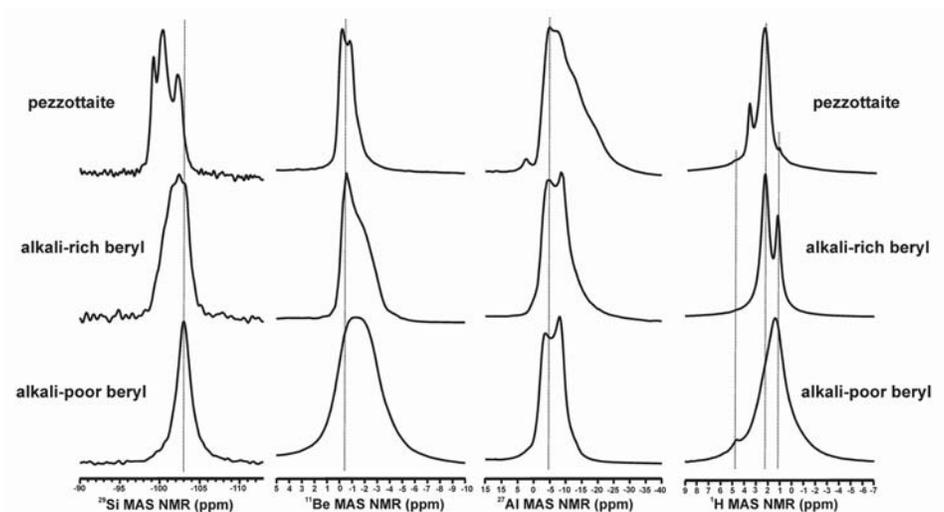


Figure 1. The ^{29}Si , ^9Be and ^{27}Al MAS NMR spectra of alkali-poor beryl, alkali-rich beryl and pezzottaite.

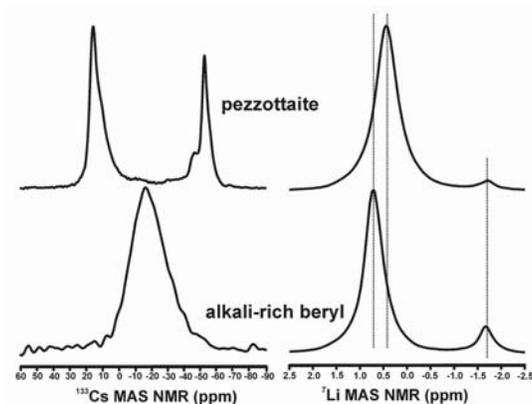


Figure 2. The ^{133}Cs and ^7Li MAS NMR spectra alkali-rich beryl and pezzottaite.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Local Structure of beta-eucryptite and beta-spodumene in the $\text{Li}_{1+x}\text{Al}_{1+x}\text{Si}_{1+x}\text{O}_4$ for $0 \leq x \leq 1$ in the LAS system by multinuclear NMR spectroscopy

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Abstract: Stuffed derivatives of the quartz structure (β -eucryptite) and of the keatite structure (β -spodumene) synthesized in the $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (LAS) system from sol-gel precursors from with SiO_2 and LiAlSiO_4 as end-member compositions, have been studied by ^{29}Si , ^{27}Al , ^7Li and ^6Li MAS NMR spectroscopy. The two different structural frameworks are extremely stable without displacements in the chemical shifts, involving in each case very similar local structure along a wide range of Si/Al ratios. Complete atomic ordering was achieved in β -eucryptite $\text{Si}/\text{Al} = 1/1$ by crystallization at 900 °C and 3 Kbars during 24 h, having a crystal structure compatible with the $P6_422$ lattice model of Pillars and Peacor (1973).

Introduction

Sol-gel precursors of the $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ (LAS) system, with $\text{Li}_{1-x}\text{Al}_{1-x}\text{Si}_{1+x}\text{O}_4$ for $0 \leq x \leq 1$ as general formula, can crystallize at the laboratory time conditions mainly in two different polymorphs: β -eucryptite or stuffed derivatives of the quartz structure and β -spodumene or stuffed derivatives of the keatite structure (see Table 1).

Table 1: β -eucryptite and β -spodumene series

N°	Si/Al ratio	x	$\text{Li}_{1-x}\text{Al}_{1-x}\text{Si}_{1+x}\text{O}_4$	Formula	675 °C 100h	850 °C 100 h	1000 °C 50h	1200 °C 100 h
0	∞	1.00	Si_2O_4	SiO_2	-	-	-	C
14	100/1	0.98	$\text{Li}_{0.02}\text{Al}_{0.02}\text{Si}_{1.98}\text{O}_4$	$\text{LiAlSi}_{100}\text{O}_{202}$	A	A (Q)	A (Q)	C
13	50/1	0.96	$\text{Li}_{0.04}\text{Al}_{0.04}\text{Si}_{1.96}\text{O}_4$	$\text{LiAlSi}_{50}\text{O}_{102}$	A	A, Q	A, Q (C)	C, Q, B?
12	25/1	0.92	$\text{Li}_{0.08}\text{Al}_{0.08}\text{Si}_{1.92}\text{O}_4$	$\text{LiAlSi}_{25}\text{O}_{52}$	A, Q, B	Q C B A	Q, C, B	C, Q, B
11	15/1	0.875	$\text{Li}_{0.125}\text{Al}_{0.125}\text{Si}_{1.875}\text{O}_4$	$\text{LiAlSi}_{15}\text{O}_{32}$	A, Q	C	Q, C, ?	C, Q, B
10	10/1	0.818	$\text{Li}_{0.182}\text{Al}_{0.182}\text{Si}_{1.818}\text{O}_4$	$\text{LiAlSi}_{10}\text{O}_{22}$	A, Q	Q, C (A)	Q, C, ?	Q, C, B
9	7/1	0.75	$\text{Li}_{0.25}\text{Al}_{0.25}\text{Si}_{1.75}\text{O}_4$	$\text{LiAlSi}_7\text{O}_{16}$	A, Q	Q, C	Q, C, B, ?	Q, C, B
8	5/1	0.667	$\text{Li}_{0.333}\text{Al}_{0.333}\text{Si}_{1.667}\text{O}_4$	$\text{LiAlSi}_5\text{O}_{12}$	A, Q	B (Q)	B (Q)	B
7	4/1	0.60	$\text{Li}_{0.40}\text{Al}_{0.40}\text{Si}_{1.60}\text{O}_4$	$\text{LiAlSi}_4\text{O}_{10}$	A, Q	B, C, Q,	B (Q)	B
6	3/1	0.50	$\text{Li}_{0.50}\text{Al}_{0.50}\text{Si}_{1.50}\text{O}_4$	$\text{LiAlSi}_3\text{O}_8$	Q, A (B)	Q + B	B (Q)	B
5	2/1	0.333	$\text{Li}_{0.666}\text{Al}_{0.666}\text{Si}_{1.333}\text{O}_4$	$\text{LiAlSi}_2\text{O}_6$	Q (A)	Q1	B + Q	B
4	1.75/1 (7/4)	0.273	$\text{Li}_{0.727}\text{Al}_{0.727}\text{Si}_{1.273}\text{O}_4$	$\text{Li}_4\text{Al}_4\text{Si}_7\text{O}_{24}$	Q !!	Q1	Q, B	Q, B
3	1.5/1 (3/2)	0.20	$\text{Li}_{0.80}\text{Al}_{0.80}\text{Si}_{1.20}\text{O}_4$	$\text{Li}_2\text{Al}_2\text{Si}_3\text{O}_{10}$	B, C, Q, E	B, Q	B, Q	B (Q)
2	1.25/1 (5/4)	0.111	$\text{Li}_{0.889}\text{Al}_{0.889}\text{Si}_{1.111}\text{O}_4$	$\text{Li}_4\text{Al}_4\text{Si}_5\text{O}_{12}$	Q1+Q2, E?	Q1+Q2	Q1+Q2	Q
1	1/1	0	LiAlSiO_4	LiAlSiO_4	Q1+Q2, E	Q1+Q2	Q1+ Q2	Q

Note : A = amorphous, Q = β -eucryptite, B = β -spodumene, C = cristobalite, E = α -eucryptite, ? = unknown phase

At low temperatures is formed mainly β -eucryptite and at high temperatures β -spodumene occurs. The two phases are the main crystalline constituents of ceramics with zero thermal expansion, involving a high thermal and chemical stability along a wide range of chemical compositions. There are several structural models for β -eucryptite with ratio $\text{Si}/\text{Al} = 1/1$ (Tscherry et al. 1972a,b, Pillars and Peacor 1973, Guth and Heger 1979, and Sartbaeva et al. 2004), whereas a single model exist for β -spodumene with ratio $\text{Si}/\text{Al} = 2/1$, tetragonal symmetry and space group $P4_32_12$

(Li Chi-Tang and Peacor 1968, Clarke and Spink 1969). In addition, we are also searching for a structural explanation of the high thermal stability of the glass-ceramics of the LAS system.

Result and discussion

Figure 1 displays the ^{29}Si spectra of the β -eucryptite and β -spodumene in samples with a single phase in X-ray diffraction patterns. A group of five signals related to Si in $Q^4(\text{Si,Al})$ environments separated ~ 5.0 ppm were recorded for both series, with lines having variable intensity depending on the Si/Al ratio (or x value). For the end-member with Si/Al = 1/1 ($x = 0$), the disordered β -eucryptite structure shows a wide single signal for Si atoms in (0Si,4Al) tetrahedral sites, whereas a signal with two maxima from two spectroscopically-different (0Si,4Al) tetrahedral sites are resolved in the ordered β -eucryptite structure. Figure 2 shows the ^{27}Al , ^7Li and ^6Li spectra of the two series. Two tetrahedral sites were recorded for Al atoms in the ordered β -eucryptite with similar area: the T_1 site has $\delta_{\text{iso}} = 60.2$ ppm and $\nu_Q = 554$ kHz, and the T_2 site was simulated with a Gaussian curve at 56.7 ppm and amplitude of 5.9 ppm. The disordered β -eucryptite have an asymmetric profile that is consistent with two site distribution of Al atoms related to the two previous tetrahedral sites. Al atoms in octahedral coordination from the original precursor are also recorded at ~ 10 ppm. In the ^{27}Al spectra of the β -spodumene series a single site distribution is inferred with no change in the position of the maxima and a widening of the signal along the studied samples with Si/Al ratio from 5/1 to 2/1. The ^7Li spectrum of the ordered β -eucryptite shows a wide signal from three sites that are resolved in the ^6Li spectrum. In this case, two peak with relative intensity of 75% and 25% were simulated two Lorentzian curves at -0.16 and -0.41 ppm.

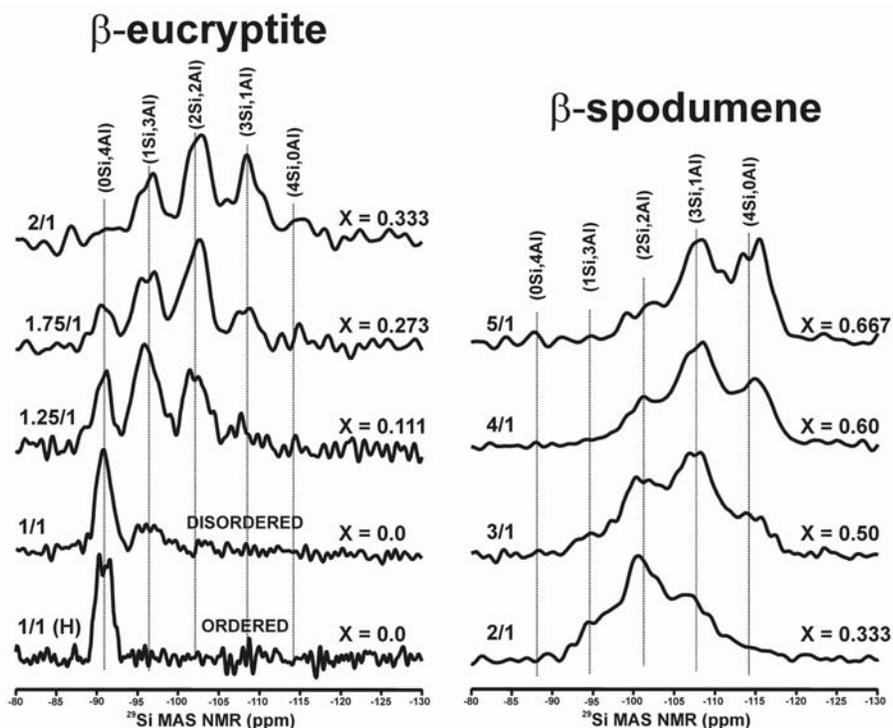


Figure 1. The ^{29}Si MAS NMR spectra of the β -eucryptite and β -spodumene series for different Si/Al ratios or x values.

The resonances in the ^7Li and ^6Li spectra (Fig. 2) of the other disordered β -eucryptite with different Si/Al ratios are extremely similar. In the same way, the ^7Li and ^6Li spectra in the studied samples with the β -spodumene structure are extremely similar. These results explain the high structural stability of these phases in the glass-ceramics with zero thermal expansion as very similar local structures occurs for very different chemical compositions. Our disordered β -eucryptite is similar to the best ordered samples in Phillips et al. (2000) who describe the ordering process as a decrease of the number of Al-O-Al linkages. However, because of the high degree of local order in our sample crystallized at 900 °C and 3 Kbars for 24 hours, it is possible to suggest that the crystal

structure is compatible with the lattice model of Pillars and Peacor (1972) consisting in a β -quartz structure with $P6_422$ space group, having two T sites for Si atoms, two T sites for Al atoms and three sites for Li atoms (one site having double multiplicity than the other two sites) at the level of Al atoms in the center of the hexagonal channels along the c -axis.

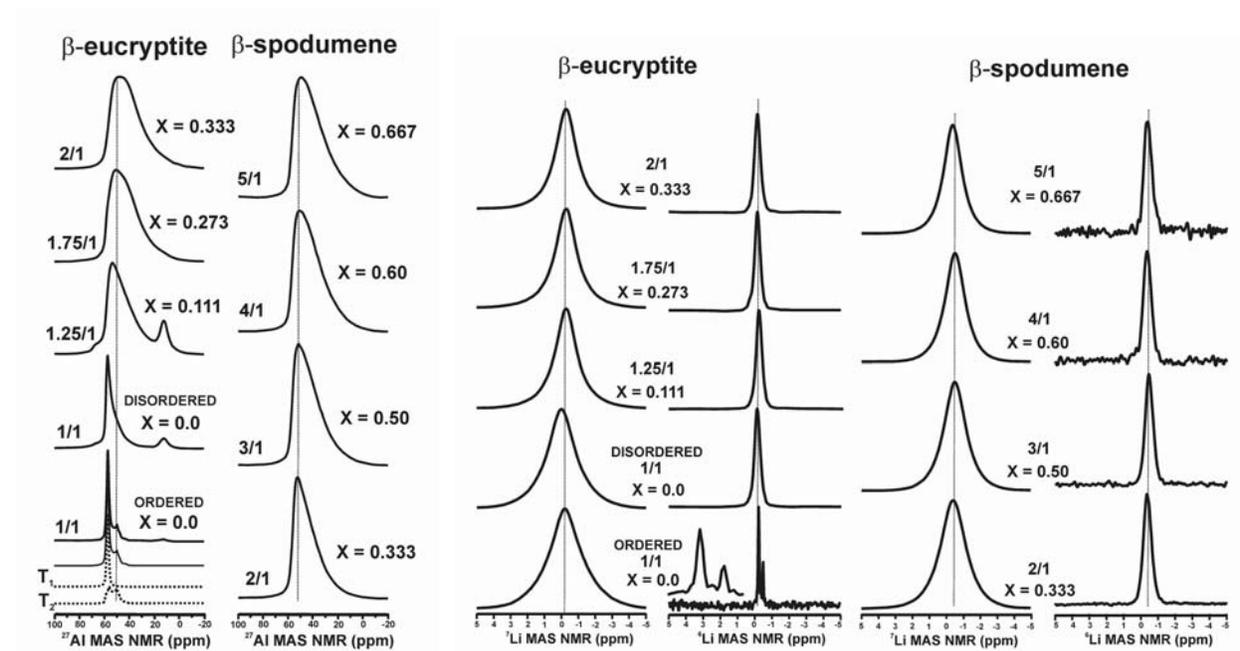


Figure 2. The ^{27}Al , ^7Li and ^6Li MAS NMR spectra of the β -eucryptite and β -spodumene series for different Si/Al ratios or x values.

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REE-Rich Pegmatites from the South Platte and Trout Creek Pass Pegmatite Districts, Colorado: Contrasting Geochemical Profiles and Tectonic Regimes

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ABSTRACT: Two Proterozoic REE-rich pegmatites districts occur in the Front range and Mosquito range in Colorado. They are the 1.0 Ga South Platte district (SP) and the 1.6 Ga Trout Creek Pass district (TCP). The extreme enrichment of HREE in minerals such as polycrase-(Y), euxenite-(Y), samarskite-(Y) and xenotime-(Y), the LREE enrichment in monazite-(Ce), allanite-(Ce), fluorocericite-(Ce) and bastnäsite-(Ce), the REE-enrichment in fluorite (where present), high field strength element enrichments exhibited by chondrite normalized plots and spider diagrams as well as the intraplate signatures demonstrated by Pearce discrimination diagrams indicate an anorogenic character for both granite-pegmatite systems. Both districts are REE and Nb enriched but TCP is less enriched. SP has the typical anorogenic NYF chemical signature, but TCP is strongly depleted in F.

These pegmatitic melts are inferred to be crustally derived with differences resulting from variable source rock composition, differing degrees of partial melting and perhaps the extent of rifting. The older TCP pegmatite district formed from melts derived by anatexis of lower crustal rocks with a significant metasedimentary component and appears to be associated with smaller, localized extensional events subsequent to the Mazatzal orogeny, possibly related to back-arc spreading. The SP pegmatites are related to granitic melts formed by anatexis of lower crust during a larger-scale rifting event. The greater enrichment in incompatible elements of SP pegmatites suggests that they originated from melts derived from smaller degrees of partial melting than pegmatites of TCP which are less enriched and require larger degrees of partial melting. The F-depletion observed in TCP pegmatites suggests a paucity of F-bearing minerals in the lower crustal source rock. Subtler geochemical differences between individual pegmatites appear to relate to the degree of internal evolution which differs both within and across the pegmatite districts.

Pegmatite Descriptions and Mineralogy

South Platte:

The South Platte Pegmatite District (SP) occurs within the Precambrian core of the Rocky Mountain Front Range in central Colorado. The district is located near the northern margin of the Pikes Peak batholith in Jefferson County, Colorado near the site of the former town of South Platte. The pegmatites of this district form a unique mineralogical, geochemical and structural group. Over 75 pegmatites occur as segregations within the parental granitic rocks of the 1 Ga Pikes Peak Batholith (Simmons & Heinrich, 1980, Simmons *et al.* 1987, 1999, 2000, 2011, Smith *et al.* 1999). All of the pegmatites occur within the parental granite rocks of the batholith and are thus genetically linked with the batholith. More than fifty of these pegmatites cluster in a relatively small, ~10 km² area, where reddish granite forms the outer zone of the batholith. The others are scattered at various distances up to 50 km from the central group. They are well known for their contents of relatively abundant REE minerals, fluorite, and metallic hematite. The pegmatites are characterized by very well-developed internal zonal structure. Selective mining completely removed the intermediate zone of some pegmatites, leaving a quartz core standing in bold relief, revealing the 3-dimensional internal zonation of these pegmatites.

The history of the district dates back to the 1930's when these pegmatites were originally opened and mined for their easily accessible feldspar. During the 1950's after most of their feldspar had been exhausted, several of these quarries were reopened and mined for rare-earth minerals, and in the 1960's and 1970's a number of the pegmatites were quarried for quartz for terrazzo stone from their large, nearly monomineralic cores. Interest in the rare-earth minerals prompted the first reports of the area (Hanley *et al.*, 1950; Heninrich, 1958; Haynes, 1958). Subsequently, Hutchinson (1960) reported on the petrology and structure of the batholith, Peterson (1964) mapped the Platte Canyon Quadrangle, and Haynes (1965) reported on the origin of three of the pegmatites. Simmons and Heinrich (1980) examined the general geology, internal structure, mineralogy, and paragenesis of the whole district.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

The pegmatites are large, complex, nearly vertical bodies with a roughly circular to elliptical shape in plan, with the long axes of the pegmatites ranging from less than a meter to almost a hundred meters in length. They contain abundant rare-earth minerals, zones of massive fluorite, and replacement zones of albite and hematite. Strongly enriched yttrian fluorite forms large masses along the core margin of the White Cloud and several other pegmatites. Colorless fluorite is the least REE-rich, with contents increasing through green, purple and tan yttrian fluorite. Almost a ton of REE concentrates were recovered from the White Cloud pegmatite alone. The most abundant HREE mineral is samarskite-(Y). Several hundred tons of samarskite-(Y) were mined from the Quartz Knob pegmatite. Some masses exceeded 60 cm in maximum dimension. Ytterbium enrichment is exceptionally high in the Little Patsy pegmatite, where samarskite-(Yb) was discovered (Simmons *et al.* 2006). The extreme HREE enrichment of samarskite-(Yb) is shown in chondrite-normalized REE plots. The columbite-group minerals (CGM) are much less abundant than samarskite-(Y), but are found in a few pegmatites. The CGM are more enriched in Ta and Mn than those of the Trout Creek Pass (TCP). Gadolinite-(Ce), gadolinite-(Y), thalénite-(Y), synchysite-(Y), synchysite-(Ce), fluocerite-(Ce) and bastnäsite-(Ce) occur in the fluorite replacement unit of the White Cloud pegmatite, and xenotime-(Y) is abundant in the yttrian fluorite unit of the Big Bertha pegmatite. Rare LREE-rich monazite-(Ce) occurs in some pegmatites, but is relatively abundant in the McGuire pegmatite. HREE- and Hf-rich zircon in large aggregates up to 15 cm across, are abundant in the core margin of the Luster pegmatite and are found in lesser amounts in most other pegmatites. Approximately a ton of topaz with individual crystals to 50 cm in length and 25 cm across was removed from the core margin of the Seerie Pegmatite. This pegmatite is also one of the few in the district with miarolitic cavities, one of which had a .5-meter-long smoky quartz crystal. The Seerie Pegmatite contained anhedral to subhedral zircon as an early-forming phase that contains inclusions of uraninite. The Seerie also contained replacement pods of albite with mm-size thorite crystals and yttrian fluorite with abundant inclusions of mm-size thorite crystals, yellowish thorogummite and Ce- and Nd-enriched bastnäsite. Large anhedral masses of allanite-(Ce) up to 10 cm across occur in the intermediate zones of several pegmatites. Recently fluocerite-(Ce), thalénite-(Y) with minor yttrifluorite, allanite, gadolinite, thorite and gadolinite have been reported from the Little Patsy pegmatite (Philip Persson per. comm.). Within the district, a geographical separation exists between pegmatites enriched in the LREE versus those enriched in the HREE. Composite core pegmatites in the southern part of the district contain allanite-(Ce) and are LREE-enriched. The fluorine-rich quartz-core pegmatites, located in the northern portion of the district, are HREE-enriched, containing predominantly samarskite-(Y) and samarskite-(Yb). The separation is attributed to fluorine complexing of HREE over LREE in the melt within the pluton, with F-enriched HREE melts rising to higher levels in the pluton, giving rise to HREE-enriched pegmatites (Simmons *et al.* 1987, 1999, 2000, 2006, Gramaccioli *et al.* 1999, Gramaccioli and Pezzotta 2000).

Trout Creek Pass:

The Trout Creek Pass (TCP) pegmatite district is located in the Mosquito Range, Chaffee County, Colorado. Numerous pegmatites ranging in size from one to several hundred meters are scattered throughout the district. The four largest include the Yard, the Clora May, the Crystal No. 8, and the Tie Gulch. These pegmatites are located either along the contact with the parent granite (Yard pegmatite) or just outside the pluton and are intrusive into granodiorite (Clora May and the Crystal No. 8). Poor exposures at the contact of the Tie Gulch pegmatite do not allow for an evaluation of the age relationship. The well-zoned pegmatites are elliptical in shape with thin, discontinuous border zones (except Crystal No. 8), a graphic granite wall-zone, a composite quartz-microcline core, and superimposed albite-rich replacement units. Polycrase-(Y), found exclusively in the albitic replacement units, is the dominant mineral containing heavy-rare-earth-elements (HREE), Nb and Ti. Polycrase-(Y) is enriched in HREE + Y by nearly two orders of magnitude relative to LREE. Minerals with such extreme levels of HREE enrichment only occur in pegmatites related to anorogenic magmatism (Černý and Ercit 2005). The presence of polycrase instead of samarskite, which is typically the dominant REE + Y, Nb, U species in NYF pegmatites, is related to the stability of polycrase over samarskite in a F-depleted, high-(Y, Ti, Nb, HREE) environment (Simmons *et al.* 1990). Monazite-(Ce) and allanite-(Ce) occur only in the core of the TCP pegmatites and are the dominant LREE minerals in the district. Notably, there are virtually no F-bearing mineral phases in TCP, suggesting a dearth of fluorine. This is a significant distinction of TCP pegmatites relative to SP pegmatites, which contain abundant fluorite and other F-bearing minerals (Simmons *et al.* 1987, Hanson *et al.* 1992). The lack of substantial fluorine suggests that F-complexing is not the mechanism for LREE and HREE separation within the TCP pegmatites. Instead, this separation appears to be related to late-stage enrichment of HREE caused by early crystallization of the LREE minerals allanite-(Ce) and monazite-(Ce) along the core margins. Very minor columbite-(Fe) is present in the core of the Yard pegmatite. It exhibits a relatively low degree of Mn and Ta enrichment, which is inferred to be related to the absence of F-Mn and F-Ta complexes in the melt (Keppler 1993, Linnen 1998). In the Clora May pegmatite, rare zircon occurs in albite-enriched replacement units, with HfO₂ ranging from 1.34 to 2.31 wt.%. In the TCP

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016 Colorado School of Mines campus, Golden, Colorado

pegmatites, Hf enrichment is low in zircon compared to the SP. Overall, the mineralogy of the TCP pegmatites exhibits extreme HREE > LREE enrichment, displays low to moderate Ta and Mn enrichment, and is strongly depleted in F relative to typical NYF pegmatites.

Geological Setting and Age Relationships

The two pegmatite districts range in age from mid to late Proterozoic and are all related to periods of crustal extension. The Proterozoic was a time of extensive growth of crust on the North American continent. As a result of four orogenic episodes, the Trans-Hudson (1.9–1.8 Ga), Yavapai (1.71–1.68 Ga), Mazatzal (1.65–1.60 Ga) and Grenville (1.3–0.9 Ga), a mixture of juvenile terranes and older fragments of crust were successively sutured to Laurentia (Whitmeyer and Karlstrom 2007). Although the timing of the events differs from location to location, in general, Laurentia grew southward by subduction-dominated arc–continent collisions from 1.9 to 0.9 Ga (Whitmeyer and Karlstrom 2007). The culmination of this series of orogenies resulted in the formation of the supercontinent Rodinia. Near the end of each orogenic pulse, crustal thickening produced a series of orogenic granites that stitched sutures and helped stabilize the continent, a process referred to as the arc-accretion-stabilization model (Bowring and Karlstrom 1990, Whitmeyer and Karlstrom 2007). During the interval between these orogenic episodes, widespread anorogenic magmatism produced voluminous plutons and batholiths emplaced in the newly formed Laurentian crust. Although the details of the nature of the crustal extension from location to location are controversial, the pegmatites that formed in these widely spaced extensional events all have one thing in common: they all are REE-enriched. However, each district has differences in mineralogy and geochemistry, especially with respect to the chondrite-normalized REE patterns. The geological setting and age of each pegmatite district are summarized below.

Trout Creek Pass:

The oldest pegmatite district, the TCP district, is located in central Colorado, in an area some authors have referred to as the Colorado Province (Bickford *et al.* 1989, Duebendorfer *et al.* 2001). However, rocks in central and southern Colorado are likely contemporaneous with the Yavapai Province or part of a broad transition between the Mazatzal and Yavapai provinces (Reed *et al.* 1993, and references therein), and are referred to here as the Yavapai Province. Orogenic Proterozoic granitic rocks were emplaced in central Colorado during the Yavapai orogeny (1.71–1.68 Ga), during which a progressive amalgamation of dominantly juvenile crustal fragments, many of which had been previously juxtaposed during a series of outboard arc collisions, were sutured to Laurentia (Whitmeyer & Karlstrom 2007). As there is no evidence for large-scale extension in Colorado during this time, anorogenic plutons have been attributed to extension related to roll back of a north-dipping subducting slab in a broadly compressive tectonic regime (Whitmeyer & Karlstrom 2007), transtension that formed localized zones of extension creating pull-apart basins (Bickford & Boardman 1984) and back-arc extension (Boardman & Condie 1986). Anderson & Cullers (1999) cited the occurrence of diabase dike swarms between the intrusions of the circa 1.4 Ga Sherman and Silver Plume intrusions as additional evidence of extension. In the Salida area near the TCP pegmatites, Condie (1986) provided compelling evidence for back-arc extension. The transition between older granitic rocks with orogenic signatures to those with anorogenic signatures began between 1.705 and 1.67 Ga in central Colorado (Reed *et al.* 1993). Extension is widely noted for some areas where these mid-Proterozoic granites occur, but such is not so everywhere throughout the then Laurentia supercontinent. For this reason, Anderson & Bender (1989), Hoffman (1989) and Anderson & Morrison (2005) have called upon a model involving mantle diapirism, coining the phrases “mantle and crustal overturn” and “mantle superswells”, which is suggested to have led to a succession of crustal melting events. The TCP pegmatites are associated with a series of small stocks and plugs that were intruded into an older granodiorite (Keller *et al.* 2004). The granodiorite is part of the Routt Plutonic Suite, an irregularly shaped intrusive body of Boulder Creek age that is exposed from west of TCP along the western edge of the Sawatch Range to the southern edge of the Front Range, north of Canon City, and has been dated at 1.68 Ga \pm .05 (Bickford *et al.* 1989). The granitic stocks and plugs intruded into the granodiorite and are interpreted to be the uppermost expression of a larger granite or quartz monzonite body at depth (Wallace & Keller 2003). New monazite age dates from the TCP give 1.59 \pm .02 Ga (Table 1). Although there are no quantitative dates for the granites, they are considered to be early to middle Proterozoic in age (Keller *et al.* 2004). Thus, the pegmatites and host granite are clearly younger than the Routt Plutonic Suite and are inferred to be contemporaneous with localized extension in central Colorado, perhaps due to back-arc spreading following the Yavapai orogeny.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

TABLE 1. ELECTRON-MICROPROBE-GENERATED MONAZITE AGE DETERMINATIONS

Pegmatite	Average age Ga and standard error	n
Trout Creek Pass (TCP)	1.59 ± .02	3
South Platte district (SP)	1.04 ± .02	8

Age dates determined using the software program MINCALC-V5 (Bernhardt 2010) and data obtained from an ARL-SEM electron microprobe. Only cores were analyzed, as the rims show evidence of alteration; n: number of analyses.

South Platte:

The final assembly of the Rodinia supercontinent occurred during the Grenville orogeny (1.3-0.9 Ga). Northwest directed contraction at the southern margin of Laurentia was accompanied by intracratonic extension that formed voluminous mafic magma and crustal anatexis. During this time, intracratonic basins formed in the western US, and a set of northwest-striking extensional faults formed over much of Laurentia. Anorogenic plutons related to this extension are the Pikes Peak and related plutons, which were emplaced into the 1.8 Ga basement of the Colorado Front Range *circa* 1.0 Ga (Simmons *et al.* 1987, Tweto 1987, Smith *et al.* 1999). New monazite age dates from the White Cloud and McGuire pegmatites within the northern lobe of the Pikes Peak batholith give ages of about 1.04 ± .02 Ga (Table 1). Along its northern margin, the composite Pikes Peak batholith intruded the metamorphic Idaho Springs Formation and consists of a zoned quartz monzonite core and a granite outer zone, which hosts most of the SP pegmatites (Simmons *et al.* 1987). This represents a major extensional event that produced significant crustal thinning across much of the Laurentia craton and the area of the large Pikes Peak batholith.

Geochemistry

Trout Creek Pass:

Major element chemistry of the pegmatite wall zones (Hanson, 1990) are very similar to the composition of the inferred granite host reported by Wallace & Keller (2003). Rocks from pegmatite border zone, wall zone and parental granite are metaluminous to weakly peraluminous (A/CNK 0.99 – 1.10), have high K₂O (5.56 – 6.31 wt. %) and exhibit typical anorogenic signatures with high FeO/(FeO+MgO) ratios (0.70 – 0.91) and REE mineral enrichment. However, the TCP pegmatites contain virtually no F as indicated by the absence of F-bearing mineral phases. This unusual “NY” chemical signature deviates from the classic NYF pegmatites of Černý and Ercit (2005).

Chondrite normalized REE plots show that the TCP pegmatites are generally LREE enriched with a pronounced negative Eu anomaly. However, the REE enrichment is significantly lower than that of SP. The pegmatites are relatively enriched in Ce, Gd and Yb over the granitic host rocks. Here in contrast to SP, the pegmatite wall zones are not depleted in REE as there is virtually no F to sequester REE in the melt. TCP wall zones have roughly the same or higher REE content as the granitic rocks.

Compared to the other districts, TCP granitic rocks and pegmatite wall zones show similar patterns of relative enrichment of high field strength elements HREE, Th, U and Zr, and relative depletions in Nb, Sr, Ba, and Ti on spider diagrams normalized to primitive mantle. TCP pegmatites are depleted in Nb relative to SP and enriched in Ti relative to SP. The Ti enrichment is reflected in the presence of “polycrase” rather than “samarskite” as the dominant REE mineral.

In tectonic discrimination diagrams of Pearce *et al.* (1984) TCP samples plot along the boundary between collisional (syn-COLG), within plate (WPG) and volcanic arc (VAG) granites. They lie in the A2 field on the Y-Nb-Ga*3 tectonic discriminant diagram of Eby (1992).

South Platte:

Pikes Peak granites are metaluminous to weakly peraluminous (A/CNK 1.00 – 1.12) and have high K₂O (5.53 – 6.44 wt%). The high REE content and very high FeO/(FeO+MgO) ratios (0.89 – 0.96) reflect the anorogenic character (Simmons *et al.* 1987). The SP chondrite normalized REE plots show that Pikes Peak granite, like TCP granite is strongly LREE enriched with negative slopes and negative Eu anomalies. The overall SP REE content is enriched by almost an order of magnitude over TCP granite. Pegmatite wall zones are relatively depleted by almost an order of magnitude as compared to the parental granites. This is interpreted to be the result of fluorine

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

complexing within the pegmatitic melt which sequestered the REE in the melt until the solubility product of fluorite was exceeded and fluorite and other REE minerals began to crystallize. Thus, the REE were swept from the wall zones and crystallized later in the interior of the pegmatite.

The spider diagram for SP granitic rocks shows a similar trend as the other districts, with deep troughs for Sr, P, and Ti and less pronounced troughs for Ba and Nb. The Y and Yb enrichment is higher than TCP, even though samarskite-(Yb) only occurs in SP.

On the Rb vs (Y+Nb) tectonic discrimination diagram (Pearce *et al.* 1984), the parental SP granites plot in the WPG field. Even though SP is enriched in Y and Nb relative to TCP, both fall in the A2 field of the Y-Nb-Ga*3 tectonic discrimination diagram of Eby (1992).

Discussion

Pegmatites are generally an unrecognized reservoir of incompatible elements that are part of the entire anorogenic pegmatite-granite system. Models for pegmatite-granite genesis must recognize the importance of incompatible elements in pegmatites because, even though they are volumetrically small, they contain extremely large concentrations of incompatible elements and thus can reveal relevant information about melt genesis of the pegmatite-granite system.

The two anorogenic pegmatite districts included in this study are located in different geographic areas and are related to 2 distinct post-orogenic tectonic events. The extreme enrichment of HREE in polycrase-(Y), euxenite-(Y), samarskite-(Y) and xenotime-(Y), the LREE enrichment in monazite-(Ce), allanite-(Ce) and bastnäsitate-(Ce), the REE-enrichment in fluorite (where present), high field strength element enrichments exhibited by chondrite normalized plots and spider diagrams as well as the intraplate signatures demonstrated by the Pearce discrimination diagrams, all indicate an anorogenic character for all of the pegmatite-granite systems. The Ba and Sr troughs on the spider diagrams and the negative Eu anomalies in the REE chondrite normalized plots are indications of differing degrees of feldspar fractionation for each pegmatite district. The Eu anomalies are similar for both districts, but SP shows slightly more pronounced negative Eu anomalies, suggesting that SP is related to melts that underwent greater degrees of feldspar fractionation. The Ti anomalies are also greater for the SP indicating greater degrees of fractionation of Ti-bearing phases, probably ilmenite. TCP contains virtually no F, much lower Nb and overall lower REE. In TCP, the lower Nb is evident where some samples plot along the boundary of WPG, syn-COLG and VAG fields of the Pearce discrimination diagrams.

Several models have been proposed for the origin of anorogenic granitic melts and their related pegmatitic melts. Frost & Frost (1997) have proposed that high K₂O and high FeO/(FeO+MgO) granites of SP are the result of extreme fractionation of mantle derived tholeiitic magma. In contrast, Anderson (1983) and Anderson & Morrison (2005) propose that anorogenic granites result from partial melting of a lower crustal source. Smith *et al.* (1999) also suggest that the SP granitic melts originated from partial melting of the lower crust. Martin & DeVito (2005) propose that anorogenic granitic melts and their associated NYF-type pegmatites originate from melts generated by anatexis of lower crust fluxed by metasomatic H₂O > CO₂ fluids outgassing from the mantle during rifting.

Anderson & Morrison (2005) have proposed that source rock and conditions of melt formation are the important factors in determining the chemical characteristics of the granites. They examined peraluminous granites from throughout central Colorado and Arizona and proposed a crustal source with a metasedimentary component to produce the observed higher $\delta^{18}\text{O}$ oxygen isotope, low LILE, and FeO/FeO+MgO ratios between 0.70 and 0.84 seen in granites throughout Arizona. The geochemical data for TCP is consistent with this interpretation of a crustal source with a metasedimentary component.

The greater abundance of incompatible elements in the SP suggests the melt was derived from a lower degree of partial melting than TCP and subsequent fractional crystallization further increased the enrichment of incompatible elements. In contrast, TCP source rocks are inferred to have included a greater metasedimentary component that lowered the melting temperature and allowed for greater degrees of partial melting. This allows K₂O to remain high and would keep the abundance of incompatible elements lower. The reason for the near absence of F in these melts is unclear but may simply be related to a lack of abundant F-bearing phases in the source rock. As with SP, subsequent fractional crystallization further increased the enrichment of incompatibles within the interior of the pegmatites.

SP is associated with a geographical area that underwent a greater amount of extension that resulted in significant thinning of the lithosphere (Anderson 1983, Whitmeyer & Karlstrom 2007). The TCP pegmatites are associated with a smaller, localized extensional event, perhaps the result of back-arc rifting subsequent to the Yavapai and Mazatzal orogenies (Whitmeyer & Karlstrom 2007). The smaller amount of rifting, as well as a greater

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

degree of partial melting in these transitional environments leads to pegmatites that exhibit unusual anorogenic chemical characteristics, such as abundant REEs, lower Nb and HREE and no F.

The melts that formed both pegmatite-granite districts are inferred to be crustally derived with differences resulting from variable source rock composition, differing degrees of partial melting and perhaps the extent of rifting. The model for melt generation of Martin and DeVito (2005) is favored because it provides a mechanism for fluxing the lower crust to achieve the observed very large enrichments in incompatible elements that would otherwise require extreme degrees of fractional crystallization from a mantle source. Such an extreme degree of fractionation that would be required to produce the enormous enrichments in REE, Zr, Nb and F in SP is less likely and would require the presence of huge amounts of cumulate material that has not been identified.

Subtler geochemical differences between individual pegmatites are probably related to the degree of evolution or fractional crystallization of the pegmatites. For example, based on Ta and Mn contents for CGM and Hf contents for zircon, the Patsy and the Luster pegmatites, with the highest Mn, Ta and Hf contents are the most evolved of the SP pegmatites. The McGuire in the SP district as well as all the TCP pegmatites have low Mn, Ta and Hf contents in CGM and zircon and are thus less evolved.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

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Evidence for an Anatectic Origin of an LCT Type Pegmatite: Mt. Mica, Maine

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Pegmatites in the Oxford Pegmatite Field are enriched in Lithium, Cesium, and to a much lesser extent Tantalum. As are most LCT type pegmatites, the Oxford Field pegmatites are genetically related to collisional tectonics and appear to be temporally related to the late-Paleozoic Alleghenian Orogeny (Bradley 2016), which otherwise has no expression in Maine. Mt. Mica pegmatite occurs near Paris, Maine in migmatite of the Sebago Migmatite Domain (SMD), which now largely replaces the previously suggested source of the pegmatites, the Sebago Pluton. Thus they are no longer adjacent to the proposed parental granite.

Recent comparative mineralogical and geochemical studies of Mt. Mica pegmatite and leucosomes from the host migmatite (Simmons et al. 2013) lead us to propose that some of the pegmatites in the Oxford Pegmatite Field formed from melts derived by anatexis.

Pegmatites are parallel to subparallel to the foliation of the migmatite and the leucosomes of the migmatite show gradational contact with pegmatite where they are juxtaposed. Texturally the pegmatite and leucosomes appear to be in equilibrium with no change in grain size or composition where the two are in contact. At Mt. Mica, garnet-biotite thermometry from sample pairs in the country rock at the contact yield a temperature range of 650-690°C (Clark et al. 2013), which is consistent with the P-T conditions inferred for an SMD assemblage of sillimanite, quartz, muscovite, biotite and alkali feldspar (650°C and 3 kb) reported by Guidry et al. (2013). Gradational contact between leucosomes and pegmatite suggests that the pegmatitic melt was in thermal equilibrium with the leucosomes of the adjacent migmatite.

Plots of the chemistry of the bulk pegmatite (from a 45-core composite) vs. leucosomes from the migmatite are strikingly similar in REE content. Chondrite normalized REE patterns of leucosomes and pegmatite have very flat patterns with no Eu anomaly, whereas Sebago granite is more strongly LREE-enriched and displays a pronounced negative Eu anomaly. Also, spider diagrams of leucosomes and pegmatite vs. average crust show very similar patterns.

In conclusion, in contrast to suggestions of previous authors that Mt. Mica must be derived by fractional crystallization from the Sebago Granite pluton (or any other pluton), we believe the chemical evidence suggests that the Mt. Mica pegmatitic melt could be derived directly from partial melting of the metapelitic rocks of the SMD. Thus the pegmatites are likely results of anatexis and not formed from the Sebago pluton via fractional crystallization.

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What does it take to make a pegmatite? Direct observations of crystal nucleation and growth

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Abstract: The onset of crystallization of synthetic pegmatite liquids was visualized and documented in dynamic crystallization experiments using a Diamond Anvil Cell (DAC) optimized for water-undersaturated conditions. The mineral assemblages were documented using Raman spectroscopy and EMPA. Time-lapse photographs served to measure crystal growth rates and to record the development of pegmatite texture in the transparent cell. The study demonstrates sequential nucleation and crystallization of virgilite/quartz, alkali feldspar, ± petalite, ± muscovite in conditions of undercooling. Extremely coarse pegmatite texture is favored by low nucleation density in a granitic liquid with 2.0% Li₂O, 4.6 % B₂O₃, and 6.5 % H₂O undercooled by 120–170°C below its liquidus, at pressure ranging from 150 to 400 MPa. “Giant” crystals exceeding 0.4 of cell diameter in less than one day are shown to grow with a constant volumetric growth rate.

Introduction and study goals

The scope of our experimental program is to directly monitor and record the crystallization behavior of water-undersaturated granitic melts using time-lapse photography in a series of Diamond Anvil Cell (DAC) experiments lasting 1.5 hours to nearly eight days. Here we report new results and observations of in situ crystallization of a pegmatite melt moderately fluxed with lithium and boron. We have generated typical pegmatitic features including coarse and zoned crystals; comb, radiating, and layered texture; graphic and skeletal intergrowths; and replacement texture. Previous in situ crystal growth studies have been dedicated to basalts (Ni et al. 2014), and to Li-rich hydrous fluid (Li et al. 2013). The latter study has produced spodumene from aqueous solutions in a hydrothermal DAC, representative for the miarolitic stage. Another pertinent hydrothermal DAC study was dedicated to studying liquid immiscibility of water-saturated hydrosaline melts but did not report on nucleation and growth of mineral phases (Veksler et al. 2004).

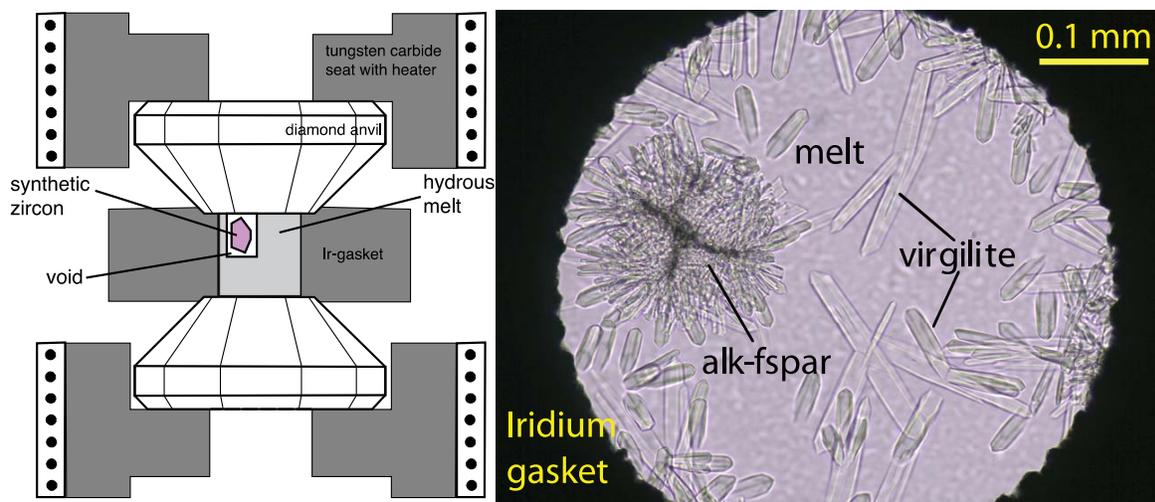


Figure 1. Water-undersaturated Diamond Anvil Cell (DAC) settings and products (Sirbescu et al. 2015). A) Design of the DAC cell prior to experiment. The inner diameter of the iridium gasket was between 170 and 550 μm . B) Overview of the DAC window showing the final mineral-glass assemblage produced in Run 3 after re-polishing, in transmitted light. Virgilite nucleated at 600°C and alkali-feldspar nucleated at 550°C.

In our study we focused on magmatic solidification processes and texture evolution of a Li-B-rich H₂O undersaturated melt, using modified DAC settings (Fig. 1A). The experimental conditions placed the hydrous melt under variable degrees of undercooling between its liquidus and glass transition. Undercooling of ~100–150°C below the liquidus produced crystals that reached 0.4 of cell diameter in less than one day. The mineral phases included virgilite (an Li-Al bearing silica-rich mineral with a stuffed-beta-quartz structure) and alkali feldspar (Fig. 1B), ± petalite and ± muscovite.

Experimental settings

We started with a simple granitic glass doped with 2.0% Li₂O, 4.6% B₂O₃, and 3.0 or 6.5% H₂O (by weight). The chemical composition approximates bulk cores of Li-rich pegmatites (Stewart 1978). To ensure seed-free starting materials, the glass was synthesized and homogenized in an internally heated pressure vessel at 1200°C and 300 to 400 MPa, followed by two hours at 800°C and rapid quench to room temperature. The final preconditioning step at 800°C ensured that the pegmatite liquid structure approaches natural conditions above liquidus. A seed crystal of spodumene was added in one experiment. The inner diameter of the charge was between 170 and 550 μm (Fig. 1A).

At the onset of each DAC experiment the glass was re-melted at 750°C, after which the liquid was undercooled rapidly to 600°C, which represents ~70 to 120°C below the liquidus surface of the liquid with 6.5% and 3% H₂O, respectively. During the DAC dynamic crystallization experiments temperature was either kept constant, or ramped down in 50°C intervals from 600°C to 400°C to simulate pegmatite cooling. Run duration varied from 1.5 to 185 hours, but was around 72 hours for most experiments. Pressures ranging from ~100 to 950 MPa were generated isochorically, based on a preconfigured ratio of glass to void space created by laser drilling (Fig. 1A). A chemically inert zircon crystal was inserted in the void space to determine pressure within the cell based on a method of Schmidt et al. (2013) who calibrated the shift in the wavenumber of the ν₃-SiO₄ Raman band of the zircon as a function of pressure.

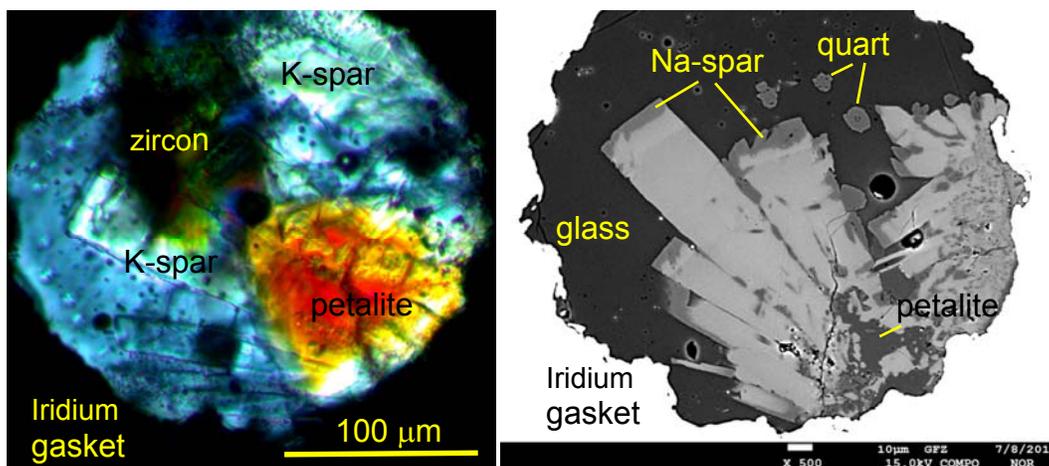


Figure 2. Pegmatitic texture developed in Run 6 at two temperature-pressure ramps: 600°C-180 MPa for 113 hours and 550°C-150 MPa for 72 hours. A) Transmitted-light microphotograph in crossed-polarized light of unpolished run. Notice the large (dark) bubbles surrounding the large petalite crystal indicating that local fluid saturation took place in the front of crystallization. B) Back Scatter electron image of polished run at a slightly deeper level of exposure than in Fig. 2A. The graphic quartz-alkali feldspar zone was followed by euhedral, zoned K-feldspar, rimmed by Na-feldspar.

Summary of results

Reproducible phase assemblages were documented after each run using optical properties, Raman spectroscopy, and Electron Probe Microanalysis. Virgilite (metastable phase with a composition intermediate between SiO₂ and LiAlSi₂O₆) nucleated at T≤600°C, petalite (LiAlSi₄O₁₀) and alkali feldspar(s) at T≤550°C, and muscovite at

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

$T \leq 500^\circ$. Virgilite, petalite, and alkali feldspar nucleated heterogeneously on surfaces of zircon, gasket, and diamond windows (Figs. 1A, 2A,B), whereas muscovite nucleated homogeneously. Virgilite was rimmed or completely replaced by pure quartz, in particular when located in the front of crystallization of rapidly growing feldspar. Development of pegmatite texture (Fig. 2) was facilitated by the relatively low nucleation density at P of ~150–400 MPa and 6.5 wt% H₂O. Radically higher nucleation density that led to an equigranular, fine-grained texture was generated if P was less than 100 MPa or greater than 950 MPa and when spodumene seeds were added. Time-lapse photography allowed for accurate growth-rate measurements and demonstrated constant volumetric (3D) growth rate of unobstructed crystals at low to moderate fraction of crystallization.

Conclusions

In traditional dynamic crystallization experiments one evaluates the crystal growth rate based on statistical analysis of “snapshot” images in time series experiments. In contrast, in situ observations allowed us to parameterize more accurately individual-crystal growth at distinct temperature ramps, from their nucleation to the end of experiments. The DAC results confirm prior experiments in hydrothermal (cold-seal) vessels in terms of sequential mineral assemblages, single-pulse nucleation behavior, and overall textural features (London 2014, Sirbescu et al. in prep.). The most important factors controlling texture development are pressure, which has an important effect on nucleation; the value of undercooling; and the initial water content. Moreover, our results indicate that constant 3D-growth rate governs the development of pegmatitic texture. This has major implications on the occurrence of giant crystals in pegmatites.

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Rare-Element Pegmatites of the Petaca District, New Mexico

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Abstract: The Petaca pegmatite district is located in north-central New Mexico in Rio Arriba County and lies within the Carson National Forest. The pegmatites in the district have been described by several authors including Jahns (1946, 1974); rare minerals were identified in the district by them, but were not studied in detail. Our study of these minerals uses state-of-the-art analytical tools and conforms to modern mineral classification. The Y-REE-Ta-Nb-Ti oxide minerals examined and classified in this study are highly complex and form a diverse array of rare and unusual minerals. The Petaca pegmatites, with their Y- and Nb-bearing minerals, amazonitic potassium-feldspar, and common occurrence of fluorite as an accessory mineral, fall within the NYF type. Further investigation will undoubtedly identify additional rare-element pegmatites and add new species to the growing list of minerals from this district.

The Petaca pegmatite district is located in north-central New Mexico in Rio Arriba County and lies within the Carson National Forest. The district, forming a north-trending belt about 7.2 km wide by 24.1 km long, is accessed by Forest Service roads extending from New Mexico State Highways 111 and 519. The pegmatites in the district have been described by Jahns (1946, 1974) and were mined for sheet and scrap mica from about 1870 through the end of World War II (1945), with perhaps one of the pegmatites mined as late as 1965. The Petaca pegmatites are classified as rare-element pegmatites as defined, for example, by London (2008). They intrude Paleoproterozoic metasedimentary and metavolcanic rocks of the Vadito Group and were emplaced approximately 1400 Ma (Konig et al. 2007, Scott et al. 2010). The Petaca pegmatites, with their Y- and Nb-bearing minerals, amazonitic potassium-feldspar, and common occurrence of fluorite as an accessory mineral, fall within the NYF type.

The geology of the Petaca pegmatites has been described in detail, and the following summary draws heavily from Jahns (1946). A border zone, wall zone, usually one or more intermediate zones, and a core zone generally comprise the pegmatites. The pegmatites are composed chiefly of microcline (perthite), quartz, albite, and muscovite, which occur as medium- to coarse-grained aggregates with granitoid textures in wall zones, and as large or giant anhedral to euhedral crystals in intermediate zones. Replacement bodies of albite ± muscovite and fracture fillings of quartz ± albite are common. Accessory minerals are spessartine, fluorite, columbite-tantalite, monazite-(Ce), ilmenite, and less commonly, beryl, bismutite and various oxides that contain rare earth elements (REE), Y, Nb, Ta, and/or Ti. Some fluorite specimens from the Petaca district, particularly those from the Globe mine, exhibit extraordinary phosphorescence, glowing for 8 minutes or longer after short-wave ultraviolet light is removed. Several of the accessory minerals are radioactive due to essential uranium or thorium, or because they contain inclusions or fracture fillings of radioactive species. During our field work in the district, radioactive minerals were collected using radiometric (scintillation) detectors.

To date, Y-REE-Ta-Nb-Ti oxides and other minerals have been collected from more than 30 individual pegmatites and analyzed by electron microprobe (Spilde et al. 2011). Several new minerals were identified or confirmed for the district, including euxenite-(Y), samarskite-(Y), polycrase-(Y), xenotime-(Y), betafite, microlite (and variety uranmicrolite), tantalum-bearing rutile (variety strüverite), and pyrochlore. See Table 1 for formulas. Yttrotantalite, fergusonite, and gadolinite, reported in earlier literature, were not found in the course of our work.

Monazite-(Ce) occurs as blocky masses and crystals weighing up to a half kilogram, and is the most abundant of the REE-bearing minerals in the Petaca district. Xenotime-(Y) was observed as vein-like alterations of monazite-(Ce) and as sub-millimeter inclusions in monazite-(Ce) and Y-rich fluorite. Thorite, containing significant phosphate, was found at the Coats mine, and a sample likely to be thorite based on gamma spectroscopy was also found at the Apache mine. Thorite also occurs as minute inclusions in monazite-Ce at the Coats, Fridlund, La Paloma, and North Star deposits. Zircon was found at the La Paloma pegmatite as millimeter-sized crystals in quartz, associated with samarskite and bismutite. Uranmicrolite, associated with strüverite, occurs at the La Jarita pegmatite in cm-sized

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
 Colorado School of Mines campus, Golden, Colorado

brownish-amber masses, and visually similar material of the same size was collected at the La Paloma. All specimens of columbite-tantalite analyzed in our study were found to be columbite-Mn.

Table 1. Y-REE-Ta-Nb-Ti Minerals identified from the Petaca pegmatites.

Mineral Name	Ideal Formula
Aeschynite-(Y)	(Y,Ca,Fe)(Ti,Nb) ₂ (O,OH) ₆
Betafite	(Ca,U) ₂ (Ti,Nb,Ta) ₂ O ₆ (OH)
Columbite-(Mn)	(Mn,Fe)(Nb,Ta) ₂ O ₆
Euxenite-(Y)	(Y,Ca,Ce)(Nb,Ta,Ti) ₂ O ₆
Microlite	(Na,Ca) ₂ Ta ₂ O ₆ (O,OH,F)
Monazite-(Ce)	(Ce,La,Nd,Th)PO ₄
Polycrase-(Y)	(Y,Ca,Ce,U,Th)(Ti,Nb,Ta) ₂ O ₆
Pyrochlore	(Na,Ca) ₂ Nb ₂ O ₆ (OH,F)
Samarskite-(Y)	(Y,Fe ³⁺ ,U)(Nb,Ta) ₅ O ₄
Ta-Rutile (Strüverite)	(Ti,Ta,Fe ²⁺)O ₂
Uranmicrolite	(U,Ca) ₂ (Ta,Nb) ₂ O ₆ (OH,F)
Xenotime-(Y)	(Y,REE)PO ₄

The Y-REE-Ta-Nb-Ti oxide minerals examined in this study are highly complex. Differentiating between Y-REE-Ta-Nb-Ti oxide minerals is hampered not only by the complex chemistry of the minerals, but also because they are often metamict and display weak or no X-ray diffraction patterns. Furthermore, gross similarity between mineral formulae (e.g. samarskite vs. euxenite vs. fergusonite) adds to the confusion (Ercit, 2005). Ewing (1976) used a statistical approach to classify the Y-REE-Ta-Nb-Ti oxides; Ercit (2005) further refined the technique using principle component analysis (PCA). We have applied PCA in our study of the mineralogy of the Petaca pegmatites.

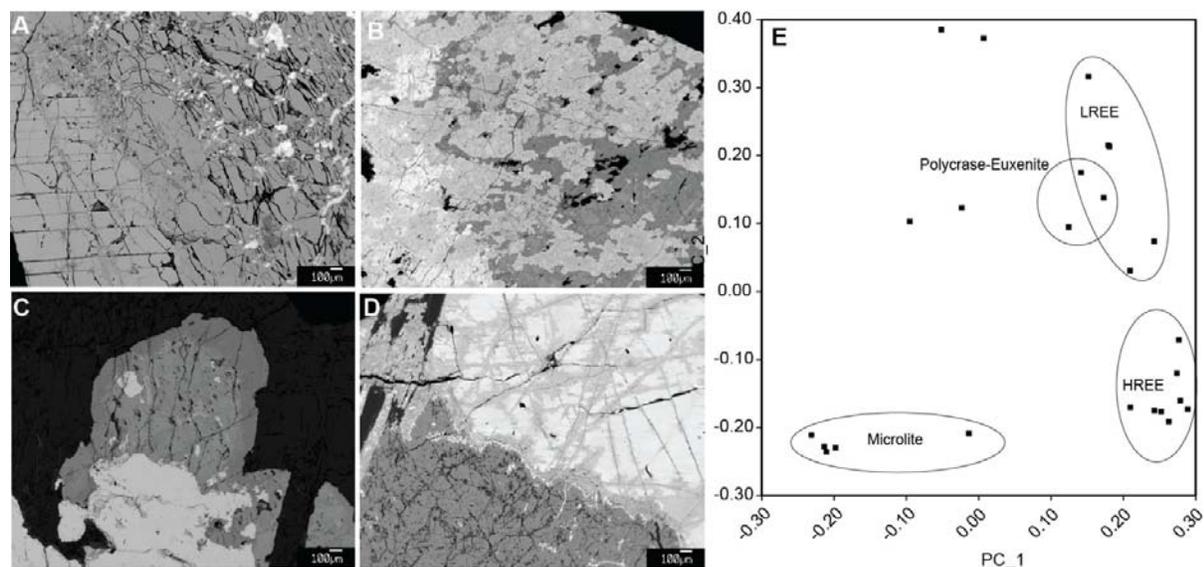


Figure 1. Backscattered electron (BSE) micrographs of Petaca minerals. Scale bars are 100 μm. (A) Thorite inclusions (white) in monazite (medium gray). Compare cleavages in the crystalline monazite-(Ce) at the left with the shattered appearance in the metamict, inclusion-rich region on the right. (B) Exsolution of polycrase-(Y) (light) from samarskite-(Y) (medium gray) and alteration by pyrochlore (gray). (C) Overgrowth of Ta-bearing rutile (strüverite) on columbite (light). (D) Dark gray zircon associated with samarskite-(Y) (light), altered by xenotime-(Y) along fractures (medium gray) with microlite veinlets (white). (E) Plot of the scores of canonical variables 1 and 2 for the Y-REE-Ta-Nb-Ti minerals.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Figure 1 shows examples of the complexity of the minerals from the Petaca pegmatites, including primary inclusions (Fig. 1A), exsolution (Fig. 1B), overgrowth (Fig. 1C), and alteration (Fig. 1D). Zoning within minerals, such as Ta exchanging for Nb across a columbite crystal, reflects changes in the composition of the pegmatite fluid during primary growth of the crystal. Furthermore, enrichment of titanium and tantalum in the late stages of pegmatite crystallization resulted in Ta-rich minerals, such as uranmicrolite and Ta-bearing rutile (strüverite), forming around the margins of pre-existing minerals (Fig. 1C), extending from the existing AB_2O_6 structure. Alteration by late pegmatitic fluids is apparent in Fig. 1D where xenotime replaces samarskite along fractures, and infiltration of fluids rich in U, Ta, and Ca has formed microlite that overprints all the other phases.

Richard Jahns (1946) lists 76 mines and prospects at Petaca that he and his co-workers observed during their field work. Nearly all of these sites have been visited by the authors; most, but not all locations yielded samples of the complex oxides and/or monazite-Ce. Furthermore, we have found several pegmatites not described by Jahns that were either prospected for, or may have produced, mica. Additionally, a few pegmatites have also been discovered that have not been prospected, and while they appear to contain little mica, in some cases they contain rare minerals that have been observed elsewhere in the district, based on radiometric surveys.

The Petaca district appears to be noteworthy in that a high percentage of the known pegmatites are of the rare-element type. It continues to yield a diverse array of rare and unusual minerals. Further exploration will undoubtedly uncover additional rare-element pegmatites and add new species to the growing list of minerals from this district.

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Role of liquid immiscibility in formation of F- and REE-rich segregations in aplite veins near Jamestown, Colorado, USA

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Abstract: F- and REE-rich segregations occur in aplite veins within the Proterozoic Longs Peak-St. Vrain granite, near Jamestown, Colorado, USA. These segregations and aplites are isotopically similar to each other, but distinct from the granite, suggesting an independent origin. The globular textures of the REE-rich segregations in aplite suggest they formed by liquid immiscibility, which may be a significant processes in concentrating REE's out of silicate magmas.

Introduction

F- and REE-rich segregations (Figs. 1 and 2) occur contained in aplitic veins within the Proterozoic 1.42(±3) Ga Longs Peak-St. Vrain Silver Plume-type granitic intrusion near Jamestown, Colorado (Goddard and Glass, 1940; Allaz et al. 2015). The segregations are zoned with gray/purple-colored cores containing dominantly fluorbritholite-(Ce), monazite-(Ce), fluorite, and minor quartz, uraninite, and sulfides, surrounded by black, typically millimeter-thick allanite-(Ce) rims, with minor monazite-(Ce) in the inner part of that rim. Monazite-(Ce) and uraninite U-Th-Pb microprobe ages yield 1.420(±25) and 1.442(±8) Ga, respectively, for the F and REE-rich segregations, suggesting a co-genetic relationship with the host granite.

Petrochemistry

The close age relation with the host granite, various petrochemical characteristic of the aplites and the F- and REE-rich segregations they contain, indicate that these were derived from an independent, possibly deeper, source from the granite, and intruded into the granite. These features include 1) different $\epsilon_{\text{Nd}1.42\text{Ga}}$ for the granites and associated pegmatites, which range from -3.3 to -4.7 and average of -3.9 for 6 samples, compared to the aplites and REE-rich segregations, which range from -1.0 to -2.2 and average of -1.6 for 7 samples), the latter two phases being similar to each other; 2) different mineral compositions for the granites (plagioclase $\text{Ab}_{>90}$; biotite $\text{FeO/MgO} = 2.5-10$, and $\text{F} < 1.5$ wt%) and aplites (plagioclase Ab_{76-82} ; biotite $\text{FeO/MgO} < 2$ and $\text{F} = 2-3$ wt%); 3) granite $(\text{La/Yb})_{\text{N}} < 50$, and with a significant negative Eu anomaly (Fig. 3), in contrast to both the aplites and segregations with $(\text{La/Yb})_{\text{N}} > 80$ and no negative Eu anomalies (Table 1); and 4) the distinctive granular texture of the aplite (Fig. 2).

Discussion

Based on the textures of the F- and REE-rich segregations, which are in many cases preserved as rounded blebs in the aplitic veins (Figs. 1 and 2), we suggest that the aplites and REE-rich segregations initially intruded as a single hypersolvus liquid (Table 1), which then separated by immiscibility into a silicate-rich aplite and a F-, P_2O_5 - and REE-rich phase. Distribution coefficients ($D = C_{\text{REE-segregations}}/C_{\text{aplite}}$) for the separation of REE between the aplites and REE-rich segregations range from 160 for La to 182 for Yb (Table 1), with the exception of Ce which is somewhat higher at 255, resulting in a negative Ce anomaly in the aplites.

The F- and REE-rich segregations may have crystallized first along their allanite rims, producing a progressively more SiO_2 -poor and F- and REE-rich core (Allaz et al., 2015). Alternatively, they may have crystallized progressively outwards from their cores, producing a less F- and REE-rich residual liquid that crystallized into the allanite rims of the segregations, which was remobilized through the aplite to form numerous cross-cutting allanite veins (Fig. 1). Small but ubiquitous concentration of fluorite and monazite-(Ce), surrounded by Fe-sulfides, within the fluorbritholite-(Ce)-rich cores of the REE-rich segregations (Fig. 4), suggest a second stage of immiscible separation of a relatively F-, S- and P-rich liquid from a less F-, S- and P-rich, but more REE-rich liquid.

The process of liquid immiscibility that produced these REE-rich segregations in aplites may be of relevance to the generation of REE enrichment in some pegmatites as well. Compared to immiscible silicate and F- and REE-rich liquids associated with the Mid-Proterozoic peralkaline Strange Lake granite pluton in Canada (Vasyukova and William-Jones 2016), the F- and REE-rich segregations within the aplites from near Jamestown are relatively rich in

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

monazite, and also contains minor quantities of carbonates (bastnäsite) and Fe-sulfides, indicating that P_2O_5 , CO_2 and SO_2 were also involved in the complex F-rich phase that immiscibly separated from the aplite.

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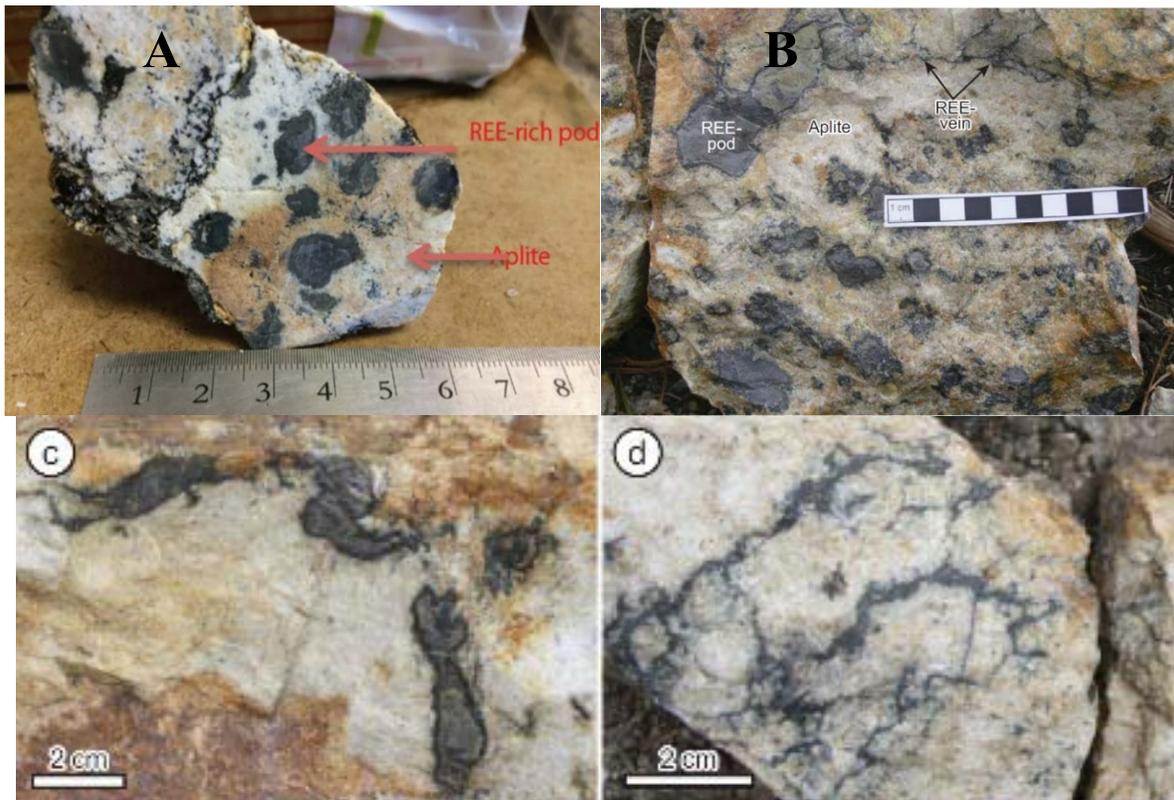


Figure 1. Images of REE-rich pods and allanite veins in aplite within granite from near Jamestown.

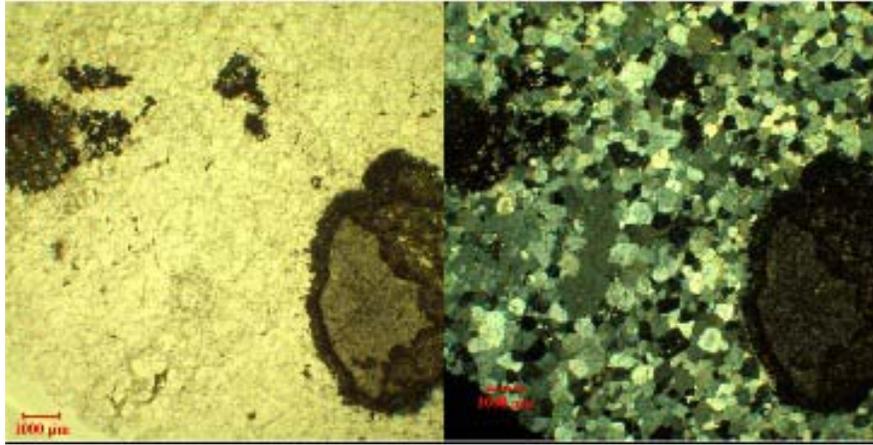


Figure 2. Photomicrograph of REE-rich pod in granular textured aplite.

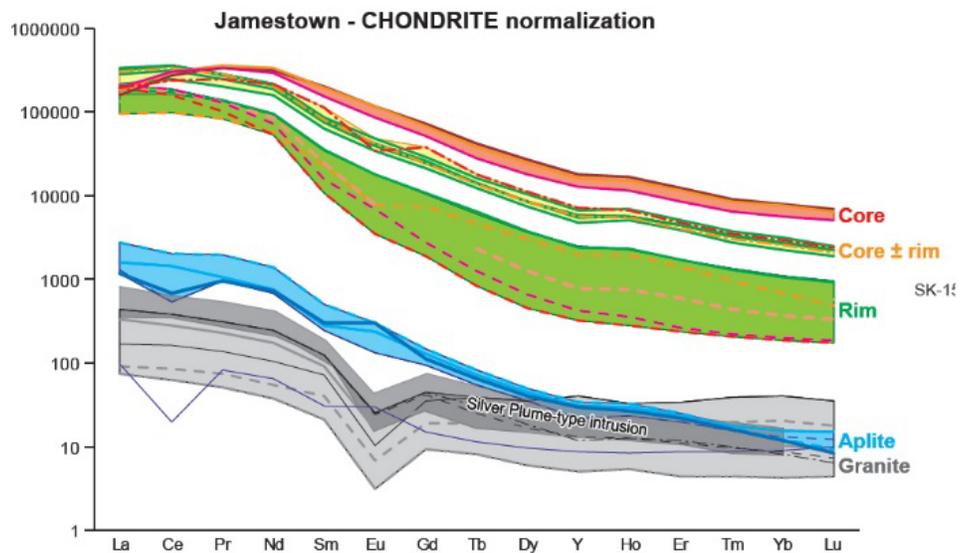


Figure 3. REE concentrations (Table 1) normalized to chondritic abundances for granite, aplite and REE-segregations (cores, rims, and cores + rims) from near Jamestown, Colorado.

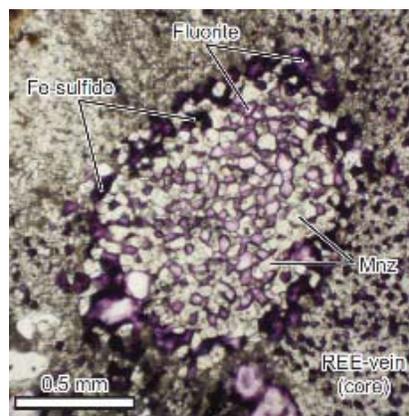


Figure 4. Cluster of monazite and fluorite surrounded by Fe-sulfide produced by a second immiscibility event in the core of a REE-rich mineral segregations.

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Table 1. Average compositions of granite, pegmatite, aplite, the hypersolvus magma (aplite + 10% REE-rich blebs), cores and rims of REE-rich phase, calculated total REE-rich fraction (85% cores + 15% rims), and distribution coefficients D between this phase and aplite.

Rock type # samples	Granite 3	Pegmatite 3	Aplite 5	+10% REE 3	core REE 3	rim REE 1	total REE calculated	D
SiO ₂	72.69	73.03	69.23	62.22	18.62	21.65	20.88	0.3
TiO ₂	0.34	0.28	0.03	0.17	0.00	0.02	0.02	0.6
Al ₂ O ₃	13.97	14.70	18.32	17.12	0.32	2.18	2.39	0.13
Fe ₂ O ₃	2.14	1.82	0.65	3.58	0.32	2.06	2.04	3.15
MnO	0.02	0.04	0.02	0.17	0.30	0.34	0.39	21.7
MgO	0.49	0.33	0.13	1.07	0.02	0.07	0.11	0.82
CaO	0.47	0.49	2.86	3.83	14.32	12.50	13.51	4.73
Na ₂ O	2.34	0.93	5.56	3.79	0.02	0.07	0.05	0.01
K ₂ O	5.38	5.34	1.51	1.44	0.03	0.05	0.04	0.03
P ₂ O ₅	0.16	0.38	0.15	0.36	4.66	4.58	4.21	28.1
F			0.16	0.52	6.85	4.72	5.87	35.6
LOI	1.52	2.19	1.03	1.93	3.91	3.46	3.57	3.45
Total	99.49	99.50	99.51	95.69	49.36	51.7	53.08	
Cs	3.9	5.7	2	1.6	<0.5	<0.5	<0.5	<0.02
Rb	277	454	44	135	<2	<2	<2	<0.05
Ba	632	135	573	1776	90	96	109	0.19
Sr	148	24	2188	1708	2133	1480	1922	0.88
Nb	18	71	3	13	<1	2	2	0.59
Zr	247	141	35	53	31	34	28	0.8
Y	20	35	41	527	9472	9154	8597	209
Hf	5.5	3.7	1.0	2.1	9.7	8.8	8.9	8.5
Th	62.8	20.2	12.8	245	3230	3060	2929	229
Pb	34.0	20.7	92.6		1960	2350	1783	19.3
U	4.3	5.2	33.3	172	4113	3680	3634	109
La	95.3	26.7	434	6325	77033	67700	69638	160
Ce	217	63.7	799	15316	221333	194000	203458	255
Pr	26.8	8.12	126	2026	26100	23400	24060	191
Nd	101	30.6	445	6945	97300	87900	89062	200
Sm	16.8	6.70	54.4	814	12200	11100	11158	204
Eu	1.23	0.38	14.4	167	2460	2220	2241	156
Gd	7.80	4.27	27.6	425	5313	4920	4831	175
Tb	0.87	0.80	2.85	40.4	537	506	489	171
Dy	4.10	5.00	12.0	155	2257	2090	2050	171
Ho	0.70	1.03	1.65	17.6	333	305	301	182
Er	1.87	3.07	3.85	37.7	751	705	677	176
Tm	0.26	0.53	0.44	4.69	86.0	81.4	77.6	176
Yb	1.47	3.53	2.33	26.2	463	446	417	179
Lu	0.19	0.47	0.29	2.92	57.8	54.7	52.3	182

Topaz on America's Mountain (Pikes Peak)

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There are several areas of pegmatites on Pikes Peak itself, including a few with miarolitic cavities on the east, north, and south sides of the mountain. Most of the pegmatites are of the simple type, composed mainly of only one type of feldspar (microcline), zinnwaldite mica, and two varieties of quartz, smoky and clear.

On the west side of Pikes Peak, just off the Pikes Peak Highway at the Glen Cove area, pegmatites are contained in the large rocks that extend to the crest of the mountain, in the area called the old gravel pit. Topaz has been found in these pegmatites.

In the 1940s this was a popular area for climbers. Topaz was first found by Luther McKnight while photographing the wildflowers at the old ski area. He found some rocks and took them to a friend, Clarence Coil. Clarence took the crystals to Colorado College and the crystals were found to be topaz.

Access to this area was and still is dangerous and requires some technical climbing. The names of early collectors here read like the "Who's Who" of early Colorado mineralogists: Clarence Coil, Ed Over, Jr., Robert Ormes, and John Alexander.

In July of 1997, Steve Russell, his brother Ed, and Jack Thompson tried their luck in this area. Topaz crystals were found, of good quality, color and crystal shape, but of much smaller size than some of the early finds. This poster presentation will include photographs of the Glen Cove collecting sites and of topaz and other mineral specimens from the area, including some "classic" topaz crystals in the Denver Museum of Nature and Science collection as well as more recent finds.

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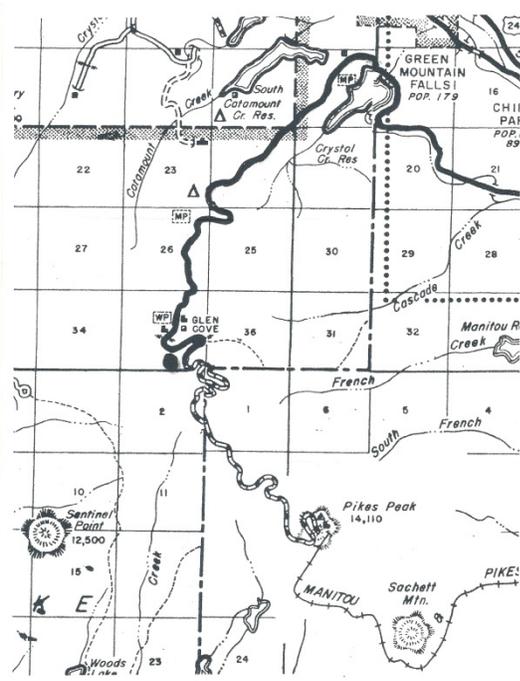


Figure 1. Map of the Pikes Peak area, showing the location of Glen Cove.

A-type granites and their pegmatites: NYF or something else?

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The present classification of granitic pegmatites distinguishes three petrogenetic families of pegmatites that are derived by igneous differentiation from S-, A- and I-type granitoids. The most extensively studied pegmatite family are those identified as LCT which are characteristically related to peraluminous S-type granites and whose pegmatites are marked by noticeable accumulations of Li, Cs and Ta (along with Rb, Be, Sn, B, P and F). The second most recognizable geochemical type of pegmatites fall into the NYF category known for their affiliation with largely peralkaline to slightly peraluminous A- and I-type granites. The NYF pegmatites (*sensu stricto*) are characterized by prominent accumulations of Nb, Y+REE and F (along with Be, Sc, Ti, Zr, Th and U). The third and least understood group of pegmatites belong to the “MIXED” category, which exhibit mineralogical and chemical features of both LCT and NYF types.

Since the initial introduction of the NYF family by Černý (1991) and the subsequent redefinition by Černý & Ercit (2005), the petrologic data of several reasonably well-documented examples of fertile (*pegmatite-generating*) A-type granites worldwide have been compiled and the results clearly confirm the existence of cogenetic pegmatites that lack appreciable REE mineralization and as well as bodies whose rare-element signature mimics that observed in some LCT granite-pegmatite suites. These pegmatites, which superficially do not resemble the “classic” NYF pegmatites in terms of their mineralogy and chemistry, include 1) mineralogically simple pegmatites consisting largely of quartz + feldspar ± biotite, muscovite or spessartine, 2) pegmatites notably enriched in iron minerals such as biotite, magnetite, fayalite or Na-rich amphibole, and 3) pegmatites with “LCT-like” signature that host beryl and subordinate boron, tantalum or lithium mineralization. This last group has caused the most confusion in terms of their classification and their “LCT-like” chemical signature has caused many “pegmatologists” to consider them as part of the MIXED category.

Simple quartz-feldspar pegmatites are cogenetic with peralkaline, metaluminous and peraluminous A-type granites. Peralkaline A-type granites generate pegmatites with sodic amphiboles whereas fayalite-bearing pegmatites are typically affiliated with mostly peraluminous A-type granites. The LCT signature appears to become much more pronounced in pegmatites derived from weakly to mildly peraluminous A-type granites as indicated by the prominent crystallization of beryl which in some cases may be accompanied by Li-bearing tourmaline, ferroan lepidolite, Ta-enriched oxides, topaz or fluorite.

Despite the non-traditional NYF mineralogy of the some pegmatites affiliated with A-type granites, their placement in the current classification scheme can be inferred from 1) the close examination and identification of associated mineral phases, 2) the use of K/Rb vs Ga and similar discrimination diagrams, 3) the fluorine content of accessory biotite and 4) the presence or absence of amazonitic K-feldspar.

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The Rare Earth Minerals of Stove Mountain and Cheyenne Canyon near Colorado Springs

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In 2014, Sarah Hanson and I wrote an article in *Rocks and Minerals* magazine entitled “Minerals from the Mirolitic Pegmatites in the Stove Mountain Area” (Zito and Hanson 2014), where the large variety of minerals (68 different minerals) found in the mirolitic pegmatites were discussed.

This presentation focuses on the rare earth minerals of this area, the geology, crystal morphologies, the different chemistries, and the secondary alteration products. Local metasomatism, dissolution-precipitation, and regrowth have caused many interesting features on rare earth minerals such as epitaxial growth, redistribution of REE cations, and syntaxial growth. The remobilization of rare earth elements can lead to the large variety of minerals seen in this area.

Stove Mountain and Cheyenne Canyon lies within the Pikes Peak Batholith and is part of the Mount Rosa Complex. The Pikes Peak batholith is exposed for approximately 3100 square kilometers along the Colorado front range from Colorado Springs to north of US 285. The Pikes Peak Batholith is a composite batholith consisting of three separate plutonic events and several satellite stocks emplaced 0.95 to 1.08 billion years ago (Hutchison 1976). These three events are the Buffalo Park Intrusive Center, Lost Park Intrusive Center and Pikes Peak Intrusive Center which are similar in composition distinguished only by their structural and textural features.

The satellite stocks however, are small late stage plutons that vary significantly in composition and structure. These late stage intrusions have been divided into two groups based on their alkali content. The potassic granite is composed of $\text{Na}_2\text{O}/\text{K}_2\text{O} < 1$, generally thought to have been formed by crustal anatexis, and the sodic granite $\text{Na}_2\text{O}/\text{K}_2\text{O} > 1$ formed by differentiation (Smith 1999). The potassic groups are fine to medium grain biotite granites that are scattered throughout the batholith. The sodic group of intrusions varies widely in composition and structure. The sodic intrusions include structures such as ring dikes (the Lake George intrusion), high fluorine granites (the Redskin Stock) and the more exotic rock types such as the sodic amphibole granites and fayalite granites (the Mount Rosa complex).

Regional and local geology are important controls to the emplacement of pegmatite dikes that contain the Rare Earth Minerals and yttrium (REEY) will be considered a rare earth element since it has a similar ionic radius and valence as the lanthanides. Stove Mountain and Cheyenne Canyon are within the alkaline Mount Rosa complex and contain the Pikes Peak Granite, fayalite Granite, and the Mount Rosa riebeckite Granite. The later intrusion of Mount Rosa riebeckite Granite into Pikes Peak Granite has created NW striking joints and pegmatites in which contain pegmatites with mirolitic cavities containing REEY minerals. Since the REEY minerals are the last to crystallize in these mirolitic cavities, they reflect any late stage metasomatism, alteration and regrowth. The following are REEY minerals that show unique growth features in this area.

Bastnaesite; cerianite epitaxy, synchysite and parasite syntaxy

The most abundant REEY mineral in this area is Bastnaesite-Ce with a REEY composition of $(\text{Ce}_{0.70}, \text{La}_{0.20}, \text{Nd}_{0.10})(\text{CO}_3)\text{F}$. Bastnaesite occurs as 0.1-5cm root beer colored hexagonal crystals elongate to the c-axis. However, on rare occasions bastnaesite will be seen as flat crystals elongate perpendicular to the c-axis with a composition of $(\text{Ce}_{0.50}, \text{La}_{0.10}, \text{Nd}_{0.40})(\text{CO}_3)\text{F}$.

Bastnaesite has also been found as epitaxial overgrowths on fluocerite $(\text{REE})\text{F}_3$. These crystals have been analyzed by Muller (2012) and found to have zones along the bastnaesite-fluocerite interface where fluocerite is being carbonated to bastnaesite. There are zones where the REEY cation will exchange from Bastnaesite-Ce to produce Bastnaesite-La, and zones where the Ce has oxidized from $(\text{Ce}^{+3}, \text{La}, \text{Nd})(\text{CO}_3)\text{F}$ to produce cerianite $(\text{Ce}^{+4}\text{O}_2)$.

Bastnaesite does not show twinning or many inclusions in this area but on occasion will show syntactic intergrowths with synchysite and parasite. Since all the fluorocarbonates have a similar structure with layers of REE and Ca separated by CaCO_3 along the (0001) plane. Van Landuyt and Amelinckx 1975 showed that

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

fluorocarbonates can be constructed by the assemblage of the atomic stacking layers D, E, F, G where; D= CeF ionic layers, E= layers of CO₃ groups between CeF groups, F= layers of Ca ions and G=layers of CO₃ groups between Ca and CeF

Thus, bastnaesite will be formed by the stacking sequence DE, synchysite will be formed by the stacking DGFG and parasite will be formed by the stacking DEDGFG each with a unique layer size (d-spacing) that can be measured by transmission electron microscopy (TEM).

Monazite and thorium substitution

The phosphate mineral monazite REEY(PO₄) has not been found as crystals in miarolitic cavities but has been found as monoclinic laths in highly altered fluorite. The highly altered monazite phase has a very high thorium signature, 5-15% by weight.

Thorium may then partition into monazite via the coupled substitution reactions $\text{Th}^{+4} + \text{Si}^{+4} = (\text{REEY})^{+3} + \text{P}^{+5}$ or $\text{Th}^{+4} + \text{Si}^{+4} = 2(\text{REEY})^{+3}$ (Forster 1998). Th^{+4} and REEY^{+3} may then be taken up by synchysite-Th, Ca(Th, Ce, La)(CO₃)₂F.

Xenotime and late stage crystallization

Xenotime YPO₄ has been found only as 1-5mm clear crystals in small quantities on prior crystals in miarolitic cavities. REE cations may substitute for Y but has been found only to be from 1-100ppm).

Kainosite and late stage crystallization inside fluorite vugs

A small amount of kainosite Ca₂(Y)₂(SiO₃)₄(CO₃).H₂O has been found in this area. It occurs as 0.1 to 1 mm orthorhombic crystals that occurs as secondary crystals on top of quartz crystals, as alteration rims and as euhedral crystals in vugs inside fluorite.

These morphologies and chemistries show the remobilization and the secondary precipitation of REEY minerals. This provides the possibility of finding new and unusual minerals in this area.

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Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

FIELD TRIPS

Specific meeting times and places for trips are determined by field trip leaders. Please contact them for confirmation of times and places.

MONDAY TRIPS	LEADER	RENDEZVOUS
Eight Mile Park pegmatite field, Mica Lode, Meyers and School Section pegmatites	Steve Wolfe and Jennifer Gerring	8 AM leave Golden. 10:30 AM meet at the Colorado Quarries office on south side of highway 50 and S. 15 th Street in Canon City.
<i>Big Bertha pegmatite, South Platte District, Jefferson County</i>	<i>Jeff Self and Donna Ware</i>	<i>8 AM leave Golden. 9:00 AM meet at the Pine Junction Park & Ride on highway 285 between Bailey and Conifer. Forest service will allow us to use the road.</i>
St. Peters Dome alkali pegmatites, El Paso County	Philip Persson	8 AM leave Golden. 10:00 AM meet at location near Colorado Springs.
<i>Northern Crystal Mountain pegmatite field, Wisom Ranch, Bull Elk Beryl Crystal and Big Boulder pegmatites.</i>	<i>Mark Jacobson</i>	8 AM leave Golden 10:00 AM meet at Masonville Mercantile Store.
Amazonite pegmatites, Smoky Hawk claim, Crystal Peak, Teller County	Amber Brenzikofer	8 AM if leaving from Golden. Meet at intersection of highway 24 and Trail Creek road in the Lake George Forest Service work center on NE corner.
TUESDAY TRIPS	LEADER	RENDEZVOUS
Platt Pegmatite, Carbon County, Wyoming	Steve Zahony	8 AM if leaving Golden, Meet up at the junction of routes 125 and 127, which is 13.2 miles north of Walden.
Brown Derby pegmatites, Quartz Creek pegmatite field, Gunnison County	Mike Perkins	5:30 AM if leaving from Golden. 10:30 AM meet at junction of State Highway 50 and graded dirt road County 44 on north side. The 4WD road starts later at NFS road 802
Devils Hole pegmatite field, Devils Hole and Chief pegmatites, Fremont County	Steve Wolfe and Jennifer Gerring	8 AM leave Golden. 10:30 AM meet at the rock shop on the south side of route 50, just east of the entrance to the Royal Gorge. Trip ends midway between Salida and Canon city.
St. Peters Dome alkali pegmatites, El Paso County	Philip Persson	8 AM leave Golden. 10:00 AM meet at a location near Colorado Springs.
Southern Crystal Mountain pegmatite field, Hyatt and Storm Mountain pegmatites, Larimer County	Mark Jacobson	8 AM leave Golden. 10 AM, meet at Highway 34 (Big Thompson road) and W. County road 22H at the Dam Store (north side) just before entering the canyon.

BIOGRAPHIES OF PRESENTERS AND POSTER AUTHORS

Compiled by Peter J. Modreski

Sandra de Brito Barreto, Dr. Sc., is a Professor Associado, Coordenadora do Laboratório de Gemologia da UFPE, and Diretora do Museu de Minerais e Rochas, at Universidade Federal de Pernambuco, Pernambuco, Brasil.

Renata Barros is a BSc Geology graduate of the University of São Paulo, São Paulo - Brazil (completed in December 2012) and currently a 3rd year PhD student in University College Dublin, Dublin - Ireland. Her PhD project is about the petrogenesis of lithium pegmatites in southeast Ireland, with CAPES/Science Without Borders funding. Her research interests include petrogenetic processes, geochemistry, isotope geology and geochronology. Renata is a member of the MDSG - Mineral Deposits Studies Group (UK and Ireland) and of the EAG - European Association of Geochemistry and she is the postgraduate students' representative in the School of Earth Sciences - UCD.

Dwight Bradley's interest in pegmatites dates from the 1960s when he started mineral collecting as a kid in New England. He received a Bachelor's degree in Geology in 1978 from the University of Vermont and a Ph.D. in 1984 from the State University of New York at Albany. He retired in 2014 after a career as a research geologist with the U.S. Geological Survey in Alaska. He spent 26 summers in the field in Alaska, and has also worked in the Canadian Arctic, New England, Maritime Canada, and Mauritania. Bradley's field experience spans a range of tectonic settings including collisional orogens, magmatic arcs, accretionary complexes, passive margins, foreland basins, and pull-apart basins. Bradley's research interests include earth history, plate tectonic interpretations of orogenic belts, geochronology, and tectonic aspects of ore-deposit genesis—with an emphasis since 2011 on LCT pegmatites.

Clara J. Brennan is an undergraduate student at Central Michigan University (CMU), planning to graduate with majors in Geology and Chemistry and a Mathematics minor in May 2017. She is an Honors student and recipient of a Centralis Award, the most prestigious scholarship at CMU. She is interested in geochemistry and sedimentology. In addition to fluid inclusions in pegmatites, she currently studies the speciation of molybdenum in lake water and modern sediments.

Tom Buchholz has been interested in minerals since about the age of ten, and after retirement from the US Army in 1992 has focused his studies on pegmatite mineralogy and chemistry, concentrating on pegmatites of Wisconsin, Michigan and Minnesota, USA. He has been affiliated with the MP2 Research Group since about 1996, and has been author or co-author of numerous abstracts for the Rochester Mineralogical Symposium, the Institute on Lake Superior Geology, the International Pegmatite Symposiums in 2011, 2013, and 2015, and co-author of several papers published in the *Canadian Mineralogist*.

Jean Cowman is a Colorado native who has spent many years hiking and exploring. Field prospecting for minerals has been a hobby for the last ten years and she has also become a mining partner of the Agnus Dei topaz claim which she co-discovered with Rich Fretterd.

Joseph Dorris grew up in McCall, Idaho. He graduated from the U.S. Air Force Academy, and served in the USAF for 20 years. His career included serving in several positions on the staff at the Air Force Academy. After retirement, Joe taught high school science and mathematics at James Irwin Charter High School in Colorado Springs. He is currently the owner of Pinnacle 5 Minerals and Glacier Peak Mining, conducting mining operations for smoky quartz, amazonite, and topaz in Colorado. Joe has become a celebrated personality on the “Prospectors” television show. He is also an accomplished artist in oil painting, and is the author of several historical fiction novels set in Idaho during the frontier gold mining era.

Steve Dubyk received his degree in geology from the University of California - Santa Barbara. He has extensive experience in uranium and precious-metal mining exploration, mine development and production, and determining the environmental impact of mining operations. He has a life-long interest in pegmatite mineralization, and has prospected numerous pegmatites in California, Arizona, Colorado and New Mexico. He and his fellow mineral collectors commenced systematic exploration of the Petaca District pegmatites for rare minerals in 2008. Steve has also designed and used radiometric equipment for both laboratory and field use in the Petaca study.

Alexander U. Falster has been working with pegmatites for over 50 years, starting at age 12 at the Hagendorf-Sued pegmatite and then working on the pegmatites of the Wausau complex since 1974, followed by the Florence Co. pegmatites in Wisconsin. Numerous trips across the world to pegmatite fields followed over the years, including a summer stay at Antandrokomby in Madagascar. Al has worked at the University of New Orleans until 2014 and then moved to Maine to take on a position at the Maine Mineral and Gem Museum in Bethel, right in the Oxford pegmatite field.

Myles Felch is the Assistant Curator at the Maine Mineral and Gem Museum in Bethel, Maine. He obtained a BA in Geology at the University of Maine at Farmington in 2012. In 2014, he received an MS in Geology at the University of New Orleans where he worked under Dr. William Simmons, Alexander Falster and Dr. Karen Webber.

Rich Fretterd is an accomplished miner and prospector who has been exploring Colorado’s backcountry for many years. Rich has previous experience working as an underground stope miner in the gold mines of Cripple Creek and has spent many years prospecting for local pegmatite minerals as well. In 2002 he uncovered record breaking smoky quartz crystals from the Lake George district. More recently he has appeared on the Weather Channel’s show “Prospectors,” where he was featured uncovering a new find of topaz crystals near Pikes Peak.

Alexander Gysi has a MS in mineralogy and petrology from ETH Zurich and a PhD in geochemistry from the University of Iceland. He has worked on the petrology of mantle rocks, and studied the sequestration of CO₂ in basaltic rock formations associated to the development of geothermal energy. Further, Alexander worked 3 years as a postdoctoral fellow at McGill University in Montreal, with a focus on REE mineral deposits and the thermodynamic properties of REE-bearing minerals. He is presently an Assistant Professor at the Department of Geology and Geological Engineering at Colorado School of Mines, where he is building a hydrothermal

geochemistry and calorimetric laboratory, and combines experiments, numerical modeling and field studies to study metal transport in crustal fluids.

Sarah L. Hanson received a BS and MS from the University of New Orleans and a PhD from the University of Utah. She is currently a professor of Geology at Adrian College in southern Michigan where she teaches courses including mineralogy, igneous and metamorphic petrology, structural geology, and supervising Senior Research. Her research interests include granitic rocks and related pegmatites, particularly rare-earth-element-mineralization in NYF pegmatites.

Rhiana Elizabeth Henry is originally from Fremont, California, and graduated with Bachelor of Arts degrees in geological sciences and physics from University of Colorado at Boulder in December 2013. She focused on mineralogy, petrology, and physics related to crystallography as an undergraduate. After graduating, she completed a Graduate Gemologist certification from the Gemological Institute of America in Carlsbad, California. Rhiana became fascinated with pegmatites specifically while visiting the Stewart Lithia Mine. Currently she is finishing her first year of graduate school at CU Boulder in geological sciences and is focusing on the petrology of rare earth element enriched pegmatites in the South Platte region of Colorado with her adviser Charles Stern. In addition to her pegmatite research, Rhiana is a freshman and sophomore level physics teaching assistant.

Mark Ivan Jacobson obtained a BS in mineralogy-geochemistry from Pennsylvania State University in 1973 and a MS in sedimentary geology from the University of California at Berkeley in 1976. After graduate school, he worked for Amoco and Chevron in oil and gas development as an earth scientist, completing 35 years with Chevron before retiring in 2013. He has published numerous articles on the geology, mineralogy, and mining-collecting histories of pegmatites since 1978 as well as two books: "Guidebook to the pegmatites of Western Australia (2007)" and "Antero Aquamarines: Minerals from the Mount Antero - White Mountain region, Chaffee County, Colorado (1993)." He has been a consulting editor for *Rock & Minerals* since 1984 and is currently president of the Colorado Chapter of the Friends of Mineralogy.

David London is a Stubbeman-Drace Presidential Professor and Norman R. Gelphman Professor of Geology, and Director of the Electron Microprobe Laboratory, at the University of Oklahoma. He is the author of the book "Pegmatites" (Canadian Mineralogist Special Publication 10) and the namesake of londonite.

Robert F. Martin was born in Ottawa, Canada, and graduated in geology from the University of Ottawa (B.Sc.), Penn State (M.S.), Stanford (Ph.D.). At Stanford, his advisors were O. Frank Tuttle, of Tuttle and Bowen fame, and Richard H. Jahns, Mr. Pegmatite. He specialized early on in the mineralogy and petrology of granitic rocks and related pegmatites. Robert joined the staff at McGill University in Montreal in 1970. He has focused on anorogenic felsic magmatism, and on the interplay of tectonic setting and petrogenetic processes. In 1978, he was invited to become editor of *The Canadian Mineralogist*, and served at the helm until 2012, a heroic (or masochistic?) 35-year stint. He recently published an Atlas of Ore Minerals, with a focus on epithermal deposits of Argentina (*The Canadian Mineralogist*, Special Publication 11). Robert is hard at work on Special Publication 13, on the minerals and mineralogists of France. He currently holds

the title of Professor Emeritus, Department of Earth and Planetary Sciences, McGill University, in Montreal.

Julian Menuge graduated from Leicester University, UK, in Geology and went on to a PhD in Cambridge University, UK, where he was one of the first generation of students to apply Nd isotope analysis to determine the timing of Proterozoic continental crust formation, working mainly in south Norway. He extended these studies to the Irish Proterozoic as a postdoc in University College Dublin, Ireland, and became a Lecturer there in 1989. He has subsequently developed an interest in ore deposits and has applied a variety of petrographic, geochemical and isotopic methods to problems of ore formation and mineral exploration. This has included work on the giant Navan Zn-Pb carbonate-hosted orebody in Ireland and most recently on rare metal pegmatites in southeast Ireland. He recently became a member of iCRAG, a multi-institutional research centre for applied geology, including minerals research, funded by Science Foundation Ireland.

Ian Merkel was born and raised in southern New York on a sandbar called Long Island. Initially enrolled as a biology student he later switched his major to geology after a five month mineral expedition that covered over thirty-five mineral localities. He graduated from the State University of New York at New Paltz in 2004 with a Bachelor of Science in Geology. At Colorado State University in Fort Collins. Ian continued his studies in geology focusing his master's research on the petrology of epidote bearing high-pressure pegmatites from the North Cascade Mountains, Washington. During this time he also spent summers interning for Phelps Dodge at the Morenci Mine in Arizona. After graduating with a Master of Science in Geology in 2007, Ian began full time work as an exploration geologist at the Morenci Mine for Freeport McMoRan—there he worked on logging, modeling, database management and running drill programs. In 2010 Ian transferred to the Henderson Mine in Empire, Colorado where up until 2015 he mapped miles of drifts and developed numerous molybdenum, alteration, and lithology models of the Henderson ore body.

Currently living in Denver, Ian now focuses on mineral specimen geology and fine art jewelry design. He is also a geologist and mineral collector at the Spruce Ridge mine (quartz and pyrite), Jacksons Crossroads mine (amethyst), Krystal Tips mine (quartz scepters) and the California Blue Mine (aquamarine), and continues to use his education and specialized training to explore and model mineral specimen localities.

Peter J. Modreski has been a geochemist since 1979 with the U.S. Geological Survey, Lakewood, Colorado. He has a B.A. in chemistry from Rutgers University and an M.S. and Ph.D. in Geochemistry from Penn State. He was one of the co-editors of the revised edition of Minerals of Colorado, published in 1997, and is a past president of National Friends of Mineralogy and of the Colorado Chapter of FM. Pete is a Department Associate at the Denver Museum of Nature and Science, and a Consulting Editor for Rocks and Minerals magazine. Pegmatites and alkalic igneous rocks are among his research interests. Pete's present work includes responsibility for public and educational outreach at the USGS.

George Morgan is the operating research scientist in the Electron Microprobe Laboratory, and an adjunct professor of geology, at the University of Oklahoma. He has been there since 1992, following a postdoctoral position in the microsampling Raman spectroscopy laboratory of the

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

Department of Earth and Planetary Sciences, Washington University in St Louis. He earned his M.S. (1986) and Ph.D. (1988) degrees in geology at the University of Oklahoma after completing two bachelor's degrees at the University of Nevada, Las Vegas. His research mostly centers on the textural and chemical evolutions of evolved silicic magmas, mainly using experimental petrology to model formation processes in granites and pegmatites.

Axel Müller is professor of mineralogy and petrology (with professorial level from 2010) at the Natural History Museum (NHM) of the University of Oslo, Norway. He is the team leader of the Mineralogy Group at the NHM and research associate of the Natural History Museum of London, UK. Axel has 20 years of research experience in the fields of petrology, mineralogy and geochemistry of igneous rocks with emphasis on granites and pegmatites and related rare-metal deposits. During his interdisciplinary career he worked also in the fields of mineral exploration, applied gravimetry, engineering geology, and development of analytical equipment in particular laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) for ultra-trace elements in economic minerals.

Axel started studying geology at the Mining Academy in Freiberg, Germany, in 1990 and finished the studies with the Master degree at the University of Göttingen, Germany, in 1996. In 2000 he completed his Ph.D. entitled "Cathodoluminescence and characterization of defect structures in quartz with applications to the study of granitic rocks." Between 2001 and 2002 he was employed by the Geotechnical Engineering Company Leipzig in Germany working with the optimization of the blasting design in open pit mines. In 2004 he finished a two-year postdoctoral fellowship about trace element and melt inclusion studies of quartz and feldspar of rare metal granites at the Natural History Museum of London, United Kingdom. Between 2004 and 2014 Axel was employed as senior geologist by NGU at the Department of Mineral Resources in Trondheim, Norway, with special focus on the genesis and mineralogy of industrial mineral deposits. From 2012 to 2013 he worked as chief geologist for the Quartz Corporation Ltd. based in Spruce Pine, North Carolina, USA, where his major working task was the exploration of high-purity quartz deposits in the Blue Mountain Range of North Carolina. Since June 2015 Axel has been a professor in mineralogy and petrology at the Natural History Museum of the University of Oslo. See also: <http://www.nhm.uio.no/english/about/organization/research-collections/people/axelmu/>

Milan Novák is Professor of Mineralogy on the Department of Geological Sciences, Masaryk University, Brno, Czech Republic. Prior to joining the Masaryk University in 1999 he worked from 1977 as curator at the Moravian Museum, Brno. In 1991-1993, he was a postdoctoral fellow with professor Petr Černý at the University of Manitoba, Winnipeg. His research includes granitic pegmatites and their minerals focused mainly on crystal chemistry of tourmalines (chairman of the IMA subcommittee on tourmaline nomenclature), Nb, Ta, Ti, Sn, W-oxide minerals, micas, beryl, garnet, cordierite, and borosilicates.

Ed Raines is the Collections Manager at the Colorado School of Mines Geology Museum.

Luis Sánchez-Muñoz has been a researcher at the Institute of Ceramics and Glasses (Spanish Council for Scientific Research, Madrid, Spain) since 2009. He has specialized in solid-state science, receiving a Ph.D. from the Department of Crystallography and Mineralogy, Faculty of Geological Sciences (Universidad Complutense de Madrid, Spain) in 1992. He has been working

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

on different topics of several natural and ceramic materials in academia and industry in Spain, France and Belgium, from the microstructural and spectroscopic points of view, but particularly by solid-state NMR. He is mainly renowned for his research works in order-disorder phenomena, exsolution, and twin structures of alkali feldspars. He has published over 70 scientific and technical refereed papers, and over 100 conferences and talks.

Philip M. Persson is currently a graduate student in the department of geology & geological engineering at the Colorado School of Mines where he is pursuing a master's degree in geology. His thesis is focused on the mineralogy and petrology of the Mesoproterozoic Mount Rosa Complex, a peralkaline granite complex with associated pegmatites hosted within the ~1.08 Ga A-type Pikes Peak Batholith in central Colorado. He earned a BA in geology from the University of Colorado at Boulder in 2012 and has worked both as an exploration geologist and summer intern for numerous mining companies including Newmont, Barrick, ASARCO, and Boliden AB, on projects in Idaho, Nevada, Arizona, and northern Sweden. He has participated in a number of research projects focusing on REE and rare-element enriched pegmatites of the Colorado Front Range, including the petrogenesis of a group of unusual fluorbritholite-enriched deposits hosted in the ~1.4 Ga Silver Plume granite which was published in the *American Mineralogist* in 2015, and several GSA abstracts and presentations. He is also passionate about mineral collecting and currently is funding his graduate studies through his small, mainly-online mineral specimen business, Persson Rare Minerals. He lives just north of downtown Denver, Colorado and enjoys rock climbing, skiing, and writing both fiction and non-fiction is his 'spare' time. He is excited to help host the 2nd Foord pegmatite symposium at the Colorado School of Mines and is especially looking forward to the opportunity to visit his research area with pegmatite experts from around the world!

Markus Raschke is professor at the Department of Physics, Department of Chemistry, and JILA at the University of Colorado at Boulder. His research is on the development of novel nano-optical spectroscopy and imaging techniques with applications to molecular, soft- and biomaterials, quantum hard matter and minerals. He received his PhD in 2000 from the Max-Planck Institute of Quantum Optics and the Technical University in Munich, Germany. Following appointments at the University of California at Berkeley, and the Max-Born-Institute in Berlin, he became faculty member at the University of Washington, before moving to Boulder in 2010. He is fellow of the Optical Society of America and the American Physical Society.

William B. (Skip) Simmons received his BS from Duke University, MS from the University of Georgia and PhD from The University of Michigan. He is the Director of the Mineralogy, Petrology and Pegmatology (MP²) Research Group in the Department of Earth and Environmental Sciences at the University of New Orleans, where he taught mineralogy and petrology for 42 years. He is a full member of the Graduate Faculty and has supervised or served on the committees of 62 graduate students. He was also Adjunct Professor at The University of Michigan where he taught field geology classes for 38 summers. The University of New Orleans also awarded him the honorary title of University Research Professor in 2000. He is recently retired from teaching and was appointed Professor Emeritus. He also serves as a Research Director at the Maine Mineral and Gem Museum (MMGM), Bethel.

Skip is a specialist in analytical mineralogy and is the director of the MP² analytical facility originally in the Department of Earth and Environmental Sciences, but recently relocated to the

MMGM which now houses the Electron Microprobe, Scanning Electron Microscope, X-ray Diffractometer and X-ray Cameras, and Direct Coupled Plasma Spectrometer. His principal specialty is the study of the mineralogy, petrology and geochemistry of pegmatites. He has conducted field research on pegmatites in the US, Russia, Brazil, Madagascar, China, Scandinavia, Zambia, Namibia and Malawi. He has published analyses of colored gemstones from these and other worldwide locations.

Research with MP² colleagues on modeling the cooling and crystal growth rates of highly evolved silicate magmas has changed the basic paradigm found in all geology text books that “big crystals are the result of slow cooling to allow time for crystals to grow to large size”. In fact, our models indicate that in some shallow-level pegmatites the solidification rates are so fast that some of the world’s largest crystals may actually grow in months to years, not millions of years. Recent research focuses on the anatectic origin of Maine pegmatites and the relationship of pegmatite melt generation and geochemistry to specific tectonic settings, i.e. convergent (orogenic), post orogenic or extensional (anorogenic).

Dr. Simmons is the organizer and Director of the Maine Pegmatite Workshop, which is a week-long short course on pegmatites. The course runs every June and involves lectures and daily fieldtrips to pegmatites. The course attracts an international audience of pegmatite professionals, aficionados and students. He is coauthor of the book *Pegmatology* which is used as a textbook for the workshop. In 2013 Simmons was the principal organizer of the bi-annual pegmatite conference, PEG 2013, which was held in New Hampshire and Maine. The meeting attracted 125 participants from 20 countries.

He is author or coauthor of the description of 23 new minerals and five discreditations. His publications include over 400 published papers in mineralogy, including six books, fifteen book chapters, nine encyclopedia articles, and two patents. The new mineral Simmonsite is named in his honor in recognition of his work on granitic pegmatites and their mineralogy. He is a Fellow of the Mineralogical Society of America and was awarded the Charles A. Salotti Earth Science Education Award for Excellence in Earth Science Education.

Mona-Liza C. Sirbescu is Professor of Geology at Central Michigan University, Mount Pleasant, Michigan, in an undergraduate-only department of Earth and Atmospheric Sciences that she joined in 2001. Since then she has mentored about 25 undergraduate–student researchers. Her research background and interests revolve around high-temperature geochemical processes involving magmas and associated ore deposits. She has conducted research on the origins of granitic pegmatites using geochemistry, mineralogy, fluid inclusion studies, and experimental petrology. Together with collaborators from the German Center for Geosciences, Potsdam – Germany, Mona has successfully visualized and documented crystal nucleation and development of pegmatite texture from lithium-boron bearing hydrous silicate liquid in modified Diamond Anvil Cell experiments. Other topics that she has addressed include conditions of formation of mesothermal gold deposits and boron contamination related to gold metallurgy at giant mine tailings in Ontario, Canada. Mona holds a Ph.D. in Geology from University of Missouri-Columbia (2002), preceded by a M.A. from State University of NY – Binghamton (1996), and a B.S. in Geological Engineering from Bucharest University, Romania (1989).

Charles Stern is professor in the Department of Geological Sciences at the University of Colorado in Boulder, where he has worked since 1979. He earned his PhD from the University of Chicago in 1973, with a thesis project that involved experimental melting of rocks at high

Second Eugene E. Foord Pegmatite Symposium July 15-19, 2016
Colorado School of Mines campus, Golden, Colorado

pressure, than began doing field and petrochemical studies of active Andean volcanoes as a postdoc at Lamont-Doherty Geologic Observatory. He continues to work on a wide range of problem related to magma genesis in different tectonic environments.

Jack Thompson and **Kaye Thompson** are volunteers in the Department of Earth Sciences, Denver Museum of Nature and Science. They have been active in the Colorado mineralogical community for more than 30 years, displaying minerals at various shows, giving presentations at symposia and club meetings, authors of mineralogical articles in several magazines and newsletters including *Rocks & Minerals*, and has served as officers in different mineral societies: Friends of Mineralogy -- Colorado Chapter, Rocky Mountain Federation of Mineralogical Societies, and the Colorado Springs Mineralogical Society.

Michael A. Wise is a native of Smithfield in southeastern Virginia. He first got interested in mineralogy as an undergraduate at the University of Virginia, when rock-hunting trips to central Virginia and North Carolina strengthened his interest in pegmatites. He obtained his doctorate from the University of Manitoba in Canada in 1987 and joined the Smithsonian National Museum of Natural History, Department of Mineral Sciences, Washington D. C. one year later as a geologist-mineralogist. His published research interests have covered the Appalachian mountains of the eastern United States, Southern California, Canada and Colorado to study pegmatites and their minerals, as well as the alpine beryl-bearing veins of North Carolina. He has been active for many years in providing geologic training to earth science teachers and graduate students through various Smithsonian programs.

Gary L. Zito received his B. S. in Geology and Chemistry from the University of Colorado, Boulder. After starting out with Barringer Laboratories as an Analytical Chemist of Mine Ore and Effluents, he finished his career after 25 years as the Vice President of Barringer Laboratories. Currently he is the Electron Microscope Laboratory Manager, Department of Metallurgical and Materials Engineering at the Colorado School of Mines, a position he has had for 12 years. Gary has been an active collector of Colorado minerals for more than thirty years.

Amazonite and cleavelandite,
Keyhole vug 1986, Crystal Peak.
Collector's Edge Minerals, Inc.
specimen and photo.



George H. Weed (left) and James D. Endicott digging
amazonite at Crystal Peak, circa 1912. D. B. Sterrett photo.

