

# THE E. E. FOORD MEMORIAL SYMPOSIUM ON NYF GRANITIC PEGMATITES

## *PROGRAM and ABSTRACTS*

September 11 and 12, 1999

Ricketson Auditorium  
Denver Museum of Natural History  
2001 Colorado Boulevard  
Denver, Colorado 80205, U.S.A.

*Held in association with and sponsored by:*

The Denver Museum of Natural History, The Canadian Mineralogist, Mineralogical Association of Canada, Rochester Mineralogical Symposium, Harvard University Mineralogical Museum, Friends of Mineralogy – Colorado Chapter, The Pegmatite Interest Group (PIGS), and

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**SATURDAY, SEPTEMBER 11, 1999**

- 08:00–08:45 *Registration, Lobby of Ricketson Auditorium*
- 08:45–09:00 **William B. Simmons**  
*Welcome and Introduction*
- 09:00–09:50 **Petr Černý\* and Johan Kjellman**  
*The NYF Family of Granitic Pegmatites: Simplistic Past, Fluid Present, Reformed Future*
- 09:50–10:10 **Victor Ye. Zagorsky\*, Vladimir M. Makagon and Boris M. Shmakin**  
*The Systematics of Granitic Pegmatites*
- 10:10–10:40 *Coffee Break*
- 10:40–11:00 **Michael Wise**  
*Characterization and Classification of NYF-Type Pegmatites*
- 11:00–11:20 **Robert F. Martin**  
*Petrogenetic Considerations: A-Type Granites, NYF Granitic Pegmatites, and Beyond...*
- 11:20–11:40 **Federico Pezzotta\*, Valeria Diella and Alessandro Guastoni**  
*Sc–Y–REE Minerals and Evolution of Mirolitic Cavities in the NYF Pegmatites in the Western Southern Alps, Italy*
- 11:40–12:00 **Carlo Maria Gramaccioli\*, Valeria Diella and Francesco Demartin**  
*An Example of the Role of Complexes in the Geochemistry of Transition Elements in Pegmatites: the Formation of Scandium Minerals*
- 12:00–13:30 *Lunch*
- 13:30–13:50 **Carlo Aurisicchio\*, Caterina De Vito, Vincenzo Ferrini, Alessandro Guastoni and Federico Pezzotta**  
*Ti–Nb–Ta–Y–REE Oxides in the NYF Pegmatites of Baveno and Cuasso al Monte, Southern Alps, Italy*
- 13:50–14:10 **František Čech, Rodney C. Ewing, Gregory R. Lumpkin and Milan Novák\***  
*Nb–Ta–Ti–REE Oxides from NYF Granitic Pegmatites in the Třebíč Durbachite Massif, Czech Republic*
- 14:10–14:30 **Vladimir M. Makagon, Boris M. Shmakin\* and Victor Ye. Zagorsky**  
*Some Features of Mineral Compositions in Granitic Pegmatites of the Rare-Metal – Rare-Earth Formation, Russia*
- 14:30–14:50 **Carl A. Francis\*, David E. Lange and Ronald C. Peterson**  
*Rare-Element Mineralogy of the J.C. Gole Pegmatite, Murchison Township, Madawaska District, Ontario*

- 14:50–15:20 *Coffee Break*
- 15:20–15:40 **Milan Novák\***, **Petr Černý** and **Julie B. Selway**  
*The Zinnwaldite – Masutomilite – Elbaite Granitic Pegmatite from the Třebíč Durbachite Massif at Kracovice: A Complex Pegmatite Related to the NYF Family*
- 15:40–16:00 **Michael A. Menzies**  
*Granitic Pegmatites of the Sawtooth Batholith, Idaho*
- 16:00–16:20 **Carl A. Francis\*** and **David E. Lange**  
*Baringer Hill, Llano County, Texas: a Classic NYF Pegmatite*
- 16:20–16:40 **T. Scott Ercit**  
*North versus South: NYF Pegmatites in the Grenville Province of the Canadian Shield*
- 16:40–17:00 **Lance E. Kearns**  
*The Morefield Pegmatite, Amelia County, Virginia*
- 18:00–19:00 *Social Hour*
- 19:00 *Banquet and Tribute to E. E. Foord*

### SUNDAY, SEPTEMBER 12, 1999

- 08:30–08:50 **Bernard H. W. S. de Jong**  
*Alkali Mixtures in Glasses and Aqueous Solutions*
- 08:50–09:10 **Joseph M. Evensen\*** and **David London**  
*Beryllium Budgets in Granitic Magmas: Consequences of Early Cordierite for Late Beryl*
- 09:10–09:30 **Igor S. Peretyazhko**, **Victor Ye. Zagorsky\***, **Vsevolod Yu. Prokof'ev**  
and **Sergey Z. Smirnov**  
*Boric Acid as the Most Typical Component of Fluid Inclusions in Minerals from Tourmaline-Bearing and Topaz–Beryl Mirolitic Pegmatites*
- 09:30–09:50 **David London**  
*Melt Boundary-Layers and the Growth of Pegmatitic Textures*
- 09:50–10:10 **Daniel E. Kile\*** and **Dennis D. Eberl**  
*Crystal-Growth Mechanisms in Mirolitic Cavities in the Lake George Ring Complex and Vicinity, Colorado*
- 10:10–10:40 *Coffee Break*

- 10:40–11:00 **T. Scott Ercit\* and Lee A. Groat**  
*The O'Grady Aplite–Pegmatite Complex: a Mixed NYF–LCT Pegmatite Group with Elbaite-Bearing Pocket Pegmatites*
- 11:00–11:20 **Harvey M. Buck\*, Petr Černý and Frank C. Hawthorne**  
*The Shatford Lake Pegmatite Group, Southeastern Manitoba: NYF or Not?*
- 11:20–11:40 **Johan Kjellman\*, Petr Černý and Sten-Anders Smeds**  
*Diversified NYF Pegmatite Populations of the Swedish Proterozoic: Outline of a Comparative Study*
- 11:40–12:00 **Daniel E. Kile\* and Eugene E. Foord**  
*Optical Properties and Composition of Micas from the Pikes Peak Batholith and their Correlation with Pegmatite Evolution*
- 12:00–13:30 *Lunch*
- 13:30–13:50 **Alexander U. Falster\*, William B. Simmons, Karen L. Webber and Thomas Buchholz**  
*The Wausau Syenite Complex, Marathon County, Wisconsin: Origin, Geochemistry, and Mineralogy of a Mid-Proterozoic Anorogenic Intrusive Complex and its Pegmatites*
- 13:50–14:10 **William B. Simmons\*, Karen L. Webber and Alexander U. Falster**  
*NYF Pegmatites of the South Platte District, Colorado*
- 14:10–14:30 **Karen L. Webber\*, William B. Simmons and Alexander U. Falster**  
*Biotope as a Tectonic Discriminant for Anorogenic and Orogenic Pegmatites*
- 14:30–16:40 *Coffee Break / Poster Session*
- Poster 1 **Michael Wise**  
*Characterization and Classification of NYF-Type Pegmatites*
- Poster 2 **Boris M. Shmakin\*, Vladimir M. Makagon, Victor Ye. Zagorsky and Igor S. Peretyazhko**  
*On the Extreme Concentration of Some Minor Elements in Granitic Pegmatites*
- Poster 3 **Jack A. Murphy**  
*Colorado Pegmatites: Map and Database*
- Poster 4 **Mohammed Lahlafi, Michel Pichavant and Jean-Louis Robert\***  
*Role of Micas in the Concentration of Light Elements (Li, Be and F) in Crustal Granites: an Experimental and Crystal-Chemical Study*
- Poster 5 **Cathleen Brown**  
*Mineralogy of NYF Pegmatites*

- Poster 6     **Sarah L. Hanson\***, **William B. Simmons**, **Karen L. Webber**,  
**Alexander U. Falster** and **Thomas Buchholz**  
*Trace-Element Chemistry of Micas in "NYF" and "NY" Pegmatites*
- Poster 7     **James W. Nizamoff\***, **Alexander U. Falster**, **William B. Simmons** and  
**Karen L. Webber**  
*Phosphate Mineralogy of NYF-, LCT-, and Mixed-Type Granitic Pegmatites*
- Poster 8     **Mark I. Jacobson**  
*Zircon, Variety Cyrtolite: a Review*
- Poster 9     **Igor S. Peretyazhko** and **Victor Ye. Zagorsky\***  
*Composition and Structural State of Potassium Feldspars from Miarolitic Pegmatites*
- Poster 10    **Giulio Morteani\*** and **Christine Preinfalk**  
*Geochemical Evaluation of the Degree of Differentiation and Economic Potential of the Pegmatites of the Eastern Brazilian Pegmatite Province*
- Poster 11    **Stanley L. Korzeb\***, **Eugene E. Foord**, **Frederick E. Lichte** and  
**Joan J. Fitzpatrick**  
*The Evolution and Paragenesis of Uranium Minerals from the Palermo No. 1 Granitic Pegmatite, New Hampshire*
- Poster 12    **Akane Sugimoto**, **Mitsuyoshi Kimata\*** and **Masahiro Shimizu**  
*REE-bearing Minerals in Ohro Granitic Pegmatite, Japanese Island Arc: Crystallization of Ortho- and Pyrosilicates Subsequent to Bowen's Reaction Series*
- Poster 13    **Jeffrey E. Patterson\*** and **Frederick A. Cook**  
*Successful Application of Ground-Penetrating Radar in Exploration for Gem Tourmaline*
- 16:40–17:00 *Field Trip Meeting*

SATURDAY MORNING, SEPTEMBER 11, 1999

## THE NYF FAMILY OF GRANITIC PEGMATITES: SIMPLISTIC PAST, FLUID PRESENT, REFORMED FUTURE

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The modern petrogenetic classification of granitic pegmatites was initiated by Ginsburg *et al.* (1979), who introduced four classes defined by depth of formation: abyssal (deepest level, anatectic), muscovite (deep, kyanite gradient, anatectic or magmatic differentiates), rare-element (intermediate-depth magmatic differentiates) and miarolitic (shallow-seated magmatic differentiates). This classification was modified by Černý (1989), but further problems started plaguing some of its aspects with progress of experimental petrology (Černý 1998, 1999).

A new subdivision of the rare-element class was devised by Černý (1990, 1991); the LCT and NYF families were characterized by typical tendencies to accumulate rare alkalis and tantalum (Li, Cs, Ta) and niobium, yttrium plus REEs and fluorine (Nb, Y, F), respectively. The LCT pegmatites were found to be linked to (syn- to) late-orogenic (sub- to) peraluminous S-type granites, whereas the NYF pegmatites were assigned to fractionation of (post- to) anorogenic, sub- to metaluminous (to peralkaline) A-type granites.

Complications of this simple scheme soon became obvious: 1) the link between the geochemical signatures of the two families and their tectonic affiliation was found to be rather tenuous, and tectonic setting was discarded from the classification criteria (Černý 1991); 2) some LCT pegmatite populations were identified as related to dominantly I-type granites, and, most importantly, 3) the petrogenesis and petrochemistry of granites generating pegmatites with the NYF signature were recognized to be quite diversified (Černý 1991, 1992).

Thus, it is becoming increasingly difficult to retain all pegmatites with the NYF signature in a single category. We are dealing with at least: 1) the classic NYF systems generated by A-type granites mobilized by mantle-generated gabbroic intrusions from depleted middle to lower crust (*e.g.*, South Platte district in Colorado, Abborsetlet among others in Sweden); 2) pegmatites differentiated from I-type granites derived from relatively short-lived juvenile lithologies (such as the Shatford Lake group in Manitoba, Ytterby and associated pegmatites in Sweden), and 3) apparently rare peraluminous systems (Blomskog and Falun groups in Sweden).

Accumulation of Li, Cs and B in the most fractionated members of some NYF populations, discussed by Černý (1990), was brought to a sharper focus recently. A mixed NYF-LCT family was devised to accommodate such geochemical crossbreeds, interpreted as NYF populations contaminated by assimilation of undepleted metasediments by their plutonic parents, as derivatives of granitic magmas mobilized from only partially depleted crust, or by partial melting of heterogeneous depleted and undepleted lithologies (Černý 1991). In any case, the number of NYF pegmatite populations whose ultimate products of fractionation are somewhat enriched in typical LCT elements is increasing (*cf.* Ercit *et al.* 1999, Novák *et al.* 1999).

The concept of LCT and NYF families is viable, but it cannot survive in its original form. A subdivision of both families is becoming increasingly desirable along petrogenetic lines of the parent granites. Criticized as they often are, the categories of S-, I-, A- and M-type granites seem to be suitable for this purpose. The LCT family would become split into derivatives of S- and (low-percentage melting?) I-type granites, whereas the NYF family would consist of progenies of at least A- and (high-percentage melting?) I-type granites. This petrogenetic approach would necessarily cut across the "depth"-related rare-element and miarolitic classes.

The main and persistent problem faced by attempts to improve petrogenetic classification of granitic pegmatites, particularly in the NYF family, is the scarcity of thoroughly examined, well-defined granite + pegmatite systems!

## REFERENCES

- ČERNÝ, P. (1989): Exploration strategy and methods for pegmatite deposits of tantalum. *In* Lanthanides, Tantalum and Niobium (P. Möller, P. Černý & F. Saupé, eds.). Springer-Verlag, Berlin, Germany (274-302).
- \_\_\_\_\_ (1990): Distribution, affiliation and derivation of rare-element granitic pegmatites in the Canadian Shield. *Geol. Rundschau* **79**, 183-226.
- \_\_\_\_\_ (1991): Fertile granites of Precambrian rare-element pegmatite fields: is geochemistry controlled by tectonic setting or source lithologies? *Precambrian Res.* **51**, 429-468.
- \_\_\_\_\_ (1992): Geochemical and petrogenetic features of mineralization in rare-element granitic pegmatites in the light of current research. *Appl. Geochem.* **7**, 393-416.
- \_\_\_\_\_ (1998): Magmatic vs. metamorphic derivation of rare-element granitic pegmatites. *Krystalinikum* **24**, 7-36.
- \_\_\_\_\_ (1999): Constitution, petrology, affiliations and categories of miarolitic pegmatites. *Soc. Ital. Sci. Nat. Milano, Spec. Vol.* (in press).
- ERCIT, T.S., GROAT, L.A. & GAULT, R.A. (1999): Genesis of the O'Grady aplite-pegmatite complex, Canada's first gem elbaite deposit. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **24**, 36.
- GINSBURG, A.I., TIMOFEEV, I.N. & FELDMAN, L.G. (1979): *Principles of Geology of Granitic Pegmatites*. Nedra, Moscow, Russia (in Russ.).
- NOVÁK, M., ČERNÝ, P. & SELWAY, J.B. (1999): The zinnwaldite – masutomilite – elbaite granitic pegmatite from the Třebíč durbachite massif at Kracovice: a complex pegmatite related to the NYF family. *Can. Mineral.* **37**, 815-816.

## THE SYSTEMATICS OF GRANITIC PEGMATITES

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There are many classifications of granitic pegmatites, based on different criteria, *e.g.*, tectonic regime, geological environment, P–T conditions of crystallization, ore specialization, mineral and chemical composition and internal structure. Černý's classification (1982) of pegmatites is widely used in English-speaking countries. However, Russian geologists commonly use pegmatitic formations (corresponding to the classes of Černý) as defined by the relative depths of pegmatite crystallization (Ginzburg & Rodionov 1960), with additional subclassifications for each pegmatitic formation.

We propose a new classification for granitic pegmatites based on characteristic features of pegmatitic fields as a whole as well as characteristics of individual pegmatites. The classification is divided into three hierarchical levels of classification units: 1) pegmatitic formations and subformations, 2) geochemical (mineragenetic) evolutionary sequences, and 3) structural-paragenetic types.

Based on initial pressure of crystallization, pegmatitic formations and subformations are categorized as follows:

I. Low-Pressure Pegmatites

1. Crystal-bearing Formation

- a. Fluorite – rock crystal-bearing Subformation  
Miarolitic Facies Evolution Sequences: Fluorite-rock crystal
- b. Subrare-metal (with precious stones) Subformation  
Miarolitic Facies Evolution Sequences: Topaz–Beryl and Tourmaline



2. Rare-metal – Rare-earth Formation
    - Evolutionary Sequences: Nb–Y, F–Ta–Y and Be–*REE*
    - Miarolitic Facies Evolution Sequences: Amazonite
- II. Moderate-Pressure Pegmatites
1. Rare-metal Formation
    - a. Petalite Subformation
      - Evolutionary Sequences: Be, Li, P–Ta–Li, F–Ta–Li, and Cs–Ta–Li
    - b. Spodumene Subformation
      - Evolutionary Sequences: Ta–Be, Li, Ta–Sn–Li, P–Ta–Li, and Cs–Ta–Li
      - Miarolitic Facies Evolutionary Sequences for the Formation as a whole: Beryl (Morganite)–Tourmaline, Tourmaline–Kunzite and Phosphate–Tourmaline
- III. High-Pressure Pegmatites
1. Mica-bearing Formation
    - a. Rare-metal – Muscovite Subformation
      - Evolutionary Sequences: Columbite–Muscovite and Beryl–Muscovite
      - Miarolitic Facies Evolutionary Sequences: Beryl–Tourmaline
    - b. Muscovite Subformation
      - Evolutionary Sequences: Quartz–Muscovite and A-shape Muscovite
      - Miarolitic Facies Evolutionary Sequences: Apatite–Muscovite
  2. Feldspar Formation
    - Evolutionary Sequences: U–*REE* and Non-specialized

All pegmatitic formations and subformations are divided into several geochemical (mineragenetic) evolution sequences, each of them, in turn, unites several spatially and genetically connected structural-paragenetic types of pegmatites, from primitive (barren) up to the most evolved mineralized ones. Paragenetic types are distinguished by mineral composition and internal structure of pegmatites and exhibit specific features in different pegmatite fields.

Evolutionary sequences are named after the elements (or minerals of practical importance) that are the most characteristic of the highest evolved paragenetic type in each sequence. For example, the Nb–Y, F–Ta–Y and Be–*REE* evolutionary sequences are represented in the rare-metal – rare-earth pegmatitic formation, whereas the U–*REE* evolutionary sequence belongs to the high-pressure feldspar pegmatitic formation. Even initial barren structural-paragenetic types of pegmatites, belonging to different evolution sequences within the same pegmatitic formation (or subformation), are recognized by geochemical peculiarities of some rock-forming and accessory minerals.

Currently, the classification of pegmatites with mineralized cavities in other classification schemes is treated ambiguously. Typically, they are combined into a low-pressure miarolitic formation or class of pegmatites. However, miarolitic cavities also occur in the rare-metal and mica-bearing pegmatites as well. Thus, we propose the idea of *miarolitic facies* that are inherent to varying degrees to the majority of pegmatitic formations. The degree of miarolitic facies manifestation decreases gradually from the low-pressure pegmatites to high-pressure ones, up to its absence in the feldspar pegmatitic formation. It is evident from the concept of *miarolitic facies of pegmatites* that the term *miarolitic* must be used as an additional characteristic of any pegmatite containing mineralized cavities. Thus along with rock crystal-bearing miarolitic pegmatites there are subrare-metal, rare-metal – rare-earth, proper rare-metal, rare-metal – muscovite and proper muscovite miarolitic ones.

Mineragenetic evolution sequences of miarolitic pegmatites belonging to different formations are named after one or two main species of crystal raw material in the most evolved structure-paragenetic type of each sequence as shown in the classifications given above. For example, the fluorite-rock crystal evolution sequence is typical for the same name subformation of crystal-bearing pegmatitic formation and the topaz–beryl and the tourmaline evolution sequences are distinguished in the fields of subrare-metal miarolitic pegmatites. Structural-paragenetic types for each evolution sequence are recognized with regard to mineral composition of pegmatites as well as peculiarities and abundance of pockets.

The principles of systematics mentioned above are used as the basis for the five-volume treatise entitled “Granitic Pegmatites”. Three published volumes are devoted to mica-bearing, rare-metal and miarolitic pegmatites (Makrygina *et al.* 1990, Zagorsky *et al.* 1997, 1999).

## REFERENCES

- ČERNÝ, P. (1982): Anatomy and classification of granitic pegmatites. *In* Granitic Pegmatites in Science and Industry (P. Černý, ed.). *Mineral. Assoc. Can., Short-Course Handbook* 8, 405-461.
- GINZBURG, A.I. & RODIONOV, G.G. (1960): On depths of formation of granitic pegmatites. *Geologiya rudnykh mestorozhdeniy* 2(1), 45-54 (in Russ.).
- MAKRYGINA, V.A., MAKAGON, V.M., ZAGORSKI, V.YE. & SHMAKIN, B.M. (1990): *Granitic Pegmatites. 1. Mica-Bearing Pegmatites*. Nauka, Siberian Enterprise, Russian Academy of Sciences, Novosibirsk, Russia (in Russ.).
- ZAGORSKI, V.YE., MAKAGON, V.M., SHMAKIN, B.M., MAKRYGINA, V.A. & KUZNETSOVA, L.G. (1997): *Granitic Pegmatites. 2. Rare-Metal Pegmatites*. Nauka, Siberian Enterprise, Russian Academy of Sciences, Novosibirsk, Russia (in Russ.).
- \_\_\_\_\_, PERETYAZHKO, I.S. & SHMAKIN, B.M. (1999): *Granitic Pegmatites. 3. Mirolitic Pegmatites*. Nauka, Siberian Enterprise, Russian Academy of Sciences, Novosibirsk, Russia (in Russ.).

## CHARACTERIZATION AND CLASSIFICATION OF NYF-TYPE PEGMATITES

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Granitic pegmatites that carry accessory Nb, Ti, Y, REE, Zr, Be, U, Th and F minerals comprise one of two major subdivisions of pegmatite, LCT and NYF. Compared to their LCT counterparts, which are enriched in Li, Rb, Cs, Be, Ga, Sn, Ta>Nb, (B, P, and F), NYF-type pegmatites are generally considered to be uncommon and show restricted rare-element fractionation, with limited variability in mineralogy. An in-depth survey of the published literature now reveals a greater diversity of NYF-type pegmatites than was previously known.

The 40 pegmatite localities to formulate this classification are related to predominantly A-type granitic intrusions covering a broad range of geological ages. They are typically post-tectonic to anorogenic plutons emplaced at shallow levels into non-compressional environments, in continental rift-zones or in oceanic basins. These A-type granites commonly are mirolitic, with elevated Nb, Y, and F contents. The principal division proposed here separates NYF pegmatites into three groups, peralkaline, metaluminous and peraluminous, based on the alumina saturation of the parent granite. Within each group, different types of pegmatite are distinguished according to characteristic mineralogical and geochemical features (Table 1).

NYF pegmatites related to peralkaline granites fall into two types characterized by the presence of (1) fayalite or (2) sodic to calcic amphiboles. Fayalite-type pegmatites probably represent the least evolved members of the NYF association, having a relatively simple association of minerals, the oxides of Fe and Ti representing the most significant accessory minerals. The amphibole-bearing type appears to be enriched in Na, Fe, Zr, F ( $\pm$  Ti, REE, Nb) and is mineralogically more diverse than fayalite-type pegmatites.

Allanite-type pegmatites, typically affiliated with metaluminous granites, are enriched in Y and REEs. Mineralogical differences have been observed between (1) the allanite subtype, enriched in LREE ( $\pm$  Ti, Zr, F), (2) the euxenite subtype, characterized by Nb>Ta, Ti, Zr, Y, P, LREE to HREE minerals, and (3) the gadolinite subtype, with Be, Y + HREE, Nb>Ta, Ti, Zr, P, and F.

Mildly peraluminous A-type granites may generate pegmatites with geochemical signatures similar to the LCT association. They are characterized by having elevated Be, Li, B and F contents, and may represent examples of extremely fractionated NYF pegmatites. Beryl, beryl-tourmaline and beryl-topaz subtypes of the beryl-type pegmatites contain high levels of Be, B and F, with subordinate Li, Nb and Sn mineralization. Pegmatites of the beryl-tourmaline subtype host elbaite  $\pm$  subordinate zinnwaldite to ferroan lepidolite, and are associated with pegmatites hosting topaz, fluorite, amazonite and REE minerals. The phenakite type is proposed to designate pegmatites in which most of the Be is typically contained in primary phenakite. Pegmatites of the topaz and fluorite types both show high concentrations of F, but may contain only minor to sparse rare-element mineralization.

**Table 1. Classification of NYF-type Pegmatites**

<i>PEGMATITE TYPE</i>		<i>PEGMATITE SUBTYPE</i>	<i>ASSOCIATED ACCESSORY</i>	
MINERALS	GEOCHEMICAL SIGNATURE		EXAMPLES	
<b>PERALKALINE</b>				
Fayalite		Magnetite, (Hematite, Ilmenite, Epidote, Titanite, Allanite)	Fe, (Ti, Ca)	Velence Mtns., Hungary Sawtooth batholith, Idaho Rockport, Massachusetts Strzegom-Sobotka, Poland Mt. Perdosu, Sardinia
Amphibole	Aegirine-Arfvedsonite	Fluorite, Allanite, Zircon, (Columbite, Fergusonite, Monazite, Pyrochlore)	Na, Fe, Zr, F ( $\pm$ Ti, REE, Nb)	Zomba, Malawi Strange Lake Complex, Quebec Stettin Complex, Wisconsin
	Riebeckite	Zircon, Fluorite, (Magnetite, Rutile, Ilmenite, Monazite, Columbite, Pyrochlore)		Mt. Rosa [St Peter's Dome], Colorado Quincy, Massachusetts Hurricane Mtn., New Hampshire Granite Peak, Franklin Mtns., Texas
	Allanite	Zircon, (Beryl, Apatite)		Pacoima Canyon, California
<b>METALUMINOUS</b>				
Allanite	Allanite	(Fluorite, Magnetite, Monazite, Zircon, Ilmenite, Rutile)	LREE ( $\pm$ Ti, Zr, F)	South Platte (south), Colorado Red Rock, Nevada Gold Butte, Clark Co., Nevada Amherst Co., Virginia
	Euxenite ( <i>Polycrase</i> )	Monazite, Zircon, Xenotime, Ilmenite, (Fergusonite, Aeschnyite, Rutile, Tourmaline)	LREE $\rightarrow$ HREE Nb>Ta, Ti, Zr, Y, P,	Trout Creek, Colorado Gloserheia, Norway West Portland, Quebec Evans-Lou, Quebec
	Gadolinite	Fergusonite, Xenotime, Samarskite Zircon, (Euxenite, Ilmenite, Rutile Magnetite, Fluorite)	Y + HREE, Be, Nb>Ta, Ti, Zr, P, (F)	South Platte (north), Colorado Pyörönmaa, Finland Ytterby, Sweden Barringer Hill, Texas Clear Creek, Texas
<b>PERALUMINOUS</b>				
Beryl	Beryl	Zinnwaldite, Spessartine, Fluorite Hematite, Muscovite	Be (Li, F)	Mt. Antero, Colorado Sawtooth batholith, Idaho
	Tourmaline	Topaz, Lepidolite, Fluorite, Danburite, Hambergite	Be, B, Li, F	Leduc, Quebec Rangkul, Pamirs, Tadjikistan Borshchovochny, Transbaikalia, USSR Malkhanski, Transbaikalia, USSR
	Topaz	Muscovite, Monazite, Euxenite, Fluorite, Columbite, Zinnwaldite, (Phenakite, Lepidolite, Schorl, Zircon, Allanite, Cassiterite)	Be, F ( $\pm$ B, Li)	Luumäki, Finland Klein Spitzkopje, Namibia Tordal, Norway Volhynia, Ukraine Morefield-Rutherford-Herbb#2,
Virginia				
Phenakite		Muscovite, Fluorite, (Topaz, Beryl, Bertrandite, Ilmenite, Zircon)	Be, F	Mt. Antero, Colorado Pikes Peak, Colorado South Baldface Mtn., New Hampshire Nine Mile pluton, Wisconsin
Topaz		Zinnwaldite, Muscovite, Fluorite, Hematite, Spessartine, Cassiterite	F, (Be, Li, Sn)	Mt. Antero, Colorado Sawtooth batholith, Idaho
Fluorite		Calcite, Hematite	F	Khantau massif, Kazakhstan

## PETROGENETIC CONSIDERATIONS: A-TYPE GRANITES, NYF GRANITIC PEGMATITES, AND BEYOND.....

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### THEME 1: METASOMATIC "GROUND-PREPARATION" OF NORMAL CONTINENTAL CRUST

The regional anatexis of normal continental crust does not yield a melt of A-type character. Rather, such a specialized type of felsic rock requires a kind of "ground preparation" in which a fluid phase issued from the mantle rises in the lower crust and "fertilizes" it. The tectonic context is deemed important in this regard: A-type granites form in regions of tectonic quiescence subject to extension and underplating of crust by mantle-derived magmas. The alkaline fluid accompanies and, in fact, precedes the invasion of mafic magma from below. Melting thus involves a metasomatized, mineralogically transformed middle to lower crust, and the partial melt can be expected to show the major-element patterns of enrichment and depletion typical of an A-type granite.

The origin of A-type granites is but one facet of the general problem of the origin of voluminous felsic magmas in rift-related suites. Where the metasomatic "ground preparation" has been more thorough, or where it has involved a fluid phase that is more strongly alkaline, or poorer in silica, or richer in CO<sub>2</sub> than the norm, the partial melt formed in the crust can in fact be silica-undersaturated. Thus A-type felsic magmas could be trachytic or phonolitic in bulk composition.

The above scenario is very simplistic in a way, but in fact very complicated because the metasomatic fertilization involves a step of open-system behavior prior to melting. Thus the scene is set for regional geochemical differences and departures from the predictability inherent in crystal-melt equilibria. For example, in some areas, A-type granites could be fluorine-rich, and in others, much less so because of the lack of fluorine enrichment at the source. Relative enrichment or depletion in minor elements will depend on the composition of the incoming fluid phase affecting the lower crust, and on pre-existing regional geochemical anomalies in the lower crust or upper mantle.

### THEME 2: FRACTIONATION OF A MANTLE COMPONENT AND MIXING

Once ponded in the extended lower crust, the underplating basic magma can be expected to fractionate efficiently, to produce a series of derivative liquids of increasing "differentiation index". In cases where the incoming mantle-derived mafic melt is slightly alkaline, as is typical in rifts, the derivative melts will become increasingly alkaline simply "by default", by the fractionation of normal rock-forming minerals. There will result small batches of A-type felsic melt formed by the fractional crystallization of a mafic magma in a closed system, much like Norman Bowen envisaged.

Here one must consider another source of serious complications. Batches of A-type felsic melt formed by anatexis of "fertilized" lower crust can be expected to mingle and mix with batches of A-type felsic melt formed by fractional crystallization. The resulting A-type magmas have geochemical patterns indicative of a mixed sources. Radiogenic and stable isotopes provide the only hope of sorting out the contributions of crust and mantle sources. In view of the heterogeneities expected in variably metasomatized crust, the challenge of quantifying the roles of crust and mantle may be beyond the realm of reality.

### THEME 3: NYF-ENRICHED GRANITES AND RELATED PEGMATITES

Geochemical discriminants routinely used to recognize A-type granites involve Nb, Y and F. One must recognize that the wave of alkali metasomatism ("fertilization") that affected the crust prior to melting brought in not only alkalis, but niobium, yttrium, fluorine, and a host of other generally incompatible constituents that were mobilized in an alkaline fluid medium. In view of the very complicated scenario briefly described above, is there any point to the pigeon-hole approach of classifying A-type granites and their pegmatitic progeny, the NYF-type pegmatites?

## THEME 4: A-TYPE GRANITES OF PERALUMINOUS CHARACTER

Granitic plutons of A-type may be metaluminous, peralkaline or peraluminous. A real challenge here is raised by the latter group. How does one differentiate between peraluminous granites of classic S type in the calc-alkaline association from peraluminous granites of A type? Although based on limited results, it seems that the peraluminous granites of A type do not represent melt compositions, but rather they crystallized at the expense of normal metaluminous granitic magma that became peraluminous by loss of alkalis through degassing. The degassing step requires that the magma be close to saturation with respect to an aqueous fluid, and also close to the surface.

## THEME 5: A-TYPE GRANITES OF PERALKALINE CHARACTER

An A-type granitic magma that is marginally peralkaline at the start of its ascent from a source area is expected to become more and more strongly alkaline as it rises owing to the removal of quartz and the feldspars as a fractionating assemblage. At the same time, the magma is crystallizing an amphibole (richterite → arfvedsonite) or pyroxene (aegirine-augite → aegirine) or both, the composition of which effectively reaches that of the iron end-members in the most evolved members of the plutonic suite. Solid solution of the arfvedsonite toward fluoro-ferroleakeite (Li-Fe<sup>3+</sup>-F enrichment) is a distinct possibility toward the end stages of crystallization.

What happens next in these systems of peralkaline A-type granite and peralkaline NYF-type pegmatite does not quite follow the traditional rules of fractionation in igneous systems as enunciated by Norman Bowen. As the system becomes more and more strongly alkaline, and iron-enriched, quartz and feldspars become the liquidus phases, and the residual magma becomes progressively more and more mafic. This is the hallmark of agpaitic and hyperagpaitic rocks. Extreme fractionation of the last batches of magma causes a progressive departure from “petrogeny’s residua” system. The melt becomes progressively enriched in alkalis, iron, titanium, zirconium, and the volatile constituents, and relatively poor in silica. The final liquid crystallizes dominantly an arfvedsonite – fluoro-ferroleakeite solid solution which encloses aegirine, albite, and a host of accessory phases. The assemblage is “lindinositic”, and associated with extreme enrichment in the incompatible elements. In the absence of aluminum, water-soluble rock-forming alkali silicate minerals can perhaps be expected, just as in the classic examples of hyperagpaitic silica-undersaturated suites at Khibina and Lovozero, Kola Peninsula, Russia.

## Sc–Y–REE MINERALS AND EVOLUTION OF MIAROLITIC CAVITIES IN THE NYF PEGMATITES IN THE WESTERN SOUTHERN ALPS, ITALY

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Postorogenic Permian plutons of K-rich alkaline affinity are present in the western part of the South Alpine basement. In these intrusive bodies, and in particular in the Baveno and Cuasso al Monte miarolitic granites, NYF pegmatites occur with abundant F, REE, Y, Sc, Be, B, Nb, Mo, and W minerals. Previous investigations (Pezzotta *et al.* 1999) indicated variable concentrations of REE, Y, Fe, and Ca in gadolinite-group minerals hosted in primitive pegmatites and in moderately to highly evolved pockets. In the present study, we report the results of further chemical (electron-microprobe data) and paragenetic investigations of Be, Y, Sc, and REE silicates.

At Baveno, among the Sc-bearing minerals, beryl is the most primitive (up to 0.30 wt% Sc<sub>2</sub>O<sub>3</sub> at the rim of the crystals). Beryl occurs as sprays of blue prisms at the contact between massive aplite and white granite, and as small grains disseminated in a granophyric aplite. Bazzite, associated with abundant “zinnwaldite”, is a late-stage

mineral in pockets. The analyses of the cotype specimen, and of other crystals found recently, show high contents of Fe (from 5.0 to 7.9 wt%  $\text{Fe}_2\text{O}_3$ ) and Na (up to 2.5 wt%  $\text{Na}_2\text{O}$ ). Thortveitite occurs together with jervisite, cascandite and, locally, calcio-ancylite-(Ce), mainly in a pegmatitic facies characterized by abundant sky-blue albite in a white granophyric facies. The crystals occur as tiny isolated prisms or radiating aggregates white to deep blue in color. The crystals are strongly and irregularly zoned, with variable contents of Sc (from 31.0 to 44.5 wt%  $\text{Sc}_2\text{O}_3$ ), Y (from 5.9 up to 14.9 wt%  $\text{Y}_2\text{O}_3$ ), *HREE* ( $\text{Dy}_2\text{O}_3$  up to 2.5 wt%), Fe (from 0.8 to 3.5 wt%  $\text{Fe}_2\text{O}_3$ ) and Mn (up to 1.3 wt% MnO). The Zr content is very low (up to 0.3 wt%  $\text{ZrO}_2$ ). Bazzite, thortveitite, and the other associated minerals of Sc crystallized in miarolitic cavities at the same time or later, with respect to fluorite. Sc may also be present in babingtonite, concentrated at the rim of the crystals (*cf.* scandiobabingtonite: Orlandi *et al.* 1998). If babingtonite occurs, no other Sc-bearing mineral is present in the cavities.

At Cuasso al Monte, thortveitite occurs in pockets, together with "zinnwaldite" and a number of other accessory phases, including fluorite and hingganite-(Y), in a single outcrop of the pink granophyric granite. Crystals of thortveitite, white to pale blue in color, are normally covered by a thick overgrowth of a spongy white cryptocrystalline aggregate. This overgrowth is composed of a mixture of minerals, including Sc, Zr, Y and *HREE* silicates, not yet characterized. The thortveitite crystals are concentrically zoned. From the core to the rim, Sc varies from 43.8 to 29.3 wt%  $\text{Sc}_2\text{O}_3$ , Y, from 0.8 to 13.4 wt%  $\text{Y}_2\text{O}_3$ , Fe, from 6.2 to 2.3 wt%  $\text{Fe}_2\text{O}_3$ , and Mn, from 3.5 to 0.8 wt% MnO. The concentration of the *HREE*, as that of Y, strongly increases from the core to the rim.

In the NYF miarolitic pegmatites at Baveno and Cuasso al Monte, the complex chemical variations in the crystals studied, as illustrated by the Y/Dy and Sc/Yb values, are indicative of a multistage evolution. The presence of fluoride complexes in hydrothermal fluids could play a major role in the enrichment of Y and Sc at the latest stages of crystallization of the pockets (Gramaccioli *et al.* 1999). In the Baveno and Cuasso al Monte pegmatites, minerals of Sc (bazzite, cascandite, jervisite, scandiobabingtonite, thortveitite), as well as the portions of the Y-bearing minerals richest in Y [gadolinite-(Y), hingganite-(Y)], crystallize at late-stage conditions, during or after the crystallization of fluorite and fluorine-rich micas ("zinnwaldite"). A model to explain this paragenesis could consider a dramatic decrease in the activity of fluorine in the fluids due to the crystallization of F-rich minerals, causing the disruption of fluoride complexes and allowing the nucleation of rare *REE*-Y-Sc minerals. In agreement with this model, at Baveno, early in the evolution of the aplite-pegmatite systems and before the crystallization of F-bearing minerals, beryl (with only minor amounts of Sc) crystallized, but not bazzite. In the pockets of pegmatites at Baveno, the intimate association of thortveitite, cascandite and jervisite crystals seems to indicate a contemporary crystallization of these Sc minerals. In this case, the significant differences of the Y/Dy and Sc/Yb values among these Sc minerals could be explained by considering crystallochemical factors.

In the Baveno and Cuasso al Monte NYF pegmatites, the differences in the Sc- and Y-rich minerals may be related to a different evolution of the latest stages of crystallization in the miarolitic cavities, which include at Cuasso al Monte open-system conditions, as pointed out by Pezzotta *et al.* (1999). Nevertheless, differences in the geochemistry of the parental silicate melts, as well as differences in the level of exposure of the plutons, should not be excluded.

#### REFERENCES

- GRAMACCIOLI, C.M., DIELLA, V. & DEMARTIN, F. (1999): An example of the role of complexes in the geochemistry of transition elements in pegmatites: the formation of scandium minerals. *Can. Mineral.* **37**, 807-808.
- ORLANDI, P., PASERO, M. & VEZZALINI, G. (1998): Scandiobabingtonite, a new mineral from the Baveno pegmatite, Piedmont, Italy. *Am. Mineral.* **83**, 1330-1334.
- PEZZOTTA, F., DIELLA, V. & GUASTONI, A. (1999): Chemical and paragenetic data on gadolinite-group minerals from Baveno and Cuasso al Monte, southern Alps, Italy. *Am. Mineral.* **84**, 782-789.

## AN EXAMPLE OF THE ROLE OF COMPLEXES IN THE GEOCHEMISTRY OF TRANSITION ELEMENTS IN PEGMATITES: THE FORMATION OF SCANDIUM MINERALS

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Scandium and yttrium are often considered together with “true” rare-earth elements (*REE*) or lanthanides in view of the similarity in electron configuration. Owing to an almost regular decrease of the ionic radii of the *REEs* because of the “lanthanide contraction”, the middle-to-heavy *REE* show a close chemical similarity to yttrium, and the heaviest ones are reasonably close to scandium. Therefore, all yttrium minerals contain notable amounts of the middle-to-heavy *REE*; in addition, thortveitite  $\text{Sc}_2\text{Si}_2\text{O}_7$  may contain non-negligible amounts of the heaviest *REE*. Instead of following the *REE*, scandium may also behave like iron, aluminum, or magnesium. In these cases, explanations based only on ionic radii are not satisfactory, and more detailed considerations are necessary. For instance, it has been noticed that fluoride complexes could be important in the migration of scandium in hydrothermal veins, as indicated by the nearly ubiquitous presence of minerals containing fluorine, such as topaz, in scandium-bearing veins. In some carbonatites, a complexing mechanism may also have been important in controlling the distribution of scandium. Recently, Montero *et al.* (1998) considered the formation and breakdown of complexes with fluorine and other ligands to be essential in the enrichment of the *REE* and high-field-strength elements (HFSE), and in the deposition of their minerals in a peralkaline gneissic rocks in northwestern Spain.

Very stable complexes of the *REE* and allied elements have long been known; their stability usually follows the trend in the ionic radius, so that chemical properties have too often been assumed to depend on the ionic radius almost exclusively. Although the *4f* electrons present in the *REE* are usually considered not to be important in the formation of chemical bonds, these electrons should lead to some geochemical differentiation with respect to yttrium and scandium, especially in the presence of complex-forming ligands. In particular, the fluoride complexes of yttrium are more stable than those of any *REE*, although the radius of  $\text{Y}^{3+}$  is notably greater than that of the heaviest *REE*. On these grounds, the exclusive role of the ionic radius would lead to an enrichment (or *vice versa*) of the heavy *REE* series (especially ytterbium) in minerals, together with scandium, but not with yttrium. The effect of complexes would be instead that of concentrating the heaviest *REE* together with yttrium and scandium (Gramaccioli *et al.* 1999).

Upon examination of the available physical and chemical data concerning some fluoride complexes of scandium, zirconium, *etc.*, it is evident that chemical equilibria are strongly affected even by a very low concentration of the ligand in the depositing solutions. For instance, the ratio  $[\text{Sc}^{3+}]/[\text{Yb}^{3+}]$  in a crystal at equilibrium can be shown to vary up to three orders of magnitude for  $[\text{F}^-] = 10^{-5}$  mol/L.

The formation of these rare minerals is the result of an increase in the activity of the constituent ions in the depositing solution. Such an increase could be caused by: 1) an increase in the concentration of the corresponding elements, or 2) the disruption of complexes, due to a decrease in the activity of the ligands. Such a decrease may be a consequence of the increased activity of other elements as competitors in forming corresponding complexes (especially Zr, Nb-Ta, Al, Ti, and possibly B), or the deposition of other minerals containing such ligands. For instance, in the case of fluoride complexes, these minerals can be fluorite, topaz, *etc.*, or fluorine-rich micas.

If fluorite or other fluorine-rich minerals are deposited together with thortveitite after deposition of these minerals, the activity of the fluoride ion in the solution will be consequently reduced. After such a process, the ratio

$[\text{Sc}^{3+}]/[\text{Yb}^{3+}]$  in the crystals of thortveitite at equilibrium should *increase* by several orders of magnitude, thereby leading to the deposition of a mineral much enriched in scandium. Similar conclusions can also be deduced for the ratio  $[\text{Sc}^{3+}]/[\text{Al}^{3+}]$ , with the consequent formation of species such as bazzite  $\text{Be}_3\text{Sc}_2\text{Si}_6\text{O}_{18}$  instead of beryl. Similarly, although to a lesser extent, the disruption of fluoride complexes should also lead to an enrichment of the heaviest REE in the mineral, just as is commonly observed. Therefore, the enrichment in Yb of scandium minerals is *not only due to crystal-chemical constraints*.

On developing such concepts, one wonders whether the comparative frequency of complex oxides containing the REE, Ti, Nb-Ta, *etc.*, in granitic pegmatites is the result of the simultaneous increase of activity of all such elements in the medium of growth as a result of the lowering of the activity of ligands such as fluorides, instead of the thermodynamic stability and crystal-chemical properties of such oxides. The same process at least partially accounts for the formation of REE- and hafnium-rich zircon in pegmatites, as it commonly accompanies the complex oxides.

The selectivity of the crystal structure of thortveitite accounts at least in part for a high concentration of the heaviest REE such as ytterbium, and for a notably *low* concentration of gadolinium, dysprosium, or other middle-to-heavy REE. However, in nature, *yttrium does not seem to have been subject to extensive impoverishment*, although its ionic radius is close to that of the middle-to-heavy REE and notably different from those of ytterbium or scandium. For instance, in a series of examples we have examined, the ratio  $\text{Y}/\text{Y}_{\text{theor}}$  (Gramaccioli *et al.* 1999) is close to the corresponding values for most yttrium minerals. This “anomaly” of yttrium is in close agreement with the above chemical arguments.

#### REFERENCES

- GRAMACCIOLI, C.M., DIELLA, V. & DEMARTIN, F. (1999): The role of fluoride complexes in REE geochemistry and the importance of 4f electrons: some examples in minerals. *Eur. J. Mineral.* (in press).
- MONTERO, P., FLOOR, P. & CORRETEGÉ, G. (1998): The accumulation of rare-earth and high-field-strength elements in peralkaline granitic rocks: the Galíñeiro orthogneissic complex, northwestern Spain. *Can. Mineral.* **36**, 683-700.



SATURDAY AFTERNOON, SEPTEMBER 11, 1999

**Ti-Nb-Ta-Y-REE OXIDES IN THE NYF PEGMATITES OF BAVENO AND CUASSO AL MONTE, SOUTHERN ALPS, ITALY**CARLO AURISICCHIO<sup>§</sup>, CATERINA DE VITO AND VINCENZO FERRINI*C.S. Equilibri Sperimentali in Minerali e Rocce, CNR, P.le A. Moro 5, I-00185 Roma, Italia*

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Ti-Nb-Ta-Y-REE oxides are accessory minerals in the NYF miarolitic pegmatites of the Baveno and Cuasso al Monte Permian granitic plutons, Southern Alps, Italy. Aurisicchio *et al.* (1998) reported on the Ti-Nb-Ta oxides from Baveno and documented the presence of metamict Y-rich and Ce-rich aeschynites. These oxides contain minor amounts of W and are Nb- and Ti-dominant at the B site.

Preliminary chemical (electron-microprobe analyses) and paragenetic data obtained from new samples of Ti-Nb-Ta-Y-REE oxides collected at Baveno and (for the first time) at Cuasso al Monte are reported here. At Baveno, these oxides are rather rare but widespread in the cavities of a white to pink granophyric facies of the granite, and in the aplitic portions of some aplite-pegmatite veins. The yellow-orange to brownish, prismatic to tabular crystals occur as single crystals or as small sprays. Typical associated minerals include "zinnwaldite", fluorite, gadolinite-group minerals, REE-carbonates and Sc minerals. In general, the crystals are covered by a thin crust of microcrystals of unidentified REE-carbonates. At Cuasso al Monte, Ti-Nb-Ta-Y-REE oxides are very rare and have been found only in a few samples in a granophyric pink-red granite, enriched in REE-carbonates and purple fluorite. The brownish yellow crystals, although generally smaller in size, are similar to those at Baveno.

Electron-microprobe analyses indicate complex chemical zonation in the oxides from Baveno. Yttrium is the dominant cation at the A site (up to 0.560 *apfu*). The heavy REE (with a marked abundance of Dy) are also abundant, and Th and U are present in variable amounts (both ranging from 0.012 to 0.151 *apfu*). Low analytical totals, related to increasing U and Th contents, can be explained by an increasing degree of metamictization of the crystals, associated with significant hydration. Structural data (Aurisicchio *et al.* 1998) confirm the metamict state of these crystals. At the B site, Ti prevails over Nb. Ta and W contents are highly variable (from 0.010 to 0.143 *apfu* Ta, and from 0.050 to 0.220 *apfu* W).

Samples from Cuasso al Monte exhibit strong concentric zonation. The compositions are similar to those of Baveno but show, at the A site, from core to rim, increasing contents of Th and U (Th > U) and decreasing values of Y + REE. The proportion of Fe, Mn and Ca shows a moderate rimward increase. Nb and Ti dominate at the B site, with local dominance of either Nb or Ti. Ta contents are very low, and W is present in lower concentrations than in the Baveno samples.

The triangular diagrams (Figs. 1a, b) show distinct fields for the Ti-Nb-Ta-Y-REE oxides from Baveno and Cuasso al Monte. Further structural studies are in progress for a complete classification of these minerals.

The complex compositions observed in the rare-element oxides in the NYF pegmatites of these two localities are indicative of a multistage process of hydrothermal crystallization, as reported by Pezzotta *et al.* (1999a, b). The differences in the chemical composition of the oxides from the two sites could be related to a difference in the chemical-physical conditions of pocket crystallization, or to geochemical differences in the parental magmas.

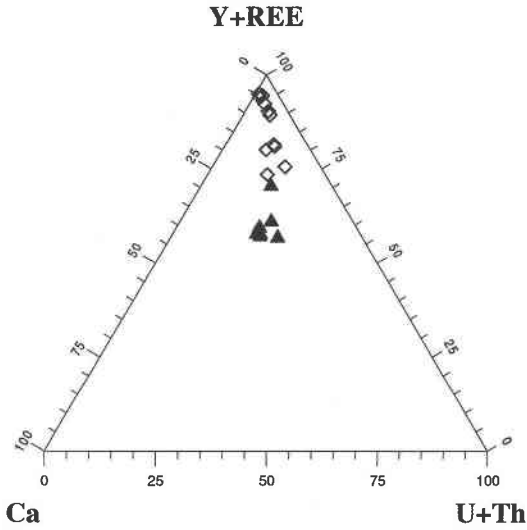


FIG. 1a. Triangular plot of the proportion of major A-site cations in complex oxides at Baveno (diamonds) and Cuasso al Monte (triangles).

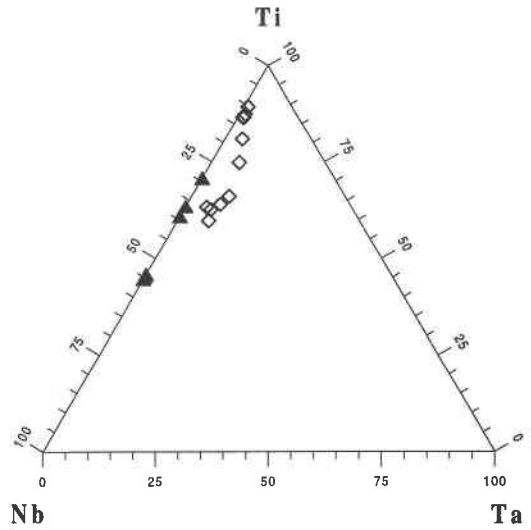


FIG. 1b. Triangular plot of the proportion of major B-site cations in complex oxides at Baveno (diamonds) and Cuasso al Monte (triangles).

#### REFERENCES

- AURISICCHIO, C., DE VITO, C., FERRINI, V. & ORLANDI, P. (1998): Complex Ti, Ta, Nb oxides from Baveno, Elba Island and Val Vigezzo (north of Italy). *Int. Mineral. Assoc., 17th Gen. Meeting (Toronto), Programme Abstr.*, A149.
- PEZZOTTA, F., DIELLA, V. & GUASTONI, A. (1999a): Chemical and paragenetic data on gadolinite-group minerals from Baveno and Cuasso al Monte, southern Alps, Italy. *Am. Mineral.* **84**, 782-789.
- \_\_\_\_\_, \_\_\_\_\_ & \_\_\_\_\_ (1999): Sc-Y-REE minerals and evolution of miarolitic cavities in the NYF pegmatites in the western Southern Aps, Italy. *Can. Mineral.* **37**, 805-806.

## Nb-Ta-Ti-REE OXIDES FROM NYF GRANITIC PEGMATITES IN THE TŘEBÍČ DURBACHITE MASSIF, CZECH REPUBLIC

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Durbachites, typical and widespread intrusive rocks of the Bohemian Massif, vary in composition from melanocratic granites and syenites to diorites and are characterized by high concentrations of *LILE* (K, Rb, Ba), radioactive elements (U, Th) and Mg, Cr, and Ni. They also have  $Ce_N/Yb_N$  in the range 13.6–16.0,  $(^{87}Sr/^{86}Sr)_{350} \approx 0.712$ , and are interpreted as a product of mixing of an enriched mantle-derived magma and crustal melt. The Třebíč durbachite massif (TDM) (about 340 Ma,  $0.85 < ASI < 0.93$ ,  $171 < K/Rb_{wt} < 133$ ,  $17.3 < Nb/Ta_{wt} < 8.3$ ) forms the largest (about 600 km<sup>2</sup>) body, probably sheet-like, to be emplaced in the high- to medium-grade metamorphic rocks of the Moldanubicum. The rocks are coarse-grained, porphyritic, locally foliated, and consist of orthoclase, biotite, oligoclase, quartz and actinolitic amphibole; accessory minerals include apatite, zircon, thorite, titanite and allanite. Within the TDM, granitic pegmatites are common only in two areas that are elongate E–W, the Třebíč–Vladislav district (TVD) and the Bochovice–Chlumek district (BCD).

Two types of pegmatite, distinct in internal structure and mineral assemblages, were distinguished (Čech 1957a): (i) simple homogeneous nests (Kfs + Pl + Qtz + Bt) with accessory allanite, and (ii) more evolved, symmetrically zoned dikes. The latter consist, from the contact inward, of a medium-grained granitic unit (Kfs + Pl + Qtz + Bt) locally transitional to the host coarse-grained durbachite, a subordinate graphic unit (Kfs + Qtz ± Bt), a coarse-grained unit (Kfs + Ab + Qtz) transitional to core-margin blocky K-feldspar (locally amazonite), and a quartz core. Medium- to coarse-grained albite locally occurs between the quartz core and blocky K-feldspar. Small pockets lined with crystals of amazonite, albite, quartz and very rare phenacite were found in the central part of dikes. Accessory minerals include: schorl, dravite, ilmenite, pseudorutile, titanite, Nb–Ta–Ti–REE oxides, niobian rutile, zircon and beryl (Čech 1957b).

Brown, yellow-brown, red-brown to black, anhedral to euhedral grains (<2 cm, usually about 5 mm) of Nb–Ta–Ti–REE oxides with a resinous luster commonly occur in blocky K-feldspar, closely associated with ilmenite, rare zircon and titanite. The grains are optically isotropic, with  $n > 1.8$ . The X-ray powder-diffraction patterns lack identifiable Bragg peaks, indicating a strong degree of metamictization. Electron-microprobe data were recalculated based on six atoms of oxygen; the atomic contents are close to the general formula  $AB_2O_6$ , with a slight excess of cations (3.02–3.16); the A:B ratio is very close to the stoichiometric value of 1:2. The A-site cations are characterized by high contents of Ca (0.21–0.38 *apfu*), which is the second most abundant cation after  $\Sigma Y + REE$ . The high variability in Y, *HREE* and *LREE* concentrations, with  $Y \gg HREE$  and  $LREE > HREE$ , and the highly variable U (0.03–0.18 *apfu*) and Th (0.02–0.09 *apfu*), with  $U > Th$ , except at Vladislav, are typical. The B-site cations commonly exhibit  $Ti \approx (Nb + Ta)$ , except the samples from Chlumek (1.34 Ti *apfu*) and Vladislav (0.84 Ti *apfu*, 0.94 Nb *apfu*). The  $Ta/(Ta + Nb)$  values are highly variable (0.15–0.58), high but variable in samples from Pozdátky (0.23–0.58), and low in other localities (0.15–0.21).

We used a canonical discrimination analysis (Ewing 1976) and a X-ray powder-diffraction study of heated samples (Ewing & Ehlmann 1975) to distinguish between euxenite- and aeschynite-group minerals. One sample from Pozdátky (POa) corresponds very well to aeschynite, and other samples (Pozdátky, Chlumek, Bochovice) are much closer to aeschynite than to euxenite in  $\text{TiO}_2$  and  $\text{Ce}_2\text{O}_3$ ; however, owing to high contents of CaO or  $\text{Ta}_2\text{O}_5$  (or both), these results are rather ambiguous. The mineral from Vladislav differs by its high Nb and  $\text{Th} > \text{U}$ . The X-ray powder-diffraction study of the samples heated in air at  $700^\circ\text{C}$  for 4 hours yielded aeschynite and pyrochlore (Pozdátky, Chlumek, Bochovice) or a very complicated pattern of euxenite, aeschynite and pyrochlore (Vladislav). On the basis of these findings and the chemical data, these minerals were tentatively determined as aeschynite-(Y) at Pozdátky, Chlumek, aeschynite-(Ce) at Bochovice, and euxenite-(Ce) at Vladislav.

The internal structure, mineral assemblages and abundance of accessory minerals indicate increasing degree of fractionation from east (Vladislav) to west (Pozdátky) in the TVD, and generally lower degree of fractionation in the BCD. This is also suggested by the presence of Be-bearing minerals and niobian rutile in the westernmost part of the TVD, but their absence in the BCD, and by elevated  $\text{Ta}/(\text{Ta} + \text{Nb})$  values in Nb-Ta-Ti-REE oxides from one of the westernmost localities of the TVD, Pozdátky.

Comparing the TDM pegmatites to the similar NYF pegmatites with F-poor mineral assemblages [*e.g.*, Trout Creek Pass, Colorado: Hanson *et al.* (1992), Arvogno, Vigizzo Valley, Italy: Albertini & Andersen (1989)], the Nb-Ta-Ti-REE oxides from pegmatites in the TDM differ significantly by their elevated Ca and *LREE* contents. The Nb-Ta-Ti-REE oxides from Colorado and other localities also have apparently lower  $\text{Ta}/(\text{Ta} + \text{Nb})$  values.

#### REFERENCES

- ALBERTINI, C. & ANDERSEN, T. (1989): Non-metamict orthorhombic  $\text{AB}_2\text{O}_6$  Y-Nb-Ta-Ti oxides from a pegmatite in Arvogno, Crana Valley (Toceno, Vigizzo Valley, northern Italy). *Rend. Soc. Ital. Mineral. Petrol.* **43**, 773-779.
- ČECH, F. (1957a): Contribution to understanding of pegmatites in the Třebíč-Velké Meziříčí massif. *Acta Mus. Moraviae, Sci. nat.* **42**, 39-48 (in Czech).
- \_\_\_\_\_ (1957b): Priotite (blomstrandine) from Pozdátky near Třebíč. *Čas. Mineral. Geol.* **2**, 346-348 (in Czech).
- EWING, R.C. (1976): A numerical approach toward the classification of complex, orthorhombic, rare earth,  $\text{AB}_2\text{O}_6$ -type Nb-Ta-Ti oxides. *Can. Mineral.* **14**, 111-119.
- \_\_\_\_\_ & EHLMANN, A.J. (1975): Annealing study of metamict, orthorhombic, rare-earth,  $\text{AB}_2\text{O}_6$ -type, Nb-Ta-Ti oxides. *Can. Mineral.* **13**, 1-7.
- HANSON, S.L., SIMMONS, W.B., WEBBER K.L. & FALSTER, A.U. (1992): Rare-earth-element mineralogy of granitic pegmatites in the Trout Creek Pass district, Chaffee County, Colorado. *Can. Mineral.* **30**, 673-686.

### SOME FEATURES OF MINERAL COMPOSITIONS IN GRANITIC PEGMATITES OF THE RARE-METAL – RARE-EARTH FORMATION IN RUSSIA

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The rare-metal – rare-earth formation of granitic pegmatites, derived by efficient differentiation of a fertile granitic magma of high alkalinity and exhibiting a high degree of fractionation of the pegmatite-forming melt, was first described by Grodnitsky (1982). This type of pegmatite forms part of the group of low-pressure pegmatites in the classification of Zagorsky *et al.* (1999), and corresponds to the NYF family of pegmatites (Černý 1991). The F-Ta-Y, Nb-Y and Be-REE evolutionary sequences have been identified in this group of pegmatites. The Ploskaya pegmatite field in western Keives, in the Kola Peninsula of Russia, is a typical representative of the F-Ta-Y evolutionary sequence. Other pegmatite fields of this region are related to the Be-REE and Nb-Y evolutionary

sequences. Pegmatites of the Ilmensky preserve (Urals) and in the Baikal area (Olkhon and Slyudyanka) belong to the Nb–Y evolutionary sequence. Compositional features of the K-feldspars, micas and other minerals in pegmatites from these Russian localities are described below.

The K-feldspar is usually amazonitic or, rarely, uncolored microcline, with a high degree of structural order. Blue and green amazonites are widespread in pegmatites of the Ploskaya deposit. They differ in Ab content and in concentrations of Rb, Cs, Tl, Ba, and Pb. The highest contents of these elements, particularly Ba (up to 0.33 wt%) and Pb (up to 0.83%), occur in the latest K-feldspar. The Rb/Ba value is low in such K-feldspar, suggesting that a process other than fractionation, such as the influence of late-stage residual fluids, affected the distribution of these elements.

Comparatively low levels of Cs, Ba and Pb characterize the K-feldspar of the Ilmensky pegmatites. In pegmatites of the Baikal area, the K-feldspar ranges from white microcline in the outer zones of pegmatites to blue amazonite in their central parts, with a corresponding increase in the concentration of Rb, Cs and Pb, and decrease in Ba and Sr contents. Rb and Cs concentrations are elevated in K-feldspar from fluorite-bearing pegmatite veins compared to fluorite-free pegmatites. Up to 0.15 wt% Cs is found in amazonite of this pegmatite. The Rb/Ba value increases from the outer graphic zone to the central zones, indicating fractionation of the pegmatite-forming melt.

Micas from pegmatites of the F–Ta–Y evolutionary sequence (the Ploskaya deposit) belong to the annite–zinnwaldite series. Within one pegmatite body, a strong correlation exists in the levels of Li and Cs, but it is less obvious for Li and Rb. The concentration of Cs increases 5–10 times from annite to Li-bearing micas, which are significantly enriched in Cs compared to micas from pegmatites in the Pikes Peak batholith (Foord *et al.* 1995). Geochemically, micas of the F–Ta–Y evolutionary sequence of pegmatites are characterized by high Pb and Zn contents (up to 0.53 and 1.36 wt%, respectively), as well as by elevated concentrations of Tl, Sn, Nb and Ta, whereas the Cr, Co, Ni and V contents are low.

Micas of the Ilmensky pegmatites range in composition from biotite to annite–ferri-annite, to the masutomilite–zinnwaldite series. In these micas, Li and Rb show a wide range of contents, whereas concentrations of Cs are comparatively low. In the Nb–Y pegmatites of the Baikal area, the micas have low concentrations of Li and belong to the annite–phlogopite series; they may contain up to 25.7 wt% Fe<sub>2</sub>O<sub>3</sub>, and Fe<sup>3+</sup> predominates over Fe<sup>2+</sup> and Mg in octahedral positions of their structure. Concentrations of Rb and, especially, Cs vary widely in these micas, with the Cs content reaching 1.32 wt%.

Among accessory minerals in pegmatites of the rare-metal – rare-earth formation, the tourmaline group is represented by a specific composition, deficient in Al, with a high Fe<sup>3+</sup> content in the octahedral sites. In accordance with these compositional and structural peculiarities, the unit-cell dimensions of these tourmalines are large. Garnet is characterized by high Ca contents and in some cases is andradite.

As a whole, minerals of the rare-metal – rare-earth formation of pegmatites are enriched in Rb, Cs and, in some cases, Li, but to a lesser degree than in the rare-metal pegmatites. The high concentrations of Pb in K-feldspar, as well as of Zn, Pb and, in some cases, Cs in the micas, are typical of this group of pegmatites. The main process of pegmatite genesis is crystallization of a fractionating melt, which may be later modified by late-stage fluids.

#### REFERENCES

- ČERNÝ, P. (1991): Rare-element granitic pegmatites. I. Anatomy and internal evolution of pegmatite deposits. *Geosci. Canada* **18**, 49-67.
- FOORD, E.E., ČERNÝ, P., JACKSON, L.L., SHERMAN, D.M. & EBY, R.K. (1995): Mineralogical and chemical evolution of micas from miarolitic pegmatites of the anorogenic Pikes Peak batholith, Colorado. *Mineral. Petrol.* **55**, 1-26.
- GRODNITSKY, L.L. (1982): *Granitic Pegmatites of the Baltic Shield*. Nauka, Leningrad, Russia (in Russ.).
- ZAGORSKY, V.YE., MAKAGON, V.M. & SHMAKIN, B.M. (1999): The systematics of granitic pegmatites. *Can Mineral.* **37**, 800-802.

**RARE-ELEMENT MINERALOGY OF THE J.C. GOLE PEGMATITE,  
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The Gole pegmatite is the largest feldspar mine in the Madawaska field, located in southern Ontario 50 km north of Bancroft. The Madawaska pegmatites intrude high-grade gneisses of the Central Gneiss Belt, a subdivision of the Grenville Province. They were metamorphosed during the 1.1 Ga Grenville Orogeny. Because this region has been mapped only at a reconnaissance level, post-tectonic granitic rocks that might be comagmatic with the pegmatites are unknown.

The Gole pegmatite strikes N30°E and has a vertical dip. It is 9 to 12 m wide by 150 m long and has been excavated to depths of 3 to 5 m. It is a simple zoned pegmatite with a milky to clear quartz core. Giant red microcline crystals and masses were mined from the intermediate zone adjacent to core. The plagioclase-rich wall zone contains radiating books of biotite that are deformed and partly chloritized. The absence of primary muscovite implies a metaluminous bulk composition.

Although the accessory minerals are quantitatively insignificant (<0.1% by volume), the Gole pegmatite is noted for its crystals of yttrium-rich allanite up to 60 cm across, and fergusonite up to 8 cm across. A 70 kg lot of accessory minerals collected by H.S. Spence in the 1940s when the mine was active is under study. It contains (in order of abundance): allanite, fergusonite, zircon, titanite, hematite-magnetite, polycrase, and uraninite. Secondary minerals are completely lacking.

The accessory minerals are rich in Y, REE, Nb, Ti, Zr, and Fe. They occur embedded in biotite or in feldspar between the sheets of biotite. This assemblage is strikingly characteristic of NYF pegmatites worldwide. The Gole pegmatite can be assigned to Černý's heavy-rare-earth (gadolinite) subtype of rare-element pegmatites. However, F, Be and P, which are typically present in NYF pegmatites, are lacking in the Madawaska field. This may be a significant reflection of their deep-seated origin, which distinguishes them chemically and mineralogically from miarolitic NYF pegmatites associated with epizonal anorogenic granite plutons.

X-ray powder diffraction, electron-microprobe analyses and trace-element analysis by laser ablation – ICP – mass spectroscopy have better characterized these minerals. An age of  $1017 \pm 13$  Ma was calculated from measured values of U/Pb.

**THE ZINNWALDITE – MASUTOMILITE – ELBAITE GRANITIC PEGMATITE  
FROM THE TŘEBÍČ DURBACHITE MASSIF AT KRACOVICE:  
A COMPLEX PEGMATITE RELATED TO THE NYF FAMILY**

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The current classification of rare-earth, NYF-family pegmatites (Černý 1991) includes two subtypes, allanite–monazite and gadolinite. Some of the NYF pegmatites, however, contain locally common Li-bearing micas, *e.g.*, zinnwaldite, Fe-rich lepidolite and masutomilite. Common lepidolite and rare elbaite, along with amazonite and REE fluorides and (Y,REE) oxides, were found particularly in the Høydalen pegmatite, near Tørdal, Telemark, Norway (Bergstøl & Juve 1988). Černý (1991) considered this locality to be an example of a mixed NYF–LCT type. In contrast, the Kracovice pegmatite described here seems to be a more fractionated member of the NYF-family proper.

The Třebíč durbachite massif (TDM) ranges in composition from melanocratic granites to syenites and is characterized in detail by Čech *et al.* (1999). The zinnwaldite – masutomilite – elbaite pegmatite at Kracovice is located only several hundred meters west of the western part of the TDM, characterized by abundant and relatively evolved NYF pegmatites with beryl and Nb–Ta–Ti–REE oxides with high values of Ta/(Ta + Nb) (Čech *et al.* 1999). The zoned Kracovice dike (about 1 m thick) cuts graphitic gneiss (Němec 1990) and consists inward of a granitic unit, a graphic unit, a blocky K-feldspar, blocky quartz and albite complex situated close to the quartz core. Major minerals are represented by quartz (commonly smoky), K-feldspar (locally amazonitic) and two textural types of albite (saccharoidal and rare cleavelandite). Typical subordinate minerals are micas and tourmaline; accessory phases include common topaz and garnet (Sp<sup>S71–61</sup>Alm<sup>29–39</sup>), rare F-rich hambergite, monazite-(Ce), zircon (Zr/Hf = 20.1), columbite, wolframioxiolite, pyrochlore, cassiterite, an unidentified Y–Nb–Ta oxide and löllingite; secondary fracture-filling minerals include beryl, bertrandite, bavenite and fluorite.

Chemical compositions and compositional trends in micas, tourmaline, hambergite and monazite differ from those found in common LCT complex pegmatites (lepidolite and elbaite subtype) in the Moldanubicum and elsewhere.

The compositional trend in micas [lithian biotite – zinnwaldite – Fe-rich muscovite – Mn-rich lepidolite – masutomilite] is similar to those found in some F-rich NYF pegmatites such as Pikes Peak, Colorado (Foord *et al.* 1995) and the Sawtooth pluton, Idaho (Boggs 1992). However, Kracovice generated apparently higher Mn/Fe<sub>at.</sub> from 0.11 in lithian biotite to 6.78 in masutomilite. The dominant substitutions seem to be MnFe<sub>-1</sub>, Li<sub>2</sub>SiFe<sub>-3</sub> and LiSiFe<sub>-1</sub>Al<sub>1</sub>.

The compositional trend in tourmaline, from Al-rich schorl to Mn-rich elbaite with very limited variation in Y-site Al, from 0.6 to 1.1 *apfu*, low level of vacancies in the X site and high F contents, is unique. The dominant schemes of substitution, MnFe<sub>-1</sub> and MnLiOHFe<sub>-2</sub>O<sub>-1</sub>, differ from the substitutions AlLiFe<sub>-2</sub> and □AlNa<sub>-1</sub>Fe<sub>-1</sub> typically found in complex (lepidolite) LCT pegmatites (Selway *et al.* 1999).

Hambergite occurs in two types, in biotite-bearing graphic pegmatite (Němec 1990) and in saccharoidal albite associated with elbaite (Novák *et al.* 1998). Based on electron-microprobe data and indices of refraction, F increases from 0.15 to 0.54 *apfu* in the two respective types. Monazite-(Ce) exhibits a limited substitution toward huttonite, ThSiREE<sub>-1</sub>P<sub>-1</sub>, but no departure toward brabantite, CaThREE<sub>-2</sub>, which is typical of monazite from LCT pegmatites in the Moldanubicum.

The mineral assemblage with amazonite, zinnwaldite–masutomilite, abundant topaz, compositionally unique schorl–elbaite series, and the close spatial relationship of the Kracovice pegmatite to the most evolved NYF pegmatites of the TDM, show that this pegmatite is distinct from other complex pegmatites of the LCT family. It

is characterized by high activities of B and particularly F, and low activity of P. The mineral assemblages indicate high alkalinity in at least some stages of pegmatite evolution.

The complex pegmatite from Kracovice seems to be more related to the NYF family than to the LCT family, and it has many similar features with the mixed NYF–LCT pegmatite Høyaldalen, near Tørdal, Telemark, Norway, (Bergstøl & Juve 1988, Černý 1991) and with the Leduc mine, Gatineau River area, Quebec, Canada (Hogarth *et al.* 1972). However, there are also similarities with Li-, Mn-, and F-enriched elbaite-subtype pegmatites (*e.g.*, Ctidružice, Moldanubicum). Whether the Kracovice pegmatite represents a highly evolved complex pegmatite affiliated to the NYF family, or an unusual LCT pegmatite, requires more thorough mineralogical, geochemical and isotopic study. However, it seems probable that fractionation in both NYF and LCT pegmatites may tend to converge and produce mineralogically similar, but not identical, dikes showing combined NYF and LCT geochemical signatures.

#### REFERENCES

- BERGSTØL, S. & JUVE, G. (1988): Scandian ixiolite, pyrochlore and bazzite in granite pegmatite near Tørdal, Telemark, Norway. A contribution to the mineralogy and geochemistry of scandium and tin. *Mineral. Petrol.* **38**, 229-243.
- BOGGS, R.C. (1992): A manganese-rich granite pegmatite assemblage from the Sawtooth batholith, south central Idaho, USA. *In* Lepidolite 2000, Int. Symp. on the Mineralogy, Petrology, and Geochemistry of Granitic Pegmatites (Nové Misto na Moravě, Czechoslovakia), 15-16 (abstr).
- ČECH, F., EWING, R.C., LUMPKIN, G.R. & NOVÁK, M. (1999): Nb–Ta–Ti–REE oxides from NYF granitic pegmatites in the Třebíč durbachite massif, Czech Republic. *Can. Mineral.* **37**, 811-812
- ČERNÝ, P. (1991): Fertile granites of Precambrian rare-element pegmatite fields: is geochemistry controlled by tectonic setting or source lithologies? *Precambrian Res.* **51**, 429-468.
- FOORD, E.E., ČERNÝ, P., JACKSON, L.L., SHERMAN, D.M. & EBY, R.K. (1995): Mineralogical and geochemical evolution of micas from miarolitic pegmatites of the anorogenic Pikes Peak batholith, Colorado. *Mineral. Petrol.* **55**, 1-26.
- HOGARTH, D.D., MOYD, L., ROSE, E.R. & STEACY, H.R. (1972): Classic mineral collecting localities in Ontario and Quebec. *XXIV Int. Geol. Congress (Montreal), Excursions Guide*, 1-78.
- NĚMEC, D. (1990): Neues zur Mineralogie eines Hambergit-führenden Pegmatitgangs von Kracovice (bei Třebíč, Westmorava, ČSFR). *Z. Geol. Wiss.* **18**, 1105-1115.
- NOVÁK, M., BURNS, P.C. & MORGAN, G.B., VI (1998): Fluorine variation in hambergite from granitic pegmatites. *Can. Mineral.* **36**, 441-446.
- SELWAY, J.B., NOVÁK, M., ČERNÝ, P. & HAWTHORNE, F.C. (1999): Compositional evolution of tourmaline in lepidolite-subtype pegmatites. *Eur. J. Mineral.* **12**, 569-584.

## GRANITIC PEGMATITES OF THE SAWTOOTH BATHOLITH, IDAHO

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The Sawtooth Batholith is one of the largest of Idaho's Tertiary granite plutons. It was emplaced at a shallow level in a postorogenic, extensional environment during the peak of the Challis volcanic–plutonic episode around 44 m.y. ago, intruding the Idaho Batholith (88 Ma). Following discovery of aquamarine and investigations for beryllium in the late 1960s, field collecting continued from the late 1970s until closure by the Sawtooth National Recreation Area authorities in 1991.

The Sawtooth Granite is medium grained and leucocratic, with color ranging from light pink (from pinkish K-feldspar) to gray. It consists of quartz, mesoperthitic orthoclase and plagioclase (oligoclase in the north to albite



in the south). The granite is peraluminous ( $A/CNK = 1.07$ ), enriched in F and Fe, with high trace levels of Nb and Mo. Its Be content is much higher than in the Idaho Batholith (6 *versus* 1 ppm).

Segregations and dikes of aplite, alaskite and pegmatite, common throughout the batholith, have a mineral makeup similar to that in the parent granite. Dikes generally dip at shallow angles, rarely at high angles. There are three types of cavity-bearing pegmatites: 1) isolated miarolitic cavities, 2) dikes, and 3) pegmatitic segregations along joint planes. Euhedral aquamarine occurs in all three types of pegmatite.

Most common are the Type-1 miarolitic “gas cavity” pegmatites that occur typically isolated in granite or within irregular, coarse-grained segregations, less commonly within dikes. The cavities, typically to 50 cm, host most of the 45 known mineral species, most notably topaz and beryl (variety aquamarine). Fe and Mn minerals also are important. Fe species include fayalite in crude crystals (typically altered) frozen in pegmatitic segregations, with hematite, siderite and rarer pyrite in the cavities. Mn minerals includes rarer species such as carpholite, helvite, masutomilite and pyrophanite. Fluorite occurs sparingly with both aquamarine and topaz, with fluorite instead of topaz as the main F-bearing species (consistent with higher Ca content of plagioclase) in one northern area. In one Type-2 pegmatite dike, crystals occur in cavities, typically up to 5 cm, in the intermediate zone and core margins. This complex, zoned, high-angle dike is 1–2 m thick and 12 m long. Aquamarine – spessartine – feldspar “line rock” borders one end of the dike. Type-3 “sheet pegmatites”, typically about 2.5 cm thick, are localized along joint surfaces and show aquamarine and spessartine mineralization. These pegmatites contain small crystals of aquamarine in vuggy zones. Massive aquamarine is locally common as spherical segregations, and fracture and cavity fillings.

Type-1 miarolitic cavity pegmatites, which are locally common throughout the batholith, are considered to have formed from bubbles of F-rich aqueous fluid that separated from the rising magma and were trapped within the intrusion during final stages of crystallization. The high F content may have enhanced the formation of Mn minerals in these pegmatites by promoting late-stage Mn enrichment over Fe, as evidenced by a greater prevalence of Mn minerals with F (*versus* Fe with Be and lower F). Type-3 pegmatites and massive aquamarine mineralization both show a stronger relationship to intrusion and fracturing and very limited void space. This suggests formation from a later-stage pulse of dryer, Be-rich (lower-F) magma. The origin of the Type-1 aquamarine-bearing miarolitic cavity pegmatites is more problematic. As with all other examples of aquamarine mineralization, they are generally restricted to the central area. Although they can occur in close proximity and are physically indistinguishable from other miarolitic types, such cavities (especially those containing predominantly or only aquamarine) are mineralogically distinct. Thus, whereas aquamarine-bearing Type-1 pegmatites show no obvious relation to fracturing, they are likely also to be late-stage.

The Sawtooths can be compared with Mt. Antero, another notable aquamarine-producing NYF pegmatite locality. Similarities include: 1) postorogenic tectonic settings, 2) both miarolitic and intruded dike pegmatites within the parent granite, and 3) associated fluorite. Both show association of aquamarine and spessartine, occurring in sheet pegmatites in the Sawtooths *versus* clots in Mt. Antero’s California Granite. However, compared to the Sawtooths, the Mt. Antero pegmatites occur in a metaluminous granite, with lower F, rare topaz, and no significant Mn mineralization.

A final comparison can be made with the beryl subtype of LCT family pegmatites. Černý’s NYF–LCT classification is based on differences in geochemical signatures, but there are corresponding differences in tectonic environment and physical relation of pegmatite to parent intrusion. Such distinctions may, however, blur for predominantly Be-mineralized pegmatites. Although many NYF-hosting (A-type) granites are anorogenic, with low aluminum-saturation indices, the granites considered here are postorogenic with a higher aluminum-saturation index, so that they overlap with LCT types. Whereas most pegmatites in the Sawtooth Batholith and at Mt. Antero are within the parent granite, as expected for NYF types, surrounding country-rocks also show minor intrusion of dikes (Mt. Antero) or aquamarine mineralization along joints (Sawtooths). Thus there is an overlap in mode of intrusion between the Sawtooths and Mt. Antero pegmatites with the LCT beryl subtype, one of the least-evolved of the LCT family pegmatites, which may show pegmatite dikes close to the contacts or even within the parent intrusion.

#### BIBLIOGRAPHY

JACOBSON, M. (1993): Antero aquamarines. L. R. Ream Publishing, Coeur d’Alene, Idaho.

MENZIES, M.A. & BOGGS, R.C. (1993): Minerals of the Sawtooth Batholith, Idaho. *Mineral. Rec.* **24**, 185-202.

REAM, L.R. (1989): *Idaho Minerals*. L.R. Ream Publishing, Coeur d’Alene, Idaho.

## BARINGER HILL, LLANO COUNTY, TEXAS: A CLASSIC NYF PEGMATITE

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Baringer Hill is the most famous NYF pegmatite in North America. It was discovered in July 1886 by John J. Baringer, and between 1889 and 1907 it was vigorously promoted both scientifically and commercially by William E. Hidden. Located on the eastern edge of Llano County, 6 km southwest of Bluffton (30.80°N, 98.43°W), in central Texas, it was inundated by Lake Buchanan in 1937, and is no longer accessible.

Baringer Hill lies on the east side of the Llano Uplift, which exposes a Grenvillian terrane of gneisses and schists intruded by a suite of post-orogenic granites. The associated pegmatites comprise the Llano pegmatite field. The Baringer Hill pegmatite intrudes the Lone Creek pluton of the Town Mountain granite and is the largest member of a pegmatite group with the NYF signature.

Baringer Hill is an asymmetrical, zoned, metaluminous pegmatite about 75 m long by 30 m wide. It has a graphic granite wall-zone <2 m thick, a quartz–perthite core, and a red albite + quartz + microcline unit that has been interpreted as a replacement. Crystals and masses up to 35 kg (!) of gadolinite [Be<sub>2</sub>Fe(Y,REE)<sub>2</sub>Si<sub>2</sub>O<sub>10</sub>], as well as fergusonite [(Y,REE,Th,U,Pb)NbO<sub>4</sub>], and zircon (“cyrtolite”) were ore minerals. A few hundred kg were mined each winter from 1902–1903 until 1906–1907 to supply “yttria” for glower strips (*i.e.*, filaments) for Nernst lamps. Other accessory minerals include allanite, biotite, fluorite, hematite (“martite”), ilmenite, magnetite, molybdenite, and polycrase. A few grams of the white REE carbonates tenerite, an alteration of gadolinite, and lanthanite, an alteration of allanite, were recovered.

Baringer Hill is the type locality for five new species named by Hidden and coworkers: mackintoshite, nivenite, rowlandite, thorogummite, and yttrialite. Masses of up to 8 kg of yttrialite, (Y,REE)(Si<sub>2</sub>O<sub>7</sub>), and of up to 1 kg of rowlandite, (Fe,Mg)(Y,REE)<sub>4</sub>(Si<sub>2</sub>O<sub>7</sub>)<sub>2</sub>F<sub>2</sub>, were found, but both remain very rare minerals. Mackintoshite and nivenite, now regarded as varieties of uraninite (or thorite?), were found in large masses of thorogummite and were believed to be the precursor(s) to thorogummite (Th,U,REE,Pb,Al,Fe,Ca)[(SiO<sub>4</sub>),(OH)<sub>4</sub>], which is clearly an alteration mineral.

Modern chemical analyses of the rare-element minerals, as well as trace-element analyses by laser ablation – ICP – mass spectrometry now in progress, will facilitate comparisons with other NYF pegmatites and may yield petrogenetic insights as well.

## NORTH VERSUS SOUTH: NYF PEGMATITES IN THE GRENVILLE PROVINCE OF THE CANADIAN SHIELD

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As in the United States, the population of Canada by Europeans and the exploitation of its mineral wealth historically show a strong east-to-west pattern. However, unlike the U.S.A., Canada also shows a south-to-north pattern, particularly in the current century. Thus, for reasons which have more to do with history than geology, granitic pegmatites of the southern part of the Grenville Province have been intensely sought, exploited and studied, but far less so those of the northern part.

The Grenville Province consists of a series of imbricate thrust sheets, generally with older and deeper-level sheets to the north, and younger, higher-level sheets to the south. One way of subdividing the tectonic assemblage

is to consider that basement gneisses make up the majority of the Province, and that these are overlain by volumetrically less significant supracrustal successions of middle Proterozoic age, such as the Grenville Supergroup. Because the more accessible supracrustal sequences lie to the south of the Province, the *vast* majority of what is known about Grenville pegmatites involves those pegmatites hosted by supracrustal rocks.

In the late 1980s, I began a research program on the granitic pegmatites in the northern parts of the Grenville Province. I expected few occurrences, and also expected that the pegmatites would be largely barren. However, I was surprised to find there are currently over 300 occurrences of pegmatite, a large number of these bodies are Nb-oxide-mineral-bearing, and many contain relatively diverse assemblages of *REE* minerals. Comparison with granitic pegmatites hosted by the Grenville Supergroup shows a number of interesting similarities: a dominantly NYF geochemistry with extremely low degrees of rare-alkali-element enrichment, an absence of contemporaneous (parental) granitic rocks, suggesting an origin by direct anatexis, and a generally postkinematic timing of emplacement (*ca.* 900 to 1000 Ma). However, important differences do exist.

On the whole, the northern pegmatites are less calcic than the southern pegmatites. Minerals such as amphiboles and pyroxenes are generally absent in the northern pegmatites, whereas they are commonly found in the margins of southern pegmatites. Calcite pods in internal units of pegmatites, such as those found in pegmatites of the Hybla district, are absent in the northern pegmatites.

Belts of anomalously syenitic “granitic” pegmatites, such as those found in the Bancroft pegmatite district, are not present in the northern parts of the Grenville Province. The relatively high degrees of enrichment in total U and in Th/U of the Bancroft pegmatite district are not shown by pegmatite districts to the north.

Although degrees of enrichment in Nb and Ta are comparable for granitic pegmatites of both the northern and southern regions, important differences in the style of mineralization exist. Euxenite-(Y) and samarskite-(Y) are the main carriers of Nb and Ta in the northern pegmatites. Pyrochlore-group minerals are extremely rare in granitic pegmatites of the north, whereas they are the main carriers of Nb and Ta in the pegmatites of the south.

Boron minerals are conspicuously absent from northern pegmatites, whereas schorl and other rare borosilicate minerals are found in some cases in the wall units of southern pegmatites.

Some of the differences of the southern pegmatites can be attributed to melt – country rock interactions. Granitic pegmatites emplaced in limestone-rich supracrustal sequences show evidence of assimilation: irregular contacts, large crystals of hornblende in wall zones, and large pods of calcite near pegmatite cores. Assimilation of limestone resulted in calcium-enriched pegmatite-forming melts, and may have affected the complexing behavior of high-field-strength elements (HFSE). The collector’s paradise of euhedral zircon and (Nb,Ta,Ti)-oxide minerals in central calcite pods, as opposed to their more usual location in wall zones, suggests that carbonate complexing has made the HFSE behave as incompatible elements.

The north–south distinction is important. Classical descriptions of granitic pegmatites in the Grenville Province are based largely on unrecognized hybrid bodies that do not represent the norm. Models attempting to explain the origin of strongly uranium-mineralized pegmatites, such as those of the Bancroft district, should be recognized as local, not regional, in applicability. Granitic pegmatites from regions poor in carbonate sequences provide the best estimates for the compositions of unhybridized pegmatite-forming melts; consideration of *these* melts and their crystallization histories is an important prerequisite to understanding the processes of hybridization.

## THE MOREFIELD PEGMATITE, AMELIA COUNTY, VIRGINIA

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The overall mineralogy of the Morefield granitic pegmatite is notably similar to other NYF pegmatites like the Pikes Peak Batholith in the St. Peters Dome area and the Zapot pegmatite in Mineral County, Nevada. The Morefield pegmatite is one of two complex NYF pegmatites of the Amelia district; the other is the nearby Rutherford pegmatite. Silas Morefield, who sporadically worked or leased the deposit during the earlier part of the century,

discovered the pegmatite in 1929. The United States Bureau of Mines conducted extensive exploration and mine development during the 1940s. The mine remained inactive until the 1980s. Since 1985, the mine has been operating as a recreational gem mine. The recent owners have been very receptive to serious scientific investigations, and to any endeavors that might lead to a greater understanding of the pegmatite. Two vertical shafts, 39 m apart, descend to an adit at the 18 m (60 ft) level. The adit trends northeast to southwest, along the strike of the pegmatite. The adit exposes the core, intermediate and wall zones of the pegmatite over a total distance of 90 m. Presently, efforts are being made to re-open the 30 m (100 ft) level of the mine, which has been flooded since the 1940s.

The mineral assemblages, as is the case in most complex pegmatites, are organized into well-developed zones. The core predominantly consists of smoky quartz with some beryl, mica and feldspar. The core margin and intermediate zones are rich in deep blue microcline ("amazonite"), white blocky albite, white to pale blue cleavelandite, zinnwaldite and muscovite, and topaz. Columbite–tantalite-group minerals, along with minor amounts of cassiterite, ixiolite, wodginite, monazite and microlite, are found as accessory minerals with the cleavelandite. Limited amounts of salmon-colored triplite give rise to secondary phosphates such as strengite, pyromorphite, apatite, bermanite and fluellite. Anhydrous crystals of orange spessartine, rimmed with black manganese oxides, are found sparingly in the intermediate zones.

Aluminum fluoride replacement bodies occur in the northeastern portion of the pegmatite. These units contain prosopite, cryolite, exceptional crystals of chiolite, purple elpasolite, thomsenolite, ralstonite, pachnolite, and gearksutite. Masses of green fluorite generally accompany the aluminum fluorides.

Recent studies of mineral compositions indicate that the pegmatite becomes progressively more differentiated toward the northeast. Micas show a progressive increase in lithium, fluorine and manganese contents. Tin-bearing minerals are entirely restricted to the northeastern portion, as are all aluminofluoride minerals.

SUNDAY MORNING, SEPTEMBER 12, 1999

## ALKALI MIXTURES IN GLASSES AND AQUEOUS SOLUTIONS

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The subcritical to supercritical character of fluids and the conjugate polar–apolar behavior of their solubility play a dominant part in pegmatite genesis. Illustrating the chemical behavior of such fluids commonly involves using alkali-containing solutions that tend to show monotonous trends in their properties as a function of cationic field-strength, ionization potential, or electron affinity. However, it is well known that mixtures of alkalis in systems in which silica rather than H<sub>2</sub>O forms the continuous phase may show very large non-linearities in their transport properties. Here, I shall show that mixtures of alkalis affect the chemical properties of R<sub>2</sub>O•2SiO<sub>2</sub> (R = Li, Cs) glasses, in particular their adsorbance of moisture and CO<sub>2</sub>. I shall also show some evidence that similar non-linearities occur in the osmotic pressure of aqueous systems containing more than one alkali. Finally, I shall discuss attempts to rationalize this mixed alkali behavior using Pauling valence arguments, using recently synthesized and determined structures of phyllosilicates in the cesium disilicate – lithium disilicate system.

## BERYLLIUM BUDGETS IN GRANITIC MAGMAS: CONSEQUENCES OF EARLY CORDIERITE FOR LATE BERYL

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### BERYL SATURATION IN GRANITIC MELTS

Experimental calibration of beryl solubility (Fig. 1) reveals that beryl saturation is most easily achieved in peraluminous, quartz-saturated granitic magmas (Evensen *et al.* 1999). The BeO content of melts, which ranges between 0.03 and 0.40 wt% from 650 to 850°C (among beryl-saturated metaluminous and peraluminous haplogranitic and “macusanitic” melts), is most sensitive to temperature (the solubility of beryl falls with decreasing *T*) and to the activity product of beryl,  $[a_{\text{BeO}}]^3[a_{\text{Al}_2\text{O}_3}][a_{\text{SiO}_2}]^6$ . High solubilities exist at high *T* and require unrealistic beryllium contents of melt for natural systems. But beryllium contents of metaluminous to peraluminous granitic melts, with or without common volatile and fluxing components, descend to a narrow range of low values at low *T*, near their solidus temperatures. Undercooling is, therefore, the likely mechanism that brings granitic magmas to beryl saturation.

### Be BUDGETS AT THE SOURCE

Experiments designed to address the partitioning of Be between cordierite and peraluminous granitic melt [200 MPa (H<sub>2</sub>O), 675–800°C, forward and reverse directions] have been run using mixtures of natural micas + feldspars + quartz ± garnet as metapelite analogues with or without significant Be (*via* addition of beryl, phenakite, or white mica). For all *T*, beryllium partitions heavily in favor of cordierite (Crd) over melt. Partitioning ratios vary principally with temperature (*D* values decrease with increasing *T*), but are 2–10 times larger in Be-poor systems not saturated with a Be mineral (beryl or chrysoberyl). Among Be-rich systems between 675 and 800°C,  $D_{\text{Be}}^{\text{Crd/melt}}$

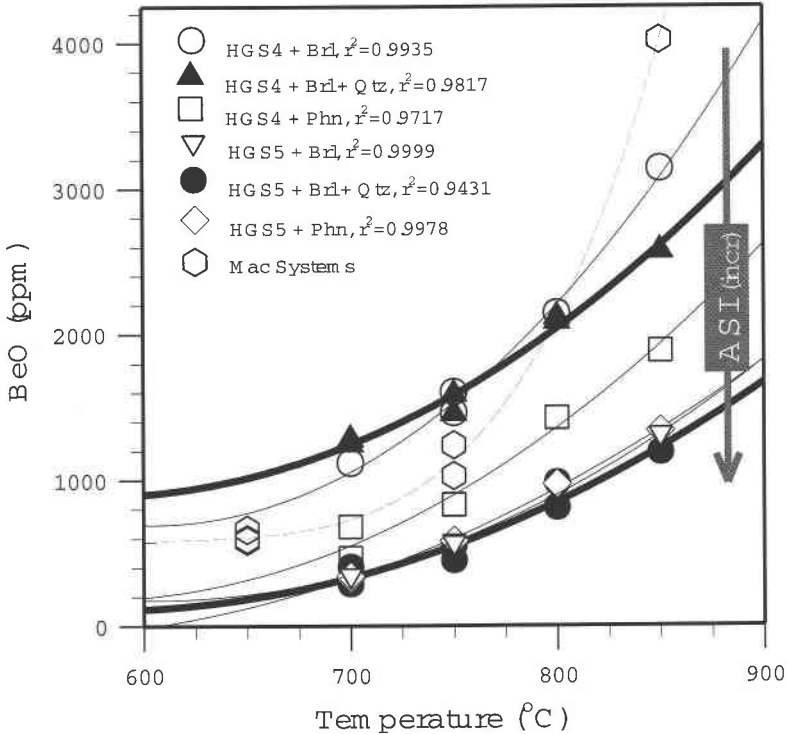


FIG. 1. BeO contents of beryl-saturated granitic melts from 650 to 850°C and 200 MPa (H<sub>2</sub>O). HGS4 and HGS5 are starting metaluminous and peraluminous haplogranitic compositions, respectively. MAC represents macusanite. Thick curves delineate quartz-saturated systems; the vertical arrow indicates increasing ASI of the melt, from 1.00 to 1.28. From Evensen *et al.* (1999).

values decrease from 26.6 to 11.5; in Be-poor systems, values at 700–800°C vary from 188.6 to 27.7. The greatest measured BeO content of Crd, 3.72 wt%, illustrates the beryllium's compatibility. For natural systems, mica breakdown and melting reactions are accepted channels for getting sedimentary Be into crustal magmas (*e.g.*, Bebout *et al.* 1993, Domanik *et al.* 1993). But if anatexis occurs within the stability field of Crd (Puziewicz & Johannes 1988, Mukhopadhyay & Holdaway 1994), cordierite will be extremely efficient in sequestering Be, probably as restite, resulting in the formation of Be-rich reservoirs. These crustal sinks of Be may become available for later modification, one case being accommodation by granulite-facies assemblages (*e.g.*, beryllian sapphirine, surinamite: Grew 1998). Whole-rock Be contents of cordierite-bearing granite distinguish Crd-present *versus* Crd-free magmatic pathways. Low Be contents typify magmas in which Crd was present ( $\leq \sim 2$  ppm Be; *e.g.*, several Spanish granite plutons: Bea *et al.* 1994a, b) and fall near or below the wholesale crustal average (2.8 ppm Be: Taylor 1964). Granites displaying greater Be enrichments ( $\geq \sim 8$  ppm Be; *e.g.*, Harney Peak Granite: Shearer *et al.* 1987, Norton & Redden 1990) indicate Crd-free histories despite an S-type character.

#### GETTING BERYL IN PEGMATITES

Though some enrichment in Be is required at the source, many granitic magmas contain enough Be to achieve beryl saturation so long as undercooling is adequately large, *e.g.*, in the case of pegmatite dikes. Although beryl saturation in supercooled melts requires as little as 5–10 times Be enrichment over the granite average, even pegmatites formed from magmas in which cordierite was present during anatexis will not contain beryl. Cordierite will substantially influence the beryllium budget within granitic melts, such that beryl will only be found in pegmatites whose parental magmas (a) never saw cordierite or (b) contained cordierite that later decomposed.

## REFERENCES

- BEA, F., PEREIRA, M.D., CORRETGÉ, L.G. & FERSHTATER, G.B. (1994a): Differentiation of strongly peraluminous, perphosphorus granites: the Pedrobernardo pluton, central Spain. *Geochim. Cosmochim. Acta* **58**, 2609-2627.
- \_\_\_\_\_, \_\_\_\_\_ & STROH, A. (1994b): Mineral/leucosome trace-element partitioning in peraluminous migmatite (a laser ablation – ICP – MS study). *Chem. Geol.* **117**, 291-312.
- BEBOUT, G.E., RYAN, J.G. & LEEMAN, W.P. (1993): B–Be systematics in subduction-related metamorphic rocks: characterization of the subducted component. *Geochim. Cosmochim. Acta* **57**, 2227-2237.
- DOMANIK, K.J., HERVIG, R.L. & PEACOCK, S.M. (1993): Beryllium and boron in subduction zone minerals: an ion microprobe study. *Geochim. Cosmochim. Acta* **57**, 4997-5010.
- EVENSEN, J.M., LONDON, D. & WENDLANDT, R.F. (1999): Solubility and stability of beryl in granitic melts. *Am. Mineral.* **84**, 733-745.
- GREW, E.S. (1998): Boron and beryllium minerals in granulite-facies pegmatites and implications of beryllium pegmatites for the origin and evolution of the Archean Napier Complex of East Antarctica. *Mem. Natl. Inst. Polar Res., Spec. Issue* **53**, 74-92.
- MUKHOPADHYAY, B. & HOLDAWAY, M.J. (1994): Cordierite – garnet – sillimanite – quartz equilibrium. I. New experimental calibration in the system FeO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub>–H<sub>2</sub>O and certain P–T–X<sub>H<sub>2</sub>O</sub> relations. *Contrib. Mineral. Petrol.* **116**, 462-472.
- NORTON, J.J. & REDDEN, J.A. (1990): Relations of zoned pegmatites to other pegmatites, granite, and metamorphic rocks in the southern Black Hills, South Dakota. *Am. Mineral.* **75**, 631-655.
- PUZIEWICZ, J. & JOHANNES, W. (1988): Phase equilibria and compositions of Fe–Mg–Al minerals and melts in water-saturated peraluminous granitic systems. *Contrib. Mineral. Petrol.* **100**, 156.
- SHEARER, C.K., PAPIKE, J.J. & LAUL, J.C. (1987): Mineralogical and chemical evolution of a rare-element granite – pegmatite system: Harney Peak Granite, Black Hills, South Dakota. *Geochim. Cosmochim. Acta* **51**, 473-486.
- TAYLOR, S.K. (1964): The abundance of chemical elements in the continental crust – a new table. *Geochim. Cosmochim. Acta* **28**, 1273-1285.

## BORIC ACID AS THE MOST TYPICAL COMPONENT OF FLUID INCLUSIONS IN MINERALS FROM TOURMALINE-BEARING AND TOPAZ–BERYL MIAROLITIC PEGMATITES

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Fluid inclusions with daughter crystals of orthoboric acid, sassolite H<sub>3</sub>BO<sub>3</sub>, were found and first described in minerals of miarolitic pegmatites of the Kukurt gemstone area, central Pamirs, and the Malkhan pegmatite field, central Transbaikalia (Smirnov *et al.* 1999a, b). In subsequent investigations, it was established that sassolite is the most characteristic daughter phase of fluid inclusions in various minerals of the majority of widely known tourmaline-bearing and topaz–beryl miarolitic pegmatites of the world, *e.g.*, central and eastern Transbaikalia, central and southwestern Pamirs, Afghanistan, Pakistan, Nepal, California and Madagascar. The detailed classification, geological setting, internal structure, mineralogy and geochemistry of these pegmatites are reported (Foord *et al.* 1991, Zagorsky & Peretyazhko 1992, 1996, Peretyazhko *et al.* 1999, Zagorsky *et al.* 1999a, b). The pegmatites bodies studied differ in anatomy, geochemical features and nature of crystalline phases, and they range in age from 560–480 Ma (Madagascar) to 5–3 Ma (Nepal).

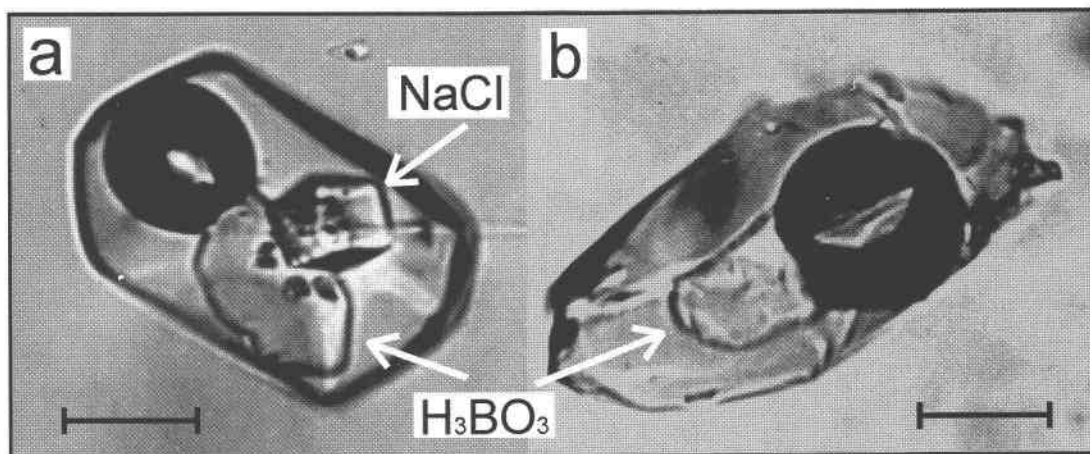


FIG. 1. Fluid inclusions with sassolite. a) Halite-bearing inclusion of the first type in morion, the Mika mine, central Pamirs. b) Inclusion of the third type in quartz, the Svetlaya mine, Malkhan field, central Transbaikalia. Scale bar in photos is approximately 25  $\mu\text{m}$ .

The inclusions with sassolite occur in quartz, tourmaline, danburite, beryl, topaz and adularia. The following types of inclusions are recognized from their phase assemblage: 1) inclusions of concentrated chloride solutions or brines with gas bubble plus one or two isotropic daughter minerals (halite, sylvite) and anisotropic sassolite (Fig. 1a); 2) inclusions of aqueous – carbonic acid solutions with a gas bubble (the meniscus of liquid carbonic acid is visible at room temperature or appears on cooling) and anisotropic sassolite (may appear on cooling only); 3) inclusions of aqueous solutions with a gas bubble and sassolite crystal (Fig. 1b), and 4) inclusions of dilute aqueous solutions with gas bubble and a mineral that resembles sassolite in optical properties and appears on cooling only.

The problem of recognizing sassolite was discussed in Smirnov *et al.* (1999a, b). Sassolite is identified by Raman spectroscopy in the majority of the first three types of inclusions studied. Experimental data on the properties of aqueous boric acid solutions are reviewed, as is the method of calculating the concentration of boric acid from the temperature of dissolution of the sassolite, along with possible errors. The unusual features of inclusions of boric acid solutions are revealed for the first time in this study. All of these features can be explained by the process of polymerization of orthoboric acid and some other properties of concentrated B-bearing solutions (Peretyazhko *et al.*, in prep.).

Sassolite-bearing inclusions of boric acid solutions, with (or without) carbonic acid, contain chlorides of Na, K, and Ca (rarely Fe, Mg, Li and Cs), bicarbonates, fluorides and, conceivably, minor quantities of organic compounds and other components. The homogenization temperature ranges from 450 to 90°C, fluid pressure, from 1480 to 40 bars, H<sub>3</sub>BO<sub>3</sub> concentrations, from 26.5 to 2.3 wt%, salinity, from 38 to 3.3 wt% NaCl equivalent (Fig. 2), and CO<sub>2</sub> concentrations in the inclusions of the second type, from 20.2 to 3.5 wt%. Clearly, boric-acid-bearing fluids are rather typical of a wide range of conditions of mineral formation.

Without doubt, the aqueous boric acid fluids played an important role in the process of formation of near-pocket mineral associations, as well as pocket mineralization in pegmatites of various types, especially the tourmaline-bearing ones. The conclusion that crystallization of tourmaline-bearing mineral associations occurs in the presence of concentrated boric acid solutions in granitic pegmatites, as well as in some hydrothermal rocks, is substantiated. The concentrations of boric acid in homogeneous solutions in inclusions are usually 6–12 wt%, but may reach 23–27 wt%. Thus the “traces” of the concentrated aqueous boric acid in mineral-forming fluids, associated with the process of tourmaline crystallization, have been recognized for the first time. The discovery of such solutions is very important for an understanding of the genesis of pegmatites and many hydrothermal formations (Peretyazhko *et al.*, in prep.). We suggest that inclusions of boric acid solutions should be expected in any tourmaline-bearing and some topaz–beryl miarolitic pegmatites in the U.S.A., Brazil, Afghanistan, Pakistan, Nepal, Madagascar, Italy (Elba) and other places. However, granitic pegmatites make up only an insignificant part



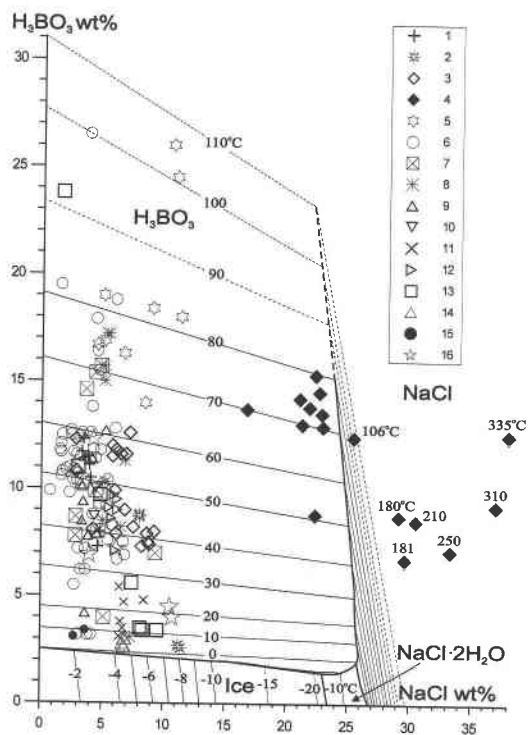


FIG. 2. The system  $\text{NaCl} - \text{H}_3\text{BO}_3 - \text{H}_2\text{O}$ , with data on fluid inclusions in minerals of miarolitic pegmatites (183 observations). 1–16: pegmatite localities: 1 Mokrusha, Middle Urals, 2 Adun-Chelon, eastern Transbaikalia, 3 Amazonitovaya, central Pamirs, 4 Mika, central Pamirs, 5 Vezdarsinskaya and Leskhovskaya, southwestern Pamirs, 6 Malkhan field, central Transbaikalia, 7 Borschovochny ridge, eastern Transbaikalia, 8 Phakuwa and Hyakule, Nepal, 9 Himalaya, California, 10 Stewart, California, 11 Vodorazdel'noye, central Transbaikalia, 12 Polimineral'naya, eastern Transbaikalia, 13 Sahatany Valley, Madagascar, 14 Elizabeth R. California, 15 Kulam, Afghanistan, 16 Azad Kashmir, Pakistan.

of the geological formations that accumulate boron within the Earth's crust. It seems that such types of inclusions could be found in many B-bearing hydrothermal rocks, greisens, and products of volcanic activity as well. On the other hand, it is evident from the properties of boric acid that one cannot expect sassolite in fluid inclusions of minerals that formed in association with concentrated alkaline B-bearing solutions.

#### REFERENCES

- FOORD E.E., LONDON, D., KAMPF, A.R., SHIGLEY, J.E. & SNEE, L.W. (1991): Gem-bearing pegmatites of San Diego County, California. In *Geological Excursions in Southern California and Mexico. Geol. Soc. Am., Annual Meeting (San Diego), Guidebook*, 128-146.
- PERETYAZHKO, I.S., ZAGORSKY, V.YE., PROKOF'EV, V.YU. & GANTIMUROVA, T.P. (1999): Miarolitic pegmatites of the Kukurt Group of gemstone deposits, central Pamirs: the evolution of physical conditions in the Amazonitovaya vein. *Geochem. Int.* **37**(2), 108-127.
- SMIRNOV, S.Z., PERETYAZHKO, I.S., PROKOF'EV, V.YU., ZAGORSKY, V.YE. & SHEBANIN, A.P. (1999a): The first find of sassolite ( $\text{H}_3\text{BO}_3$ ) in fluid inclusions in minerals. *Geologiya i Geofizika* (in press, in Russ.).
- \_\_\_\_\_ & GORYAINOV, S. (1999b): Daughter sassolite ( $\text{H}_3\text{BO}_3$ ) in fluid inclusions: the first evidence of natural fluids with high boron acid content. *Proc. XV ECROFI Conf. (Potsdam)* (abstr.).
- ZAGORSKY, V.YE., MAKAGON, V.M. & SHMAKIN, B.M. (1999a): The systematics of granitic pegmatites. *Can. Mineral.* **37**, 800-802
- \_\_\_\_\_ & PERETYAZHKO, I.S. (1992): *Pegmatites with Precious Stones, Central Transbaikalia*. Nauka, Novosibirsk, Russia (in Russ.).
- \_\_\_\_\_ & \_\_\_\_\_ (1996): Tourmaline deposits in Russia and Tajikistan. *Geologiya i Geofizika* **37**(2), 36-50 (in Russ.).
- \_\_\_\_\_ & SHMAKIN, B.M. (1999b): *Granitic Pegmatites. 3. Miarolitic Pegmatites*. Nauka, Siberian Enterprise Russian Academy of Sciences, Novosibirsk, Russia (in Russ.).

## MELT BOUNDARY-LAYERS AND THE GROWTH OF PEGMATITIC TEXTURES

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Most granitic pegmatites possess abrupt mineralogical and textural zonation. Convection, crystal settling, and the buoyant ascent of aqueous vapor can be discounted as dominant mechanisms for this zonation. Likely crystallization temperatures of shallowly emplaced dikes (<~3 km) are ~450°–550°C, approximately 100°–200°C below their liquidus temperatures (Webber *et al.* 1999). At such low temperatures, the viscosity of hydrous granitic melts would be near  $10^8$  to  $10^{10}$  Pa·s (Dingwell *et al.* 1998). In high-viscosity melts, excluded components are likely to build up along an advancing crystal–melt interface, creating a boundary layer of evolved or highly fluxed melt. Constitutional zone-refining, which results when a molten boundary-layer rich in excluded fluxing components sweeps into a glassy solid or semisolid ahead of a crystal-growth front, represents an attractive mechanism to produce sharp compositional and textural zones in pegmatites; however, boundary layers have not been identified in any natural igneous rocks. They are implicit in the prevailing model for the generation of graphic intergrowths of crystals, such as graphic granite (Fenn 1986). Evidence for boundary-layer melts may also exist in trapped inclusions of melt. Crystal-rich inclusions from the Tanco pegmatite, Manitoba, fit the criteria expected of trapped boundary-layers: the inclusion contents represent an alkaline, sodic, and highly fluxed silicate–H<sub>2</sub>O fluid (London 1986) that was radically different from the bulk composition of the pegmatite (Stilling 1998). Recent modeling of chemical fractionation in the Little Three pegmatite, Ramona, California, established constitutional zone-refining as the probable process to explain the zonation of the dike, in which boundary-layer melts that advanced inward from the hanging wall and footwall coalesced near the center of the dike to form chemically exotic miarolitic pegmatite (Morgan & London 1999). Boundary layers and their products have now been captured in experiments at 200 MPa with bulk compositions representative of granitic pegmatites. In these experiments with hydrous granitic compositions, ranging from simple haplogranite to evolved and flux-rich melts, liquidus undercooling of melts by as little as ~75°C was sufficient to induce the formation of graphic quartz–feldspar intergrowths, though no measurable boundary-layers were observed. With greater undercooling, ~100°–150°C, rhythmic banding of quartz and plagioclase (Fig. 1) evolved texturally to monophase feldspar, followed sequentially by monophase quartz “cores” (Fig. 2). The results are pegmatitic in texture and zonation. Similar experiments that were quenched before crystallization was complete preserved boundary layers in glass (Fig. 3). In experiments with B, F, or P added to the granitic melt, the boundary layers that develop invariably are alkaline and sodic in composition. Recent experiments with P-rich compositions indicate that if alkali feldspars are forced to grow at conditions of large undercooling below the liquidus (>100°C), the usual substitution of AlPSi<sub>2</sub> is replaced by □P[(Na,K)Si]<sub>-1</sub>. With this recent result, it may become possible to estimate the magnitude of liquidus undercooling attending feldspar crystallization from the detailed chemistry of P substitution.

## REFERENCES

- DINGWELL, D.B., HESS, K.U. & ROMANO, C. (1998): Viscosity data for hydrous peraluminous granitic melts: comparison with a metaluminous model. *Am. Mineral.* **83**, 236–239.
- FENN, P.M. (1986): On the origin of graphic granite. *Am. Mineral.* **71**, 325–330.
- LONDON, D. (1986): Magmatic–hydrothermal transition in the Tanco rare-element pegmatite: evidence from fluid inclusions and phase equilibrium experiments. *Am. Mineral.* **71**, 376–395.
- MORGAN, G.B., VI & LONDON, D. (1999): Crystallization of the Little Three layered pegmatite–aplite dike, Ramona District, California. *Contrib. Mineral. Petrol.* (in press).
- STILLING, A. (1998): *Bulk Composition of the Tanco Pegmatite at Bernic Lake, Manitoba, Canada*. M.Sc. thesis, Univ. of Manitoba, Winnipeg, Manitoba.
- WEBBER, K.L., SIMMONS, W.B., FALSTER, A.U. & FOORD, E.E. (1999): Cooling rates and crystallization dynamics of shallow level pegmatite–aplite dikes, San Diego County, California. *Am. Mineral.* **84**, 708–717.

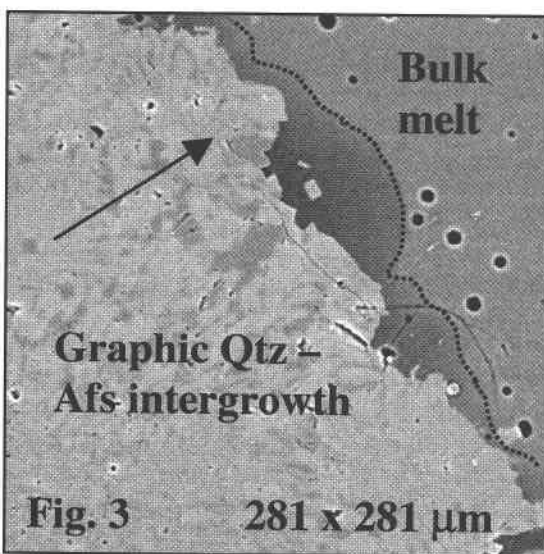
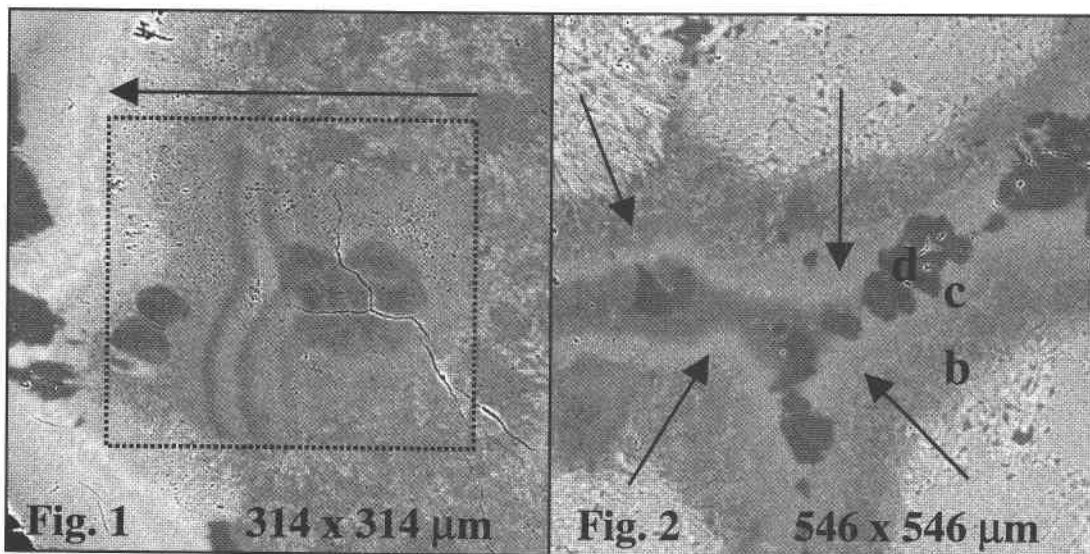


FIG. 1. Back-scattered electron (BSE) image of experiment PEG16, metaluminous haplogranite plus  $B_2O_3$ : layered aplitic texture (dotted box), alternating bands of very fine-grained quartz (dark) and plagioclase (medium gray). The arrow shows the direction of growth toward more potassic layers (bright). Note deflection (curvature) as banding grew beyond a (dark) quartz "megacryst".

FIG. 2. BSE image of experiment PEG16, metaluminous haplogranite plus  $B_2O_3$ : zonation within central portion of the same experiment as Figure 1; normative compositions are reconstructed from analytical averages of the very fine-grained crystalline intergrowths: (a)  $Ab_{13}Or_{62}Qtz_{25}$ , (b)  $Ab_{62}Or_{13}Qtz_{25}$ , (c)  $Ab_{61}Or_{35}Qtz_4$ , and (d)  $Ab_{00}Or_{00}Qtz_{100}$ . The arrows show the direction of crystal growth.

FIG. 3. BSE image of experiment PEG25, metaluminous haplogranite plus  $B_2O_3$ : boundary layer in melt (dark region bounded by dashed line) in advance of a graphic quartz - alkali feldspar intergrowth. The arrow shows the direction of crystal growth. Compositions (electron-microprobe data) of the boundary layer and the bulk melt are as follows. Boundary layer: 50.88 wt.%  $SiO_2$ , 7.79%  $Al_2O_3$ , 6.66%  $Na_2O$ , 2.90%  $K_2O$ , 18.30%  $B_2O_3$ , 13.42%  $H_2O$  (calculated by difference). Bulk melt: 68.94%  $SiO_2$ , 12.01%  $Al_2O_3$ , 5.10%  $Na_2O$ , 3.37%  $K_2O$ , 2.93%  $B_2O_3$ , 7.61%  $H_2O$  (calculated by difference).

## CRYSTAL-GROWTH MECHANISMS IN MIAROLITIC CAVITIES IN THE LAKE GEORGE RING COMPLEX AND VICINITY, COLORADO

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The Crystal Peak area of the Pikes Peak batholith, near Lake George in central Colorado, is renowned for its blue-green amazonite variety of microcline and smoky quartz crystals. A recent study by Kile & Eberl (1999) has shown that crystals from individual miarolitic cavities have remarkably small variations in size (Fig. 1), and the shapes of their crystal-size distributions (CSDs) are consistently lognormal (*i.e.*, the logarithms of the crystal sizes are normally distributed), or nearly so.

These observations can be explained by a crystal-growth model recently proposed by Eberl *et al.* (1998), in which crystal growth is presumed to be governed initially by surface-controlled kinetics, during which the growth rate is proportional to size (*i.e.*, larger crystals grow more quickly), generating a lognormal CSD. The shape of the CSD is established in the nanometer size-range, and is subsequently preserved by longer periods of size-independent, supply-controlled (*e.g.*, diffusion-limited) growth during which all surfaces grow at the same rate. The transition from surface-control to transport-control growth is shown in Figure 2.

The change from surface- to supply-controlled growth kinetics likely resulted from an exponentially increasing demand for nutrients that exceeded diffusion-imposed limitations of the system. The mechanisms of crystal growth proposed for this locality appears to be common in the geological record, and can be used with other information to deduce physicochemical conditions during crystal formation. Thus, evaluation of the mean size, variance, and shapes of crystal-size distributions may provide a method of assessing crystal-growth mechanisms in geological systems. This model of crystal growth may account for the relative scarcity (and corresponding high monetary value) of natural specimens that have a wide range of crystal sizes.

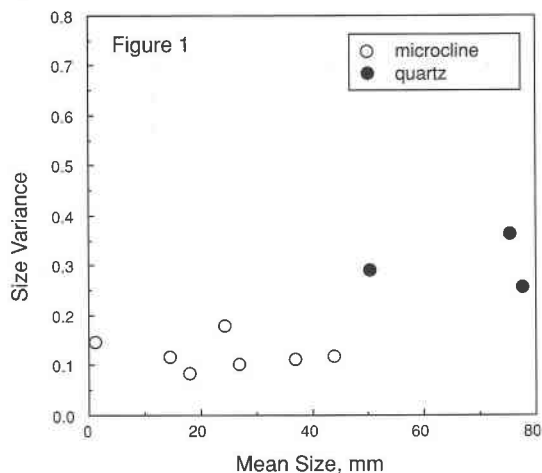


FIG. 1. Plot of size variance (dimensionless) as a function of mean size of crystals (mm) of quartz and microcline from the pegmatite bodies studied.

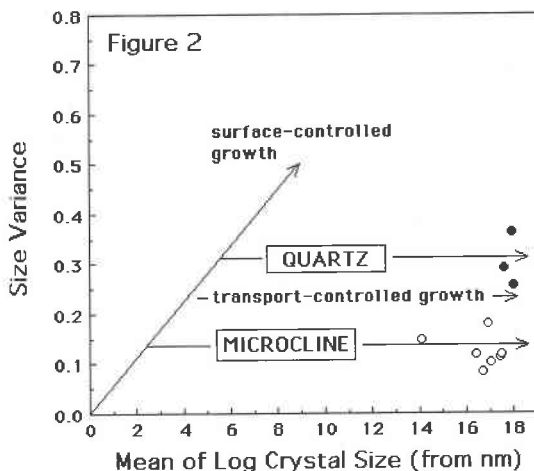


FIG. 2. Plot of size variance as a function of mean of log crystal size (calculated on the basis of nanometers) for quartz and microcline from the pegmatite bodies studied.

## REFERENCES

- EBERL, D.D., DRITS, V.A. & ŚRODOŃ, J. (1998): Deducing growth mechanisms for minerals from the shapes of crystal size distributions. *Am. J. Sci.* **298**, 499-533.
- KILE, D.E. & EBERL, D.D. (1999): Crystal growth mechanisms in miarolitic cavities in the Lake George ring complex and vicinity, Colorado. *Am. Mineral.* **84**, 718-724.

## THE O'GRADY APLITE-PEGMATITE COMPLEX: A MIXED NYF-LCT PEGMATITE GROUP WITH ELBAITE-BEARING POCKET PEGMATITES

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A new gem province is opening up in Canada, in the northeastern parts of the Omineca belt of the Cordillera. Many of the gem occurrences are associated directly or indirectly with granitic rocks of the mid-Cretaceous Cassiar and Selwyn plutonic suites. These include aquamarine, topaz, emerald, smoky quartz and, most recently, tourmaline. The subject of the current study involves a discovery we made in 1994 of gem elbaite in the vicinity of a pluton known as the O'Grady batholith.

The O'Grady batholith is located in the western Northwest Territories, approximately 100 km NNW of Tungsten, in the Sapper Ranges of the Selwyn Mountains. The regional grade of metamorphism is typically subgreenschist facies, an unusual environment for rare-element pegmatites. The batholith is a 270-km<sup>2</sup> hornblende-bearing, alkali-feldspar-rich composite intrusion with mixed S- and I-type characteristics. It consists of a core of megacrystic hornblende quartz syenite, a marginal massive equigranular hornblende-biotite granodiorite, and a foliated transitional phase between the core and margin. In addition, the batholith hosts a number of satellitic peraluminous dykes and a marginal 5-km<sup>2</sup> aplite-pegmatite belt of mixed NYF-LCT geochemical character. Aplites predominate over pegmatite in the belt, and occurrences of pegmatite without associated aplites are rare.

The transition from NYF geochemistry to LCT geochemistry can be quite sharp. Pegmatite bodies with magnetite, allanite and biotite as the main accessory phases can be found only a few meters from lithium-mineralized bodies. In addition to gross changes in mineralogy, there are also subtler changes in mineralogy and mineral color. The K-feldspar in NYF-type and barren pegmatites is typically dark pink. In the vicinity of lithium pegmatites, the color changes to white. Furthermore, in the vicinity of lithium-mineralized *pockets*, the K-feldspar is commonly amazonitic, a useful local prospecting tool. Ferroaxinite is counter-indicative of lithium mineralization, as it is found only in barren or NYF-type pegmatites.

The aplite-pegmatite complex achieves relatively high degrees of fractionation in a 0.5-km<sup>2</sup> region of the belt. In this region, the complex occurs as subhorizontal dikes to 50 m thick. The pegmatites are typically miarolitic and host a number of exotic and well-crystallized minerals. These include: microcline, smoky quartz and plagioclase (*var.* cleavelandite), abundant gem tourmaline (elbaite, *var.* rubellite, verdellite and indicolite), less common danburite, polythionite-lepidolite, a nanpingite-like mineral, titanite, ilmenite, stilbite, boromuscovite, and rare scheelite, hambergite, stibicolumbite and pollucite. Elbaite is the main carrier of lithium, with polythionite-lepidolite a distant second. Individual bodies of pegmatite show high levels of alkali fractionation. Lithium- and cesium-dominant mineral species are present, and K-feldspar and micas are enriched in Li, Rb and Cs relative to K. Pocket K-feldspar commonly shows pervasive "nanpingitization", which petrographically mimics "sericitization".

Major- to trace-element data unambiguously indicate that the quartz syenite and the aplite-pegmatite complex were generated by one and the same fractionation event, with crystallization of the aplite-pegmatite immediately

following the quartz syenite. The abundance of boron-bearing species during all stages of crystallization, local evidence of tourmalinized K-feldspar, the absence of phosphate minerals and paucity of (Ta,Nb,Sn) oxide minerals indicate that boron activity ( $a_B$ ) was extremely high relative to  $a_P$ ,  $a_{Nb}$  and  $a_{Ta}$  during consolidation, even  $a_{Si}$  during the latest stages of consolidation. All of the above features, coupled with the high alkalinity of the parental melt, imply that the aplite-pegmatite complex is an excellent example of the newly recognized elbaite subtype of the rare-element class of granitic pegmatites.

## THE SHATFORD LAKE PEGMATITE GROUP, SOUTHEASTERN MANITOBA: NYF OR NOT?

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The Shatford Lake pegmatite group is located at Shatford Lake and south of it on the Winnipeg River, in the Bird River Subprovince of the western Superior Province of the Canadian Shield (Černý *et al.* 1981a). The pegmatite group comprises 33 well-defined dikes around Shatford Lake, including the historically famous Huron Claim pegmatite, and a considerable number of barren pegmatites straddling the Winnipeg River.

Pegmatite dikes of the Shatford Lake population cross-cut the foliation of host metabasaltic (rarely metasedimentary or granitic-plutonic) lithologies at variable angles, and their dips also are variable, from subhorizontal to subvertical. The pegmatites are gently to moderately deformed, particularly at the easternmost extension of their population. Internal zoning of the dikes is poor to well expressed, in most cases with border (Pl + Kfs + Qtz + Bt), wall (Kfs + Pl + Qtz + Bt + Ms), and intermediate to core-margin zones (Kfs + Ab + Qtz + ferroan Ms), and a largely indistinct quartz core. Exomorphic effects consist of a rather restricted development of biotite at the expense of the host metabasalts.

Accessory minerals are mostly associated with saccharoidal albite units or, locally, cleavelandite. Garnet and beryl are widespread, and topaz, less so. All the other minerals occur in generally low concentrations, with a few exceptions of local accumulations in individual dikes: allanite-(Ce), gadolinite-(Y), euxenite-(Y), yttrantalite-(Y)-formanite-(Y), columbite-tantalite, pyrochlore – microlite – betafite, niobian and tantalian rutile, ilmenite, magnetite, monazite-(Ce), xenotime-(Y), xenotime-(Yb), apatite, zircon, thorite, uraninite, fluorite, epidote, chlorite, sulfides of Fe, Mo, Zn, As, and Pb, and a few ill-defined metamict and secondary phases.

K-feldspar contains from 897 to 7850 ppm Rb, from 51 to 1026 ppm Cs, and its Ba/Rb ranges from 0.34 to 0.003. Biotite exhibits a Fe/Mg value of 0.9 to 10, K/Rb of 85 to 8, and K/Cs of 207 to 43. Muscovite ranges from 69 to 8 in K/Rb and from 2 to 88 in Fe/Mg, whereas curvilamellar ferroan muscovite contains up to 0.61 wt.% Li<sub>2</sub>O and from 3.11 to 7.47 wt.% total Fe as FeO, whereas K/Rb ranges from 66 to 17, and Fe/Mg, from 2 to 81. Both muscovite and the curvilamellar mica rarely contain Ba and Cs above the detection limits of electron microprobe. Almandine-spessartine garnet contains from 27 to 78 mole % spessartine; the grossular component increases (to 10%) and that of pyrope decreases (from 5%) with increasing Mn content. Anomalous grossular-dominant compositions were found in a single endocontact. Green beryl shows ≤0.19 wt.% Li and ≤0.16% Cs, and Na/Li from 25 to 4.

Gadolinite-(Y), euxenite-(Y), yttrantalite-(Y)-formanite-(Y) and minerals of the pyrochlore group are explicitly Y-rich and relatively poor in the HREE, whereas allanite-(Ce) and monazite-(Ce) are distinctly (Ce + LREE)-dominant. Xenotime is the only exception in the Y-rich assemblage; its composition varies from the usual Y-dominant species to compositions with strong positive Yb anomaly, which define in some cases a new mineral, xenotime-(Yb) (Buck *et al.* 1999). Phases of the columbite group are restricted to ferrocolumbite, manganocolumbite and, rarely, marginal manganotantalite, with Mn/(Mn + Fe) (at.) from 0.08 to 0.83 and Ta/(Ta + Nb) (at.) from 0.11 to 0.60. Secondary fersmite also is Nb-dominant. In contrast, minerals of the pyrochlore group are largely Ta-dominant, with a broad range of Ta/(Ta + Nb) (at.) values, from 0.09 to 0.93. Niobian rutile (Černý *et al.* 1981b) is rare, tantalian rutile even more so. Rare titanite is (Nb>Ta)-enriched (Paul *et al.* 1981). Thorian uraninite is widespread in some of the most fractionated pegmatites, such as Huron Claim; thorite is rare

and totally metamict (Paul 1984). Fluorite forms rare late veinlets, but also constitutes apparently primary subhedral grains associated with (F,Li)-enriched micas. Epidote and chlorite are late minerals, probably a result of infiltration from retrograded host-rocks. Apatite is rare, and the sulfides are extremely scarce.

The overall geochemical signature of the Shatford Lake pegmatites shows distinct enrichment in Nb over Ta, in Y (+ HREE) and, to a degree, also in F, with significant presence of Be, Ti, Zr, U and Th. In contrast, the pegmatite group is very poor in Li, Rb, Cs, P and S, and minerals of B are absent.

The Shatford Lake pegmatites were originally considered differentiates of a subaluminous pre-orogenic leucogranite of the Lac du Bonnet batholith (Černý *et al.* 1981a, 1987). The leucogranite shows some A-type affinities and is strongly foliated to lineated, in apparent accord with the deformation suffered by some of the pegmatites. However, according to recent dating, the age of the dominant phase of the Lac du Bonnet batholith, biotite granite, is  $2665 \pm 20$  Ma (zircon); the pegmatites give  $2657 \pm 1$  Ma [gadolinite-(Y)], and the leucogranite,  $2705 \pm 6$  Ma (zircon; Baadsgaard & Černý 1993, and a review in Černý *et al.* 1998). The ages tie the Shatford Lake pegmatites clearly to the main-phase synorogenic biotite granite, which is an I-type granite derived by partial melting of (meta)tonalitic basement, with a minor component of supracrustal protoliths also involved (Černý *et al.* 1987).

Biotite granites of similar I-type derivation, geochemical features, and more or less synchronous timing relative to major orogeny, are parental to magnetite- and uraninite-bearing pegmatites farther east in the Superior Province of northwestern Ontario (Breaks *et al.* 1985, Beakhouse *et al.* 1989), and to pegmatites analogous to the Shatford Lake group in southeastern Sweden (Ytterby and associated bodies; *e.g.*, Wilson 1980). Despite some significant geochemical similarities, this category of granite + pegmatite systems differs distinctly from the classic NYF-family of post- to anorogenic A-type granites and their pegmatite progeny.

#### REFERENCES

- BAADSGAARD, H. & ČERNÝ, P. (1993): Geochronological studies in the Winnipeg River pegmatite populations, southeastern Manitoba. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **18**, A5.
- BEAKHOUSE, G.P., BREAKS, F.W., STONE, D. & SUTCLIFFE, R.H. (1989): Granitoid rocks and their significance for crustal evolution in the western Superior Province. *Geol. Assoc. Can. – Mineral. Assoc. Can., Program Abstr.* **14**, A8.
- BREAKS, F.W., CHERRY, M.E. & JANES, D.A. (1985): Metallogeny of Archean granitoid rocks of the English River Subprovince, northwestern Ontario, Canada: a review. In *High Heat Production Granites, Hydrothermal Circulation and Ore Genesis*. Institute of Mining and Metallurgy, London, U.K. (9-31).
- BUCK, H.M., COOPER, M.A., ČERNÝ, P., GRICE, J.D. & HAWTHORNE, F.C. (1999): Xenotime-(Yb), YbPO<sub>4</sub>, a new mineral from the Shatford Lake pegmatite group, southeastern Manitoba. *Can. Mineral.* **37** (in press).
- ČERNÝ, P., FRYER, B.J., LONGSTAFFE, F.J. & TAMMAMAGI, H.Y. (1987): The Archean Lac du Bonnet batholith, Manitoba: igneous history, metamorphic effects, and fluid overprinting. *Geochim. Cosmochim. Acta* **51**, 421-438.
- \_\_\_\_\_, PAUL, B.J., HAWTHORNE, F.C. & CHAPMAN, R. (1981b): A niobian rutile – disordered columbite intergrowth from the Huron Claim pegmatite, southeastern Manitoba. *Can. Mineral.* **19**, 541-548.
- \_\_\_\_\_, TRUMAN, D.L., ZIEHLKE, D.V., GOAD, B.E. & PAUL, B.J. (1981a): The Cat Lake – Winnipeg River and the Wekusko Lake pegmatite fields, Manitoba. *Manitoba Energy and Mines, Mineral Res. Div., Econ. Geol. Rep.* **ER80-1**.
- \_\_\_\_\_, VANSTONE, P.J. & ERCIT, T.S. (1998): Mineralogy and petrology of the Tanco rare-element pegmatite deposit, southeastern Manitoba. *Int. Mineral. Assoc., 17th Gen. Meeting (Toronto), Field Trip Guidebook* **B6**.
- PAUL, B.J. (1984): *Mineralogy and Geochemistry of the Huron Claim Pegmatite, Southeastern Manitoba*. M.Sc. thesis, Univ. Manitoba, Winnipeg, Manitoba.
- \_\_\_\_\_, ČERNÝ, P., CHAPMAN, R. & HINTHORNE, J.R. (1981): Niobian titanite from the Huron Claim pegmatite, southeastern Manitoba. *Can. Mineral.* **19**, 549-552.
- WILSON, M.R. (1980): Granite types in Sweden. *Geol. Fören. Stockholm Förh.* **102**, 167-176.

## DIVERSIFIED NYF PEGMATITE POPULATIONS OF THE SWEDISH PROTEROZOIC: OUTLINE OF A COMPARATIVE STUDY

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New data on the NYF family of the rare-element class of granitic pegmatites suggest that this family is not as coherent as originally considered. To understand the emerging variability, a thorough characterization of diverse NYF populations is necessary. The Swedish Proterozoic hosts several populations of classic rare-earth-element-bearing pegmatites eminently suited for such a study, especially if one considers that they have not been properly re-examined during the 20th century (Gahn *et al.* 1818, Nordenskjöld 1908). Three pegmatite localities were selected for a comparative study using several criteria: 1) genetic link with a parent granite (a fundamental premise of any rare-element-class pegmatite) to study geochemical relations; 2) diversity (to represent broadly variable examples of the NYF pegmatites); 3) representativity (to examine typical examples, as opposed to exotic oddities), and 4) logistics (exposure and accessibility of the granite-pegmatite populations).

Abborrselet, in the Bräcke area in Jämtland, is a "textbook" NYF pegmatite, similar to the rare-earth-element-bearing pegmatites of the South Platte district, Colorado (Simmons & Heinrich 1980, Simmons *et al.* 1987). The horizontally subrounded pegmatite is internal to its granitic parent, the subaluminous Gröttingen granite. The reddish granite contains plagioclase-mantled microcline phenocrysts, and biotite is the dominant mica and the major mafic mineral. Geochemically, it is characterized by elevated amounts of niobium, yttrium and fluorine (Smeds 1994a). The main minerals are microcline perthite, plagioclase, quartz and minor biotite. Accessory minerals comprise at least two generations of fluorite, fluocerite-(Ce), REE fluorocarbonates, early allanite, zircon – xenotime-(Y) intergrowths, fergusonite-(Y) and, sporadically in the innermost zones, beryl and topaz.

Finnbo is one of the external vertical pegmatite dykes that have intruded metavolcanic and early granitoid rocks east and west of Falun, in south-central Sweden. The Finnbo pegmatite is the most fractionated derivative of a suite of pegmatitic granites, considered to compose pegmatitic cupolas of the moderately peraluminous Malingsbo granite (Smeds 1994b). The field relations resemble those commonly observed in LCT groups. K-feldspar, quartz, cleavelanditic albite and muscovite are the dominant rock-forming minerals. The accessory minerals are typical of NYF pegmatites: allanite-(Ce), gadolinite-(Y), Y-Nb-Ta oxides, monazite-(Ce), xenotime-(Y), and fluorite (Y-bearing, in several generations). However, peraluminous minerals (muscovite, almandine-spessartine, topaz), cassiterite and Ta-dominant members of the columbite family indicate a "mixed" character of the pegmatite.

Ytterby is situated on Resarö Island northeast of Stockholm. The pegmatite has been connected, by analogy with simple pegmatites of the Stockholm area, to the Stockholm granite, which occurs in lenses and small massifs in and around Stockholm (Brotzen 1959). Some authors consider it a locally derived anatectic granite, whereas others connect it with larger massifs of rooted granite derived from deep crustal sources. The bulk mineralogy consists of K-feldspar, oligoclase, quartz, large crystals of biotite (chloritized) and minor muscovite. Accessory minerals comprise allanite-(Ce), gadolinite-(Y), thortveitite, zircon, yttrantalite-(Y), formanite-(Y), fergusonite-(Y), uraninite, so far ill-defined Y-Ti-Nb-Ta oxides, xenotime-(Y), fluorapatite, scheelite, calcite, REE (fluoro)-carbonates, fluorite, almandine-spessartine, several sulfides and rare Be-dominant minerals.

The study of these granite-pegmatite systems involves: 1) geochemical and isotopic characterization of granitic parents, 2) trace-element analyses of the feldspars across the zoning of the pegmatites, and 3) update of the chemical composition of important accessory minerals by means of electron-microprobe analysis.



## REFERENCES

- BROTZEN, O. (1959): Outline of mineralization in zoned granitic pegmatites. A qualitative and comparative study. *Geol. Fören. Stockholm Förh.* **81**, 1-98.
- GAHN, J. G., BERZELIUS, J., WALLMAN, C. & EGGERTZ, H. P. (1818): Undersökning af några i trakten kring Fahlun funna fossilier, och af deras lagerställén. *Afhandlingar i Fysik, Kemi och Mineralogi* **5**, 1-91.
- NORDENSKIÖLD, I. (1908): Der Pegmatit von Ytterby. *Bull. Geol. Inst., Univ. Upsala* **9**, 183-228.
- SIMMONS, W.B. & HEINRICH, E.W. (1980): Rare-earth pegmatites of the South Platte District, Colorado. *Colorado Geol. Surv., Dep. Nat. Resources, Resource Ser.* **11**.
- \_\_\_\_\_, LEE, M.T. & BREWSTER, R.H. (1987): Geochemistry and evolution of the South Platte granite-pegmatite system, Jefferson County, Colorado. *Geochim. Cosmochim. Acta* **51**, 455-471.
- SMEDS, S.-A. (1994a): Rare-element granitic pegmatites of the Räggen area, Bräcke, north-central Sweden: two types of mineral assemblages, geochemistry and origin. In *Geochemical Fractionation and Zoning of some Granitic Pegmatite Fields in Sweden*. Ph.D. thesis, Uppsala Univ., Uppsala, Sweden.
- \_\_\_\_\_. (1994b): Zoning and fractionation trends of a peraluminous NYF granitic pegmatite field at Falun, south-central Sweden. *GFF* **116**, 175-184.

## OPTICAL PROPERTIES AND COMPOSITION OF MICAS FROM THE PIKES PEAK BATHOLITH AND THEIR CORRELATION WITH PEGMATITE EVOLUTION

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Optical properties and chemical composition were determined for a large set of mica samples from localities throughout the Pikes Peak batholith (PPB), Colorado. Samples range from annite, biotite, zinnwaldite and ferroan lepidolite (trioctahedral) to ferroan muscovite (dioctahedral). They were collected from within granitic units of the PPB as well as from cross-sections throughout different pegmatites. Earlier work (Foord *et al.* 1995) established a correlation between composition of micas (particularly Fe) and geochemical evolution of the PPB. Subsequent correlation of the  $\beta$  index of refraction with total Fe and degree of fractionation within the PPB permitted an assessment of pegmatite paragenesis (Kile & Foord 1998). Optical properties of the trioctahedral micas show a consistent trend of decreasing index of refraction, from an average  $n\beta$  of 1.693 in annite of the host granite to 1.577 in zinnwaldite and ferroan lepidolite of miarolitic cavities. This decrease in  $n\beta$  correlates with a progressively decreasing iron content. Figure 1 illustrates the geochemical evolution of the micas with respect to their major constituents.

A comparison of optical and compositional data for mica samples from localities throughout the PPB shows variation in geochemical evolution between pegmatites of different districts, and between the Pikes Peak Granite and its late satellitic intrusive bodies. Within individual pegmatites, micas enclosed within massive quartz are paragenetically older than those within miarolitic cavities, indicating the earlier formation of the massive quartz core structure within the pegmatite relative to crystallization within the miarolitic cavity, with the miarolitic cavity representing the final stage of primary crystallization. Figure 2 shows the sequential differentiation of the micas relative to their modes of occurrence for cross-sections within individual pegmatites.

These findings permit an assessment of the sequence of pegmatite paragenesis as well as inferences regarding the mechanism of formation, *e.g.*, miarolitic cavities developed in part as a consequence of pegmatite configuration

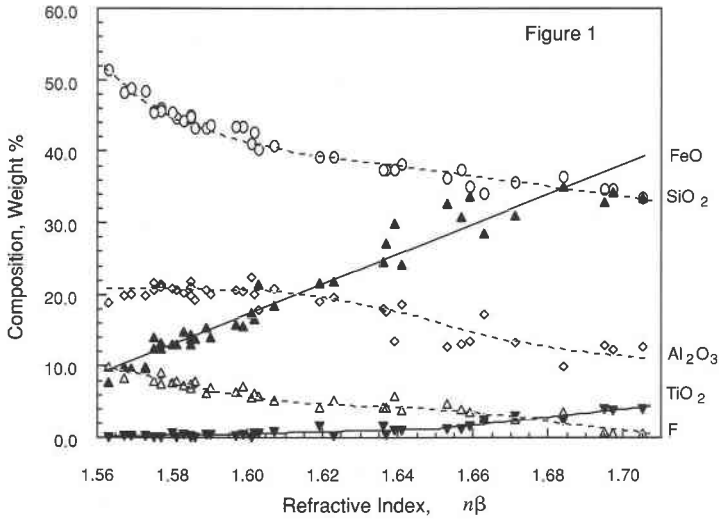


FIG. 1. Plot of the index of refraction  $n\beta$  as a function of the composition of the mica samples.

and inclination, but also as a result of early crystallization of massive quartz that confined the silicate melt and volatile phase, resulting in closed-system crystallization. A concomitant increase in pressure within the miarolitic cavities resulted in episodic rupture of the cavity, with corresponding changes in mica composition.

REFERENCES

FOORD, E.E., ČERNÝ, P., JACKSON, L.L., SHERMAN, D.M. & EBY, R.K. (1995): Mineralogical and geochemical evolution of micas from the miarolitic pegmatites of the anorogenic Pikes Peak batholith, Colorado. *Mineral. Petrol.* **55**, 1-26.

KILE, D.E. & FOORD, E.E. (1998): Micas from the Pikes Peak batholith and its cogenetic granitic pegmatites, Colorado: optical properties, composition, and correlation with pegmatite evolution. *Can. Mineral.* **36**, 463-482.

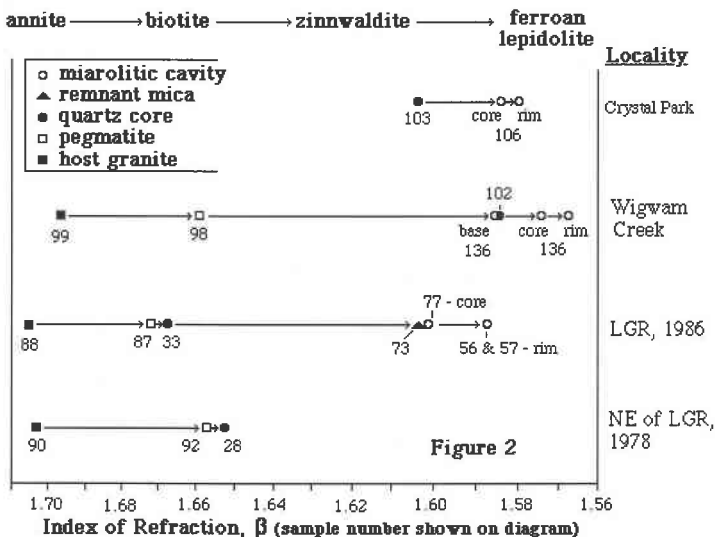


FIG. 2. Sequential differentiation of micas through cross-sections within individual pegmatites in the Pikes Peak batholith.

SUNDAY AFTERNOON, SEPTEMBER 12, 1999

**THE WAUSAU SYENITE COMPLEX, MARATHON COUNTY, WISCONSIN: ORIGIN, GEOCHEMISTRY, AND MINERALOGY OF A MID-PROTEROZOIC ANOROGENIC INTRUSIVE COMPLEX AND ITS PEGMATITES**ALEXANDER U. FALSTER<sup>§</sup>, WILLIAM B. SIMMONS AND KAREN L. WEBBER*Department of Geology and Geophysics, University of New Orleans, New Orleans, Louisiana 70148, U.S.A.*

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The Wausau Syenite Complex is a Proterozoic (1.52–1.48 Ga) shallow-level, anorogenic intrusive complex, consisting of four distinct intrusive centers: the Stettin, the Wausau, the Rib Mountain, and the Nine Mile plutons (Myers *et al.* 1984). Of the four, the syenitic Stettin pluton is the oldest and most strongly alkaline. This pluton is roughly concentrically zoned, with two nepheline syenite rings, one as the outermost unit, the other as a core margin around a pyroxene syenite core. The three other plutons, the Wausau, Rib Mountain, and Nine Mile, are progressively more silica-rich. The Nine Mile pluton consists of alkali granite and monzonite. Mirolitic pegmatites are found in all four intrusive centers. Pegmatites in the Stettin pluton range from nepheline-bearing to pyroxene- and amphibole-bearing types. Minor minerals include magnetite, zircon, apatite, ilmenite, xenotime, cheralite, and titanite. Rare accessories include eudialyte, catapleiite, fluorite, pyrochlore, allanite, thorite, and thorumite (Falster 1986). Pegmatites in the Nine Mile pluton are characterized by feldspars, quartz and minor biotite (siderophyllite). Minor minerals include magnetite, hematite, titanium oxide minerals, and siderite. Rare minerals include phenakite, bertrandite, cheralite, xenotime, zircon, and pyrite (Falster 1987). Significantly, columbite–tantalite-group minerals are virtually absent except in one localized area in the central Nine Mile pluton. Pegmatites of the Wausau and Rib Mountain plutons have characteristics between those of the Stettin and Nine Mile plutons. The presence of metastable potassium feldspar assemblages in mirolitic cavities attest to shallow levels of intrusion and rapid and complete degassing of these mirolitic cavities (Martin & Falster 1986). The intrusion of the Wausau Syenite Complex and the slightly younger Wolf River batholith to the east represent the last large-scale intrusive event in central Wisconsin.

As is the case in other anorogenic complexes, the Wausau Syenite Complex contains relatively low levels of B; however, the levels of Li and Ga are considerable, compared to the South Platte district in Colorado, for example.

Geochemically, samples from the Wausau Syenite Complex can be classified as within-plate granites (WPG) using the discrimination diagrams (Fig. 1) of Pearce *et al.* (1984), and as A<sub>1</sub>-type (rift, plume, and hotspot environments) granitic rocks (Fig. 2), according to Eby (1992). This interpretation is consistent with the anorogenic tectonic environment of the complex, and suggests that the melts that formed the Wausau Syenite Complex were derived from lower crustal materials. The older rocks of the Stettin pluton are enriched in Nb and Ga compared to the younger rocks of the Nine Mile pluton. Even though the overall content of Ta is low in the Nine Mile rocks, there is evidence for late enrichment in Ta in mirolitic columbite–tantalite species, which show a dramatic trend of Ta enrichment over Nb in the latest-formed columbite–tantalite species. Mn does not exhibit a similarly extensive enrichment, even though the latest columbite–tantalite members show a noticeable increase in Mn (Fig. 3). The high Fe:Mn ratio in rocks of the Wausau Syenite Complex may limit the formation of Mn-dominant phases.

## REFERENCES

- EBY, G.N. (1992): Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology* **20**, 641–644.
- FALSTER, A.U. (1981): Minerals of the Wausau Pluton. *Mineral. Rec.* **12**, 93–97.

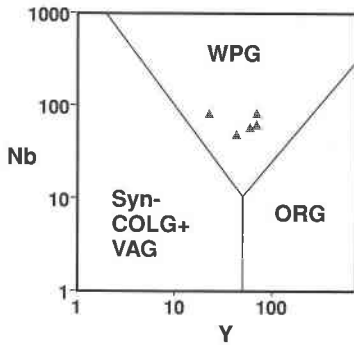


FIG. 1. Plot of  $Y$  versus  $Nb$  as a tectonic discriminant (Pearce *et al.* 1984) applied to the suites of the Wausau Syenite Complex. Trend from Stettin pluton to Nine Mile pluton rocks is indicated by the arrow.

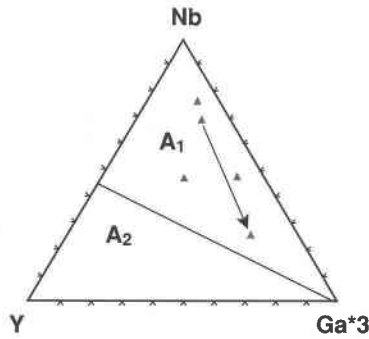


FIG. 2. Triangular plot for distinguishing between A1 (rift, plume, and hotspot environments) and A2 (post-collisional, postorogenic and anorogenic environments) granitic rocks (Eby 1992). Trend from Stettin pluton to Nine Mile pluton rocks is indicated by the arrow.

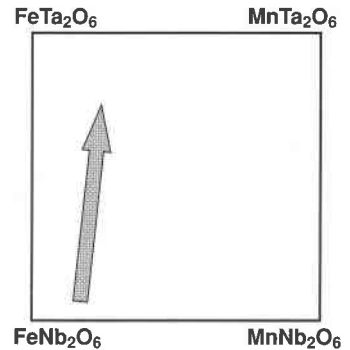


FIG. 3. Columbite-tantalite fractionation trend for the pegmatites of the Wausau Syenite Complex.

\_\_\_\_\_ (1986): Minerals of the Stettin Pluton. *Rocks & Minerals* **61**, 74-78.

\_\_\_\_\_ (1987): Minerals of pegmatite bodies in the Wausau Pluton, Wisconsin. *Rocks & Minerals* **62**, 188-193.

MARTIN, R.F. & FALSTER A.U. (1986): Proterozoic sanidine and microcline in pegmatite, Wausau Complex, Wisconsin. *Can. Mineral.* **24**, 709-716.

MYERS, P.E., SOOD, M.H., BERLIN, L.A. & FALSTER, A.U. (1984): The Wausau Syenite Complex, central Wisconsin. *Thirtieth Annual Inst. on Lake Superior Geology, Field Trip Guidebook* **3**.

PEARCE, J.R., HARRIS, N.B.W. & TINDLE, A.G. (1984): Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* **25**, 956-983.

## NYF PEGMATITES OF THE SOUTH PLATTE DISTRICT, COLORADO

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Pegmatites of the South Platte district, Jefferson County, Colorado, constitute one of the world's classic NYF pegmatite districts. The district is located within the Precambrian core of the Rocky Mountain Front Range in central Colorado, near the northern margin of the Pikes Peak batholith. More than 75 pegmatite bodies belong to this district, and all are enriched in Niobium, Yttrium and Fluorine. Samarskite-(Y) is abundant throughout the district, and many tonnes were mined from several pegmatites. Synchysite-(Y) and xenotime-(Y) are abundant in several pegmatites, and fluorite is abundant in most. Several contained mapable zones of fluorite. The whole pegmatite-granite system is extremely REE-enriched, and the pegmatites are well known for their contents of relatively abundant rare-earth minerals (Simmons & Heinrich 1980, Simmons *et al.* 1987). Boron is virtually absent, and beryllium is present only in rare gadolinite-(Ce). Only a few samples of beryl have been found in the entire district. All of the mica occurs as biotite, and the feldspars are pink. The pegmatites are enriched in Fe, and pods of metallic hematite occur in some pegmatites. In addition, there is abundant secondary replacement by hematite.

In addition to the common rock-forming minerals such as quartz, microcline, sodic plagioclase, and biotite, the following accessory minerals are prevalent: hematite, fluorite, zircon (cyrtolite), muscovite, siderite, calcite, pyrolusite, and widespread rare-earth minerals, which include yttrian fluorite, cerian fluorite, monazite-(Ce), xenotime-(Y), allanite-(Ce), samarskite-(Y), fergusonite-(Y), yttriotantalite-(Y), gadolinite-(Ce), gadolinite-(Y), molybdenite, thorite, thalénite-(Y), synchysite-(Y) and bastnäsité-(Ce). In some deposits, one or more of these minerals may be very abundant in secondary units. Very rarely, minerals such as sellaite and autunite have been found.

The pegmatites are characterized by an extraordinarily well-developed internal zonation, which is spectacularly well displayed in three dimensions, owing to selective mining techniques, which have completely removed the intermediate zones, leaving quartz cores standing in bold relief. The structure of these pegmatites, from the outer margin to the core, consists of: 1) a poorly developed thin border zone (rarely present), 2) a wall zone of biotite graphic granite, 3) an outer-intermediate zone of giant biotite crystals (rarely present), 4) an intermediate zone of microcline perthite, 5) a core-margin zone of green fluorite, 6) a large core of massive quartz (quartz-core pegmatites) or quartz-microcline (composite-core pegmatites), and 7) secondary replacement units superimposed on the primary zonal sequence, containing albite, fluorite, *REE* minerals, and hematite.

Quartz-core pegmatites are roughly circular in plan and contain four or more well-developed, mappable zones, including a wall zone, an intermediate zone of microcline perthite, a core-margin zone of green fluorite, and a large core of nearly pure, monomineralic quartz. Typically, this type is more extensively replaced by secondary mineralization that is more complex and variable than that of the other zonal type. Composite-core pegmatites are distinctly zoned, but generally display only a core and a wall zone and lack an intermediate zone. Composite-core pegmatites tend to be more irregular in shape and commonly have elliptical horizontal cross-sections. The cores in this type are characteristically large in proportion to the rest of the pegmatite, compared to the quartz-core pegmatites. Within the South Platte district, the quartz-core and the composite-core pegmatites cluster into two geographical groups. The quartz-core pegmatites cluster in the northern part of the district, whereas composite-core pegmatites occur in the south.

All the pegmatites in the South Platte district are contained within the parental Pikes Peak batholith and are thus unambiguously genetically related to the Proterozoic A-type Pikes Peak granite. Geochemically, granitic rocks from the South Platte district have high Ga/Al values and high  $K_2O + Na_2O$  compared to M-, S-, and I-type granites, and plot in the A-type field of Whalen *et al.* (1987) (Fig. 1). These rocks can be classified as within-plate granites (WPG) using the Nb-Y discrimination diagram (Fig. 2) of Pearce *et al.* (1984). A triangular plot of Nb, Y and  $Ga*3$  reveals that the South Platte granitic rocks can be classified as of the A2 type (postcollisional, postorogenic and anorogenic environments) of within-plate granite (Fig. 3), according to Eby (1992).

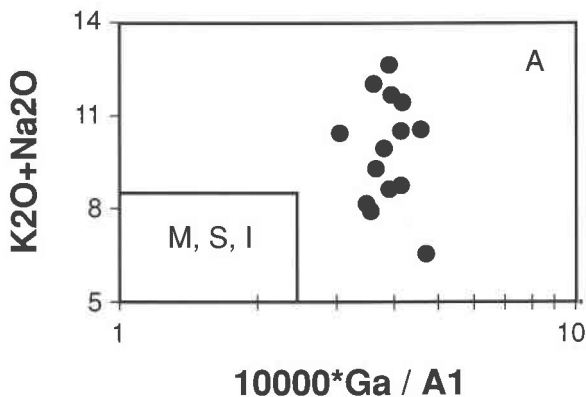


FIG. 1.  $Ga*10000/Al$  versus  $K_2O + Na_2O$  discrimination diagram of Whalen *et al.* (1987). South Platte granitic rocks plot in the A-type field and have high Ga/Al ratios and high  $K_2O + Na_2O$  compared to the field of M-, S-, and I-type granites.

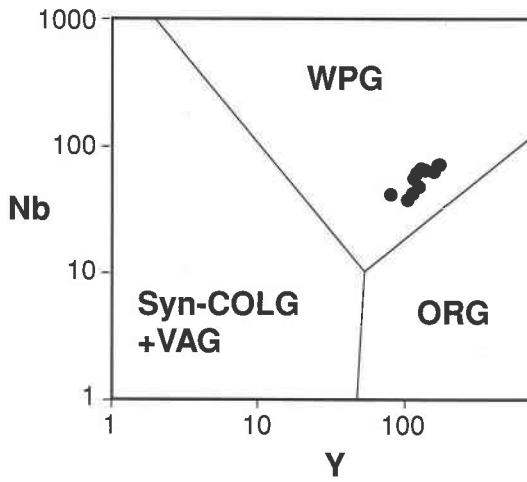


FIG. 2. Y versus Nb tectonic discrimination diagram of Pearce *et al.* (1984), showing the within-plate signature for granitic rocks of the South Platte district.

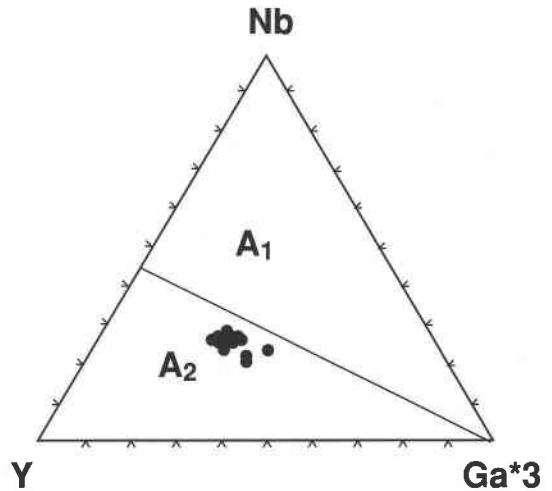


FIG. 3. Triangular plot for differentiating between A1-type (rift, plume, and hotspot environments) and A2-type within-plate granites (post-collisional, postorogenic and anorogenic environments) (Eby 1992), showing the A2-type character of the South Platte suite of granitic rocks.

The degree of pegmatite fractionation is typically evaluated by using fractionation indicators such as K/Rb, K/Cs, and Fe/Mn, *etc.* Whereas this approach works well for LCT-type pegmatites, these elements do not effectively measure the degree of fractionation in NYF-type pegmatites. Fractionation in NYF-type pegmatites may be better evaluated by considering elements enriched in A-type granites, such as Nb, Y, F, REE, Zr and Ga. The degree of fractionation of REE + Y, Nb, and F in South Platte pegmatites is extreme and suggests that their relative degree of fractionation is comparable to that of LCT-type pegmatites.

#### REFERENCES

- EBY, G.N. (1992): Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology* **20**, 641-644.
- PEARCE, J.R., HARRIS, N.B.W. & TINDLE, A.G. (1984): Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* **25**, 956-983.
- SIMMONS, W.B. & HEINRICH, E.W. (1980): Rare-earth pegmatites of the South Platte district, Colorado. *Colorado Geol. Surv., Resource Ser.* **11**.
- \_\_\_\_\_, LEE, M.T. & BREWSTER, R.H. (1987): Geochemistry and evolution of the South Platte granite-pegmatite system, Jefferson County, Colorado. *Geochim. Cosmochim. Acta* **51**, 455-471.
- WHALEN, J.B., CURRIE, K.L. & CHAPPELL, B.W. (1987): A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contrib. Mineral. Petrol.* **95**, 407-419.

## BIOTITE AS A TECTONIC DISCRIMINANT FOR ANOROGENIC AND OROGENIC PEGMATITES

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Biotite from three pegmatite districts was analyzed in order to compare and contrast its chemical composition in suites from anorogenic and orogenic tectonic regimes. Pegmatite districts investigated included the orogenic Trout Creek Pass (TCP) district and two anorogenic districts, the South Platte (SP) and the Wausau Syenite Complex (WSC). Compared to orogenic granites, anorogenic granites are characterized by high FeO/MgO values, high abundances of SiO<sub>2</sub>, K<sub>2</sub>O + Na<sub>2</sub>O, F, Rb, Ga, Y, REE (except Eu), Zr, Th, Nb, U, and Zn, and by low concentrations of CaO, MgO, Al<sub>2</sub>O<sub>3</sub>, Cr, and Ni (Eby 1990). Typically, NYF-type pegmatites are hosted in A-type granites. The major- and trace-element chemistry of the pegmatite suites in these districts should be reflected in the mineralogy of the pegmatites, and thus variations in mineral chemistry should be apparent between anorogenic and orogenic tectonic settings. For this study, biotite was examined, as it is present in all three pegmatite districts.

The Trout Creek Pass (TCP) pegmatite district, in Chaffee County, Colorado, is associated with the catazonal, orogenic, 1.7 Ga Denny Creek Granodiorite, emplaced during the Boulder Creek Orogeny. Pegmatites are notably enriched in REE, Nb, Y and Ti, and depleted in F, and are simply zoned, composite-core pegmatites (Hanson *et al.* 1992). TCP was included in this study as it is associated with an orogenic event, yet the chemical composition of the pegmatites suggests a close affiliation with NYF-type pegmatites.

The South Platte (SP) pegmatite district is located in Jefferson County, Colorado, in the Colorado Front Range. All the pegmatites are associated with the 1.0 Ga anorogenic, epizonal, composite Pikes Peak Batholith (Simmons & Heinrich 1980). They are significantly enriched in F, REE, Nb and Y, and exhibit well-developed internal zonation (Simmons *et al.* 1987). Geochemically, granitic rocks from the South Platte district can be described as A<sub>2</sub>-type granites according to Eby (1992) and within-plate granites (WPG) using the discrimination diagrams of Pearce *et al.* (1984).

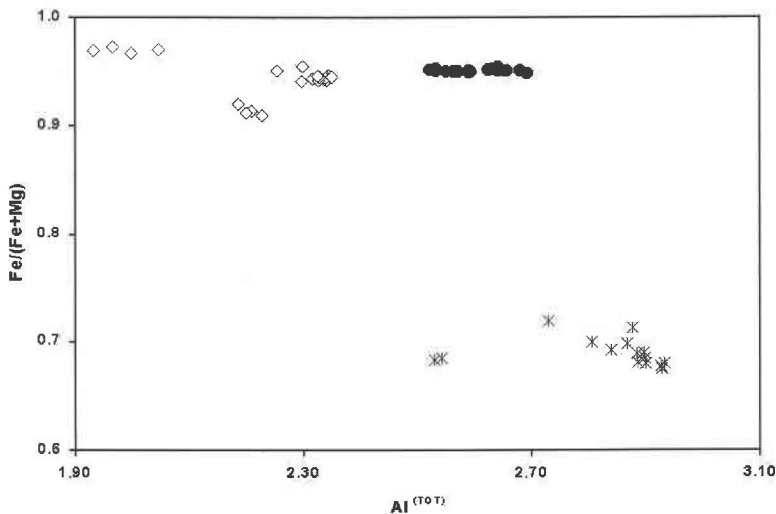


Fig. 1. Fe/(Fe + Mg) versus total Al in biotite from the TCP district (stars), WSC (open diamonds), and the SP district (filled circles). Biotite compositions were recalculated on the basis of 22 atoms of oxygen.

The Wausau Syenite Complex (WSC) is a Proterozoic (1.52–1.48 Ga) epizonal, anorogenic intrusive complex, consisting of four distinct intrusive centers, the Stettin, the Wausau, the Rib Mountain, and the Nine Mile plutons (Myers *et al.* 1984). Within the Nine Mile pluton, a group of more evolved F-enriched pegmatites (Koss pegmatite group) has recently been found. Mirolitic pegmatites are found in all four intrusive centers and are enriched in REE, Nb, Y and F (Falster 1987). Geochemically, samples from the Wausau Syenite Complex can be classified as within-plate granitic rocks (WPG) using the discrimination diagrams of Pearce *et al.* (1984), and as A<sub>1</sub>-type granites according to Eby (1992).

Biotite compositions from all three areas are distinct. Biotite from pegmatites and granites in the SP and WSC suites is annite-rich, with high Fe/(Fe + Mg) values ranging from 0.91 to 0.95 for the WSC and ~0.95 for the SP district (Fig. 1). Biotite in the TCP suite is more Mg-rich, with a Fe/(Fe + Mg) value of ~0.70. Biotite compositions in the WSC suite have lower Mn<sup>2+</sup> and higher Ti than do SP biotite compositions, whereas TCP biotite has intermediate levels of both. F varies from 2.5 to 4.0 wt % in WSC biotite, with the most F-rich biotite compositions coming from the Koss granite and pegmatite. SP biotite contains between 3.0 and 3.75 wt% F, whereas TCP biotite contains only 1.0 to 1.5 wt% F (Fig. 2). Biotite compositions in the TCP suite have the highest Al<sup>TOT</sup> of all three districts (Fig. 1). Interestingly, two discrete populations of biotite can be differentiated in the SP district on the basis of their Al<sup>TOT</sup> and Si contents (Fig. 3). The first group of biotite, which is found in topaz-bearing pegmatites, is characterized by lower Si and <sup>VI</sup>Al, and higher <sup>IV</sup>Al, Mn<sup>2+</sup> and Ti. The second group of biotite, characterized by higher Si and <sup>VI</sup>Al, is taken from SP pegmatites that have little to no topaz. The Al-rich biotite population may be explained by the contamination of the pegmatite-forming melts by metasedimentary rocks of the overlying Idaho Springs Formation, which produced local enrichments of aluminum, as evidenced by the presence of topaz. The chemical composition of the biotite was also used to determine *f*(H<sub>2</sub>O) for the pegmatite districts, using the formula of Wones & Eugster (1965). Consistent with the Fe/(Fe + Mg) values in biotite at the QFM buffer, a temperature of 800°C and log *f*(O<sub>2</sub>) of -15 bars for biotite in the TCP suite and a temperature of 725°C and log *f*(O<sub>2</sub>) of -17 bars for both SP and WSC was used for the calculations. The TCP suite had the highest *f*(H<sub>2</sub>O), ~10<sup>3.8</sup> bars. Both SP and WSC suites crystallized at a lower *f*(H<sub>2</sub>O), ~10<sup>3</sup> bars.

The chemical composition of biotite in the SP and WSC districts is distinctly different from that in the TCP suite, accurately reflecting the different tectonic settings. In the SP and WSC districts, the biotite has a high Fe/(Fe + Mg) value and is F-rich, which are characteristics of anorogenic granites. Even though the TCP district is enriched in REE, Nb and Y, and thus has some chemical characteristics in common with anorogenic granites, the composition of the biotite [lower Fe/(Fe + Mg) value, low F, *etc.*] accurately reflects its orogenic tectonic setting.

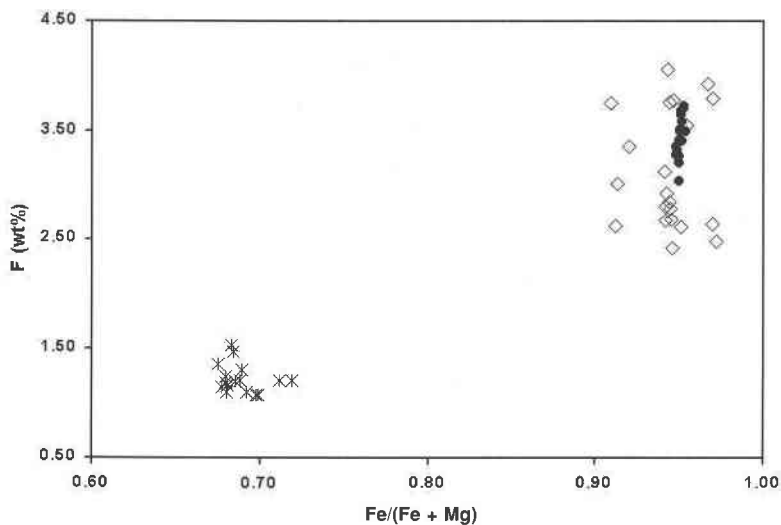


FIG. 2. Weight percent F versus Fe/(Fe + Mg) for biotite from the TCP, WSC and SP districts. Symbols as in Figure 1.



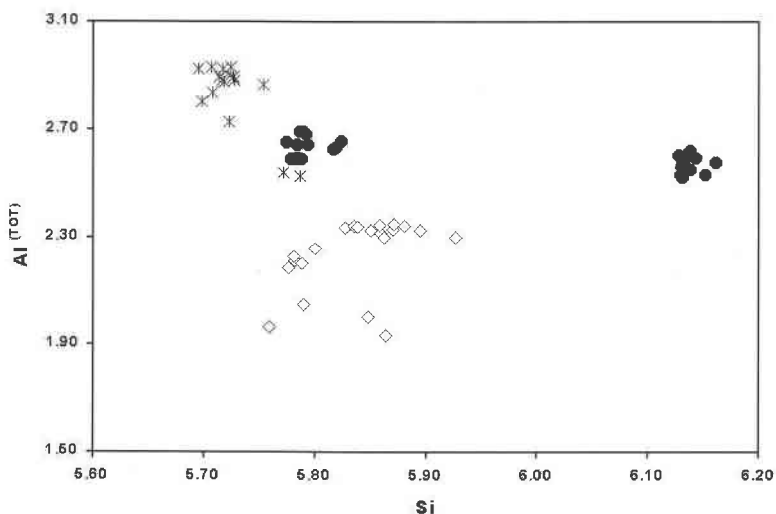


FIG. 3. Total Al versus Si (apfu) for biotite from the TCP, WSC and SP districts. Symbols as in Figure 1.

#### REFERENCES

- EBY, G.N. (1990): The A-type granitoids: a review of their occurrence and chemical characteristics and speculations on their petrogenesis. *Lithos* **26**, 115-134.
- \_\_\_\_\_ (1992): Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology* **20**, 641-644.
- FALSTER, A.U. (1987): Minerals of the pegmatitic bodies in the Wausau pluton. *Rocks & Minerals* **62**, 188-193.
- HANSON, S.L., SIMMONS, W.B., WEBBER K.L. & FALSTER, A.U. (1992): Rare-earth-element mineralogy of granitic pegmatites in the Trout Creek Pass district, Chaffee County, Colorado. *Can. Mineral.* **30**, 673-686.
- MYERS, P.E., SOOD, M.K., BERLIN, L.A. & FALSTER, A.U. (1984): The Wausau Syenite Complex, central Wisconsin. *Thirtieth Annual Inst. on Lake Superior Geology, Field Trip Guidebook* **3**.
- PEARCE, J.R., HARRIS, N.B.W. & TINDLE, A.G. (1984): Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* **25**, 956-983.
- SIMMONS, W.B. & HEINRICH, E.W. (1980): Rare-earth pegmatites of the South Platte District, Colorado. *Colorado Geol. Surv., Dep. Natural Resources, Resource Ser.* **11**.
- \_\_\_\_\_, LEE, M.T. & BREWSTER, R.H. (1987): Geochemistry and evolution of the South Platte granite-pegmatite system, Jefferson County, Colorado. *Geochim. Cosmochim. Acta* **51**, 455-471.
- WONES, D.R. & EUGSTER, H.P. (1965): Stability of biotite: experiment, theory, and application. *Am. Mineral.* **50**, 1228-1272.

SUNDAY AFTERNOON, SEPTEMBER 12, 1999

## POSTER SESSION

ON THE EXTREME CONCENTRATION OF SOME MINOR ELEMENTS  
IN GRANITIC PEGMATITESBORIS M. SHMAKIN<sup>§</sup>, VLADIMIR M. MAKAGON, VICTOR YE. ZAGORSKY  
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As shown by Černý *et al.* (1985), extreme fractionation in rare-element granitic pegmatites starts in metamorphic protoliths, then takes place in pegmatite-generating granites and in pegmatite bodies. Those authors recommended a systematic collection of data on elemental abundances in pegmatites of different classes and types. In our studies of granitic pegmatites, we found many cases in which minerals of REE, Th, U, Sn, Nb, Ta, Bi, Sb, S and some other *minor elements* (ME), considering granitic pegmatites, formed during the final stages of pegmatite crystallization. In the group of ME, we include elements that are not essential isomorphous admixtures in any rock-forming minerals of pegmatites (feldspars, quartz, micas, spodumene, petalite, amblygonite). The behavior of Li, Rb, Cs, Ba, Sr, Pb, Tl, Ga, Ge, Mn, as well as P, B, F and some other major and trace elements is beyond the limits of this paper.

Most rare minerals concentrating ME occur in miarolitic pegmatites, in which cavities form during the final stages of crystallization (Zagorsky *et al.* 1999). The group of REE-concentrating minerals includes gadolinite, hellandite, allanite and, less commonly, bastnäsite and minasgeraisite. Minerals concentrating Nb and Ta, together with minor amounts of Bi, Sb, Sn, W, U and Th, include columbite-tantalite as well as betafite, pyrochlore, microlite, ixiolite, and behierite. Bismuth minerals include beyerite, native Bi, bismutite, bismite and bismuthinite. In addition to bismuthinite, other sulfides found in this group of pegmatites are sphalerite, pyrite, galena, chalcopyrite, and arsenopyrite. The As-mineral zimbabweite,  $(\text{Na},\text{K})_2\text{PbAs}_4(\text{Ta},\text{Nb},\text{Ti})_4\text{O}_{18}$ , was discovered in the St. Anne (Zimbabwe) deposit of mica, beryl and precious stones (Foord *et al.* 1986), where the miarolitic facies is manifested in veins of rare-metal – muscovite pegmatites.

In rare-metal – rare-earth pegmatites of the Baikal area (Shmakin 1992), betafite, euxenite, fergusonite and other minerals concentrating ME formed during the final stages of pegmatite crystallization. However, the average contents of Nb, REE, U and Th in pegmatite bodies and parental granites are very low, even lower than in the metamorphic country-rocks (Bobrov *et al.* 1996). This observation implies that REE mineralization is a result of ME accumulation in residual fluids in view of their absence (less than detection limits) in feldspars, micas and quartz of the main parts of pegmatite bodies.

Proper rare-metal (rare-element after Černý 1991) pegmatites are themselves the result of fractionation processes, which begin in the fertile granitic magma and continue to their final emplacement. For ME, the mechanism of concentration seems to involve an accumulation in residual fluids. In many rare-metal pegmatites, there are “strange” minerals such as sulfides of Cu, Pb, Zn, Cd, and Sn, including chalcopyrite, chalcocite, galena, sphalerite, hawleyite, černýite, kęsterite, stannite, *etc.* In the complex pegmatites of Bikita, Tanco, or Tin Mountain, sulfide minerals are late phases of crystallization in the central parts of pegmatite bodies.

In mica-bearing pegmatites, many accessory minerals concentrate ME. In the Karelia–Kola region, about 60 such minerals were stabilized, including uraninite, allanite, monazite, xenotime, zircon, and some sulfides. As shown by Nikitin (1957) and Leonova (1965), most of these minerals have a metasomatic origin, having deposited from late solutions. The pegmatites of the Mama mica-bearing region contain allanite, monazite, zircon and galena in the central parts of veins. Sulfides such as pyrite and pyrrotite are more common in the so-called quartz–muscovite replacement assemblage, which formed in primary feldspar zones.

The U-REE pegmatites of the Aldan Shield show evidence for the late crystallization of the accessory minerals zircon, titanite, apatite, rutile, magnetite, various sulfides, and the REE-, Th- and U-rich phases allanite, thorite and chevkinite (Shmakin 1958).

For the extreme concentration of ME in pegmatites, the main mechanism of formation of minerals is an accumulation of these elements in residual fluids under closed-system crystallization of a pegmatite body (Fersman 1940). Whereas major elements create rock-forming minerals and many trace elements enter as isomorphic admixtures, some ME are preserved in melts or solutions up to the time when they form minerals in central parts of veins, in metasomatic zones, or in cavities. The crystallization of ME-dominant minerals or the inclusion of ME as isomorphic admixtures depends upon the necessary levels of ME concentration and on the stability of minerals with respect to P-T-pH-Eh conditions.

#### ACKNOWLEDGEMENTS

This work is supported by the Russian Fund for Fundamental Research (RFFR), grant 98-05-64197.

#### REFERENCES

- BOBROV, V.A., MAKAGON, V.M. & SHMAKIN, B.M. (1996): Rare earths in granites and pegmatites of Prebaikalia. *Dokl. Akad. Nauk* **349**(1), 86-89 (in Russ.).
- ČERNÝ, P. (1991): Rare-element granitic pegmatites. I. Anatomy and internal evolution of pegmatite deposits. *Geosci. Canada* **18**, 49-67.
- \_\_\_\_\_, MEINTZER, R.E. & ANDERSON, A.J. (1985): Extreme fractionation in rare-element granitic pegmatites: selected examples and mechanisms. *Can. Mineral.* **23**, 381-421.
- FERSMAN, A.E. (1940): *Pegmatites. 1. Granitic pegmatites*. The USSR Academy of Sciences, Moscow, Russia (in Russ.; translated into French and published in 1951 by Univ. of Louvain, Belgium).
- FOORD, E.E., TAGGART, J.E., GAINES, R.V., GRUBB, P.L.C. & KRISTIANSEN, R. (1986): Zimbabwe, a new alkali-lead-arsenic tantalate from St. Anne mine, Karoi district, Zimbabwe. *Bull. Minéral.* **109**, 331-336.
- LEONOVA, V.A. (1965): Some questions of geochemistry and genesis of the Chupa pegmatite veins (northern Karelia). *Zap. Vses. Mineral. Obshchest.* **94**, 272-287 (in Russ.).
- NIKITIN, V.D. (1957): Peculiarities of rare-metal mineralization in pegmatite veins. *Zap. Vses. Mineral. Obshchest.* **86**, 18-27 (in Russ.).
- SHMAKIN, B.M. (1958): Archean granitoids of the Kuranakh phlogopite-bearing area at Aldan Shield. *Izvestia vuzov, Geologia i razvedka* **1**(10), 46-60 (in Russ.).
- \_\_\_\_\_. (1992): Mineralogy and geochemistry of REE in granitic pegmatites, Baikal region, eastern Siberia, Russia. *Appl. Geochem.* **7**, 459-468.
- ZAGORSKY, V.YE., PERETYAZHKO, I.S. & SHMAKIN, B.M. (1999): *Granitic pegmatites. 3. Mirolitic pegmatites*. Nauka, Siberian Enterprise, Russian Academy of Sciences, Novosibirsk, Russia (in Russ.).

## COLORADO PEGMATITES: MAP AND DATABASE

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No single publication gives the locations, minerals, and references for Colorado's principal pegmatites. Few new pegmatite localities were added to *Minerals of Colorado* (Eckel *et al.* 1997). Emphasis in updating Eckel's 1961 edition of *Minerals of Colorado: a One Hundred-Year Record* was on adding data on various species, many new to Colorado. Much new information on Colorado pegmatites came from papers presented at the 1986 Pegmatite Symposium, sponsored by the Colorado Chapter of the Friends of Mineralogy and the Denver Museum of Natural History. A review of the state's pegmatite districts by Jacobson (1986) at that symposium was the first compilation since the maps and overviews of Colorado rare-earth and pegmatite minerals by Heinrich (1957), Haynes (1960), and Adams (1964a, b). Those early reports drew upon detailed information in Hanley *et al.* (1950), published as a result of U.S. Geological Survey explorations for strategic minerals.

Since the 1997 publication of *Minerals of Colorado*, our emphasis at the Denver Museum of Natural History has been on computerizing data for specimens in the collections and developing a comprehensive locality database. Many of our efforts have been directed toward the collection of Colorado minerals donated in 1982 by Dr. E. William Heinrich (1918–1991), long-time professor of mineralogy at the University of Michigan. This collection consists primarily of pegmatite minerals from classic Colorado localities collected by Heinrich and his students. Many of the species represented in this collection are described in the literature.

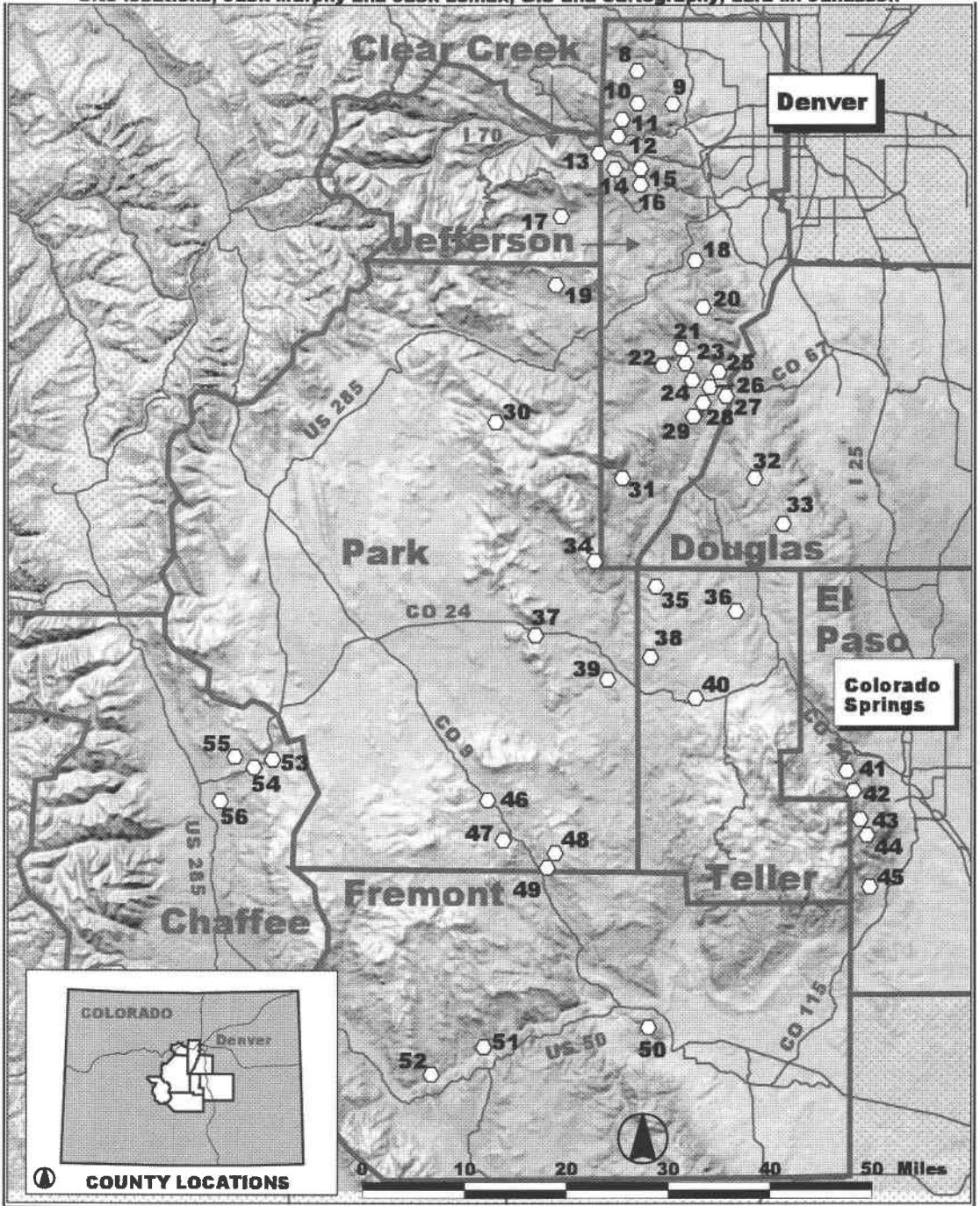
A new program has been initiated to use combined data from specimens in the Museum's collections and Geographic Information Systems technology to develop maps of Colorado mineral localities. The accompanying map (Fig. 1) of selected Colorado pegmatites shows localities represented in the collection available to researchers. A future interactive exhibit in the Museum's Coors Mineral Hall will allow visitors to determine which Colorado minerals occur in their neighborhood. An on-line version with a map and collections database will serve as a resource for educators, curators, researchers, and collectors.

### REFERENCES

- ADAMS, J.W. (1964a): Rare earths. In *Mineral and Water Resources of Colorado. U.S. Geol. Surv. and the Colorado Minerals Industrial Development Board, 88th Congress, 2nd session* (127-132).
- \_\_\_\_\_ (1964b): Pegmatite minerals. In *Mineral and Water Resources of Colorado. U.S. Geol. Surv. and the Colorado Minerals Industrial Board, 88th Congress, 2nd session* (169-173).
- ECKEL, E.B. (1961): Minerals of Colorado – a 100-Year Record. *U.S. Geol. Surv., Bull.* **1114**.
- \_\_\_\_\_, COBBAN, R.R., COLLINS, D.S., FOORD, E.E., KILE, D.E., MODRESKI, P.J. & MURPHY, J.A. (1997): *Minerals of Colorado* (updated and revised). Friends of Mineralogy – Colorado Chapter and the Denver Museum of Natural History, Fulcrum Publishing, Denver, Colorado.
- HANLEY, J.B., HEINRICH, E.W. & PAGE, L.R. (1950): Pegmatite investigations in Colorado, Wyoming, and Utah, 1942–1944. *U.S. Geol. Surv., Prof. Pap.* **227**.
- HAYNES, C.V., Jr. (1960): The rare earths. In *Mineral Resources of Colorado, First Sequel: Denver* (S.M. del Rio, ed.), State of Colorado Mineral Resources Board, Denver, Colorado (370–385).
- HEINRICH, E.W. (1957): Pegmatite provinces of Colorado. In *Selected Studies of Colorado Pegmatites and Sillimanite Deposits. Colorado School of Mines Quarterly* **52**(4), 1-22.
- JACOBSON, M.I. (1986): Granitic pegmatite districts of Colorado: an overview. In *Colorado Pegmatites – Abstracts, Short Papers, and Field Guides from the Colorado Pegmatite Symp.* (Denver) (P.J. Modreski, ed.). *Colorado Chapter, Friends of Mineralogy*, 6-15.

# SELECT COLORADO PEGMATITES

Site locations, Jack Murphy and Jack Lomax; GIS and Cartography, Lara M. Juliusson



8	Drew Hill pegmatite	25	White Cloud pegmatite	42	Tenney Crags – Specimen Rock
9	Cressmans Gulch pegmatite	26	Dazie Bell pegmatite	43	Stove Mountain pegmatites
10	Guy Hill pegmatite	27	Madonna pegmatite	44	Eureka Tunnel
11	Centennial Cone pegmatite	28	Shuttle Run pegmatite	45	Deadmans Canyon pegmatites
12	Roscoe pegmatite	29	Big Bertha pegmatite	46	Meyers Ranch pegmatite
13	Floyd Hill – Beaver Brook	30	McGuire pegmatite	47	Betty mine
14	Creswell mine	31	Wigwam Creek pegmatites	48	Rose Dawn pegmatite
15	Burroughs mine	32	Devils Head pegmatites	49	Climax pegmatite
16	Swede Gulch pegmatite	33	Long Hollow – Rampart Range	50	Eight Mile Park pegmatites
17	Bald Mountain pegmatite	34	Spruce Grove pegmatites	51	Devil's Hole pegmatite
18	Bigger pegmatite	35	Hackett Mountain pegmatite	52	Henry pegmatite
19	Harris Park pegmatites	36	Snowflake pegmatite	53	Clora May pegmatite
20	Critchell mine	37	Pipe Springs pegmatites	54	Crystal #8 (Luella) pegmatite
21	Bossie pegmatite	38	Crystal Peak pegmatites	55	Yard pegmatite
22	Seerie pegmatite	39	Teller pegmatite	56	Tie Gulch pegmatite
23	Little Patsy pegmatite	40	Black Cloud pegmatite		
24	Oregon Group pegmatites	41	Cameron Cone pegmatites		

## ROLE OF MICAS IN THE CONCENTRATION OF LIGHT ELEMENTS (Li, Be AND F) IN CRUSTAL GRANITES: AN EXPERIMENTAL AND CRYSTAL-CHEMICAL STUDY

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We present results of a study of the role of micas in the processes of concentration of the light elements Li, Be and F during the crystallization of peraluminous granites. The study is based on two complementary approaches. 1) We have carried out an experimental investigation of equilibria between micas and granitic melts under various conditions of T, P and  $f(\text{O}_2)$ . Two naturally occurring compositions have been selected: the Beauvoir granite (French Massif Central), and the Manaslu granite (Himalaya). 2) We also have studied the short- and long-range order of  $\text{Li}^+$ ,  $\text{Be}^{2+}$ ,  $\text{OH}^-$  and  $\text{F}^-$  in pertinent mica solid-solutions (lepidolite series).

Our study demonstrates that oxygen fugacity controls the nature and the composition of micas that crystallize from leucogranitic melts, at a constant bulk-composition. As a matter of fact, from the Beauvoir granite composition, the stable mica is close to zinnwaldite under oxidizing conditions ( $\text{NNO} + 1.2 \log \text{units}$ ), whereas under reducing conditions ( $\text{NNO} - 1.5 \log \text{units}$ ), the stable mica is biotite. In experiments performed on the Manaslu granite, the composition of the biotite is mainly controlled by the temperature, the fugacity of oxygen, and the presence or absence of muscovite. The presence of muscovite is controlled by the initial  $\text{H}_2\text{O}$  content of the melt and by the fugacity of oxygen. As for the light elements, the study demonstrates that trioctahedral micas are capable of trapping Li, Be and F at the magmatic stage. Lithium and fluorine favor trioctahedral micas, *i.e.*, biotite-series minerals and their solid solution toward zinnwaldite, whereas beryllium is preferentially incorporated into dioctahedral mica solid-solutions. In this case, it is invariably associated with an additional proton, located on the apical oxygen of a  $(\text{BeO}_4)^{6-}$  tetrahedron, adjacent to a vacancy in the octahedral position.

The positive correlation between Li and F observed in naturally occurring micas, as well as in experimental systems, results from the disappearance of the dioctahedral character of the mica, which, in turn, is controlled by oxygen fugacity, *i.e.*, by the valence state of the iron.

## MINERALOGY OF NYF GRANITIC PEGMATITES

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NYF granitic pegmatites are characterized by an overall geochemical affinity for Nb, Y, and F, as well as Ti, Zr, U, REEs, Mo, Sb and Bi. In the past, the mineralogy of NYF pegmatites was considered to be mundane; yet upon closer investigation, such pegmatites seem to be more diverse than previously considered (Table 1). NYF pegmatites are composed predominantly of K-feldspar, quartz, plagioclase and biotite. Typical accessory phases include garnet, amphibole, Fe oxides and REE-bearing phosphates, oxides and silicates. Nb-Ta-Sn oxides, halides, beryl, topaz and tourmaline are present in rare amounts. The minerals occur as accessory or rare phases throughout the pegmatite body, including miarolitic cavities.

K-feldspar and quartz are ubiquitous and may change color where near radioactive minerals. More rarely, amazonite, the blue-green variety of microcline, appears to be typical of NYF pegmatites. Plagioclase ranges from dominantly albite to oligoclase in composition. Biotite is the dominant mica, occurring as black, dark green or brown books or laths in the outer zones of the pegmatites. Zinnwaldite and ferroan lepidolite are even more uncommon and mainly relegated to either crystals in vugs and pockets or to the innermost zones of the most fractionated NYF pegmatites. Muscovite occurs as rare minute books and flakes, mainly in pocket assemblages. Almandine and spessartine form subhedral to euhedral cinnamon to orange crystals and may be scattered throughout the pegmatite.

Sodic amphiboles (arfvedsonite and riebeckite) form blue to black crystals in peralkaline NYF pegmatites. They are found mainly in the outer zones of a pegmatite or in miarolitic cavities, but may also occur as fibrous or radial aggregates concentrated around decomposing aegirine or fayalite. Fayalite (manganoo) typically appears as dark brown anhedral masses.

Rare-earth-element enrichment is typical of NYF pegmatites; it results in a vast array of minerals, including silicates, phosphates, oxides and carbonates. Allanite and gadolinite are the dominant REE silicates, typically occurring as black masses that are commonly metamict owing to radioactivity. Polycrase, aeschynite, euxenite, samarskite, and fergusonite are often mistaken for allanite or gadolinite because they are similar in appearance, although they are REE-bearing oxides containing Nb, Ta and Ti. Zircon forms gray or purple euhedral to subhedral prisms that are opaque, translucent or, rarely, gemmy. Monazite is the dominant REE phosphate. It occurs as rose, red or rusty subhedral to anhedral crystals. Xenotime and REE-bearing apatite are much less common.

Columbite, stibiocolumbite, pyrochlore, microlite, and cassiterite occur in rare amounts and, where present, occur only in the more chemically evolved pegmatites. Columbite compositions range from ferrocolumbite to manganocolumbite, whereas manganotantalite is rare. Oxides of Fe and Ti common to NYF pegmatites include magnetite, hematite, goethite, ilmenite and niobian rutile. Magnetite, ilmenite and niobian rutile form subhedral to euhedral crystals that are randomly scattered throughout the pegmatite. Magnetite is commonly a major product of the alteration of fayalite. Hematite and goethite are typically late phases found in pocket assemblages.

Beryl, phenakite and bertrandite represent the Be silicates found in NYF pegmatites. Beryl is mainly yellow or gold, but can be green or blue. Where present, beryl may occur throughout the pegmatite or as euhedral to subhedral crystals in pockets. Phenakite also occurs as a primary phase, whereas bertrandite occurs as an alteration product after beryl.

Topaz may occur as opaque white or blue masses embedded in K-feldspar or quartz or as white, yellow or blue transparent to gemmy crystals in pockets. The weathering of topaz produces assemblages of fine-grained white mica and clays.

The presence of B promotes the crystallization of tourmaline, danburite and hambergite. The most common tourmaline is schorl, although rare elbaite has been reported. Tourmaline is found as well-formed crystals in the main body of the pegmatite or, rarely, in pockets and vugs. Hambergite and danburite are found only in pockets.

Halides are composed of combinations of Na or Ca, Al with F. Fluorite is the dominant halide and is generally purple, green or colorless; it occurs mainly as small crystals in vugs and cavities or as pods and lenses within the

pegmatite. The fluorite may be yttrium-enriched. Cryolite is rarer than fluorite and is also primary. The alteration of topaz or cryolite may produce rare late-stage halides such as prosopite, elpasolite, pachnolite and ralstonite. Likewise, carbonates and sulfides are also late-stage minerals occurring in pockets and vugs. Carbonates include calcite, aragonite, siderite, rhodochrosite and bastnäsite. Sulfides occur as disseminated flakes or masses and include pyrite, galena, sphalerite and molybdenite.

TABLE 1. MINERALS TYPICAL OF NYF GRANITIC PEGMATITES

Simple Silicates	REE Silicates	Nb, Ta, Sn Oxides	Phosphates	Carbonates
Quartz	Allanite	Columbite	Apatite Group	Calcite
v. smoky	Gadolinite	Pyrochlore Group	Monazite	Aragonite
v. amethyst		Cassiterite	Xenotime	Siderite
Microcline	<b>Be Silicates</b>	Stibiocolumbite		Rhodochrosite
v. amazonite		Yttrotantalite	<b>Halides</b>	Bastnäsite
Albite	Beryl	Euxenite		
v. cleavelandite	Phenakite	Polycrase	Fluorite	<b>Sulfides</b>
Biotite Series	Bertrandite	Samarskite	Cryolite	
Muscovite		Fergusonite	Prosopite	Pyrite
Aegirine	<b>B Silicates</b>	Aeschnyite	Elpasolite	Galena
Arfvedsonite			Pachnolite	Sphalerite
Riebeckite	Tourmaline Group	<b>Fe Oxides</b>	Ralstonite	Molybdenite
Fayalite	Schorl		Thomsenolite	
Epidote	Elbaite	Hematite	Weberite	<b>Zeolites</b>
Garnet Group	Danburite	Magnetite	Cryolithionite	
Almandine		Goethite		Stilbite
Spessartine	<b>Li Silicates</b>		<b>Borates</b>	
Topaz		<b>Ti Oxides</b>		<b>Native Elements</b>
Zircon	Zinnwaldite Series		Hambergite	
	Lepidolite Series	Ilmenite		Bismuth
		Rutile		

## TRACE-ELEMENT CHEMISTRY OF MICAS IN "NYF" AND "NY" PEGMATITES

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Micas from four classic NYF pegmatite districts and an "NY" pegmatite district were analyzed to relate trace-element chemistry to the degree of pegmatite fractionation and to evaluate whether mica compositions may be useful indicators of the tectonic regime prevailing during magma genesis. Pegmatite districts studied include Trout Creek Pass (TCP), South Platte (SP), the Lake George Ring Complex (LGR) and the Wigwam Creek area (WWC), all in Colorado, and the Wausau Syenite Complex (WSC) in Marathon County, Wisconsin.



The F-depleted "NY" TCP pegmatites in Chaffee County, Colorado, consist of a group of simply zoned, composite-core pegmatites associated with the orogenic 1.6 Ga Denny Creek Granodiorite (Hanson *et al.* 1992). Accessory minerals present in these pegmatites include either aeschynite-(Y) or polycrase-(Y), monazite-(Ce), allanite-(Ce),  $\pm$  spessartine and schorl.

The F-rich SP pegmatites in Jefferson County, Colorado, exhibit well-developed zonation and are associated with the 1.0 Ga anorogenic composite Pikes Peak Batholith (Simmons & Heinrich 1980). Accessory minerals include samarskite-(Y), allanite-(Ce), monazite-(Ce), xenotime-(Y), cyrtolite and REE-enriched fluorite (Simmons *et al.* 1987). The LGR and the WWC pegmatites also are associated with the Pikes Peak batholith, along its southwestern margin near the younger Lake George intrusive center (Foord *et al.* 1995).

The WSC is comprised of a sequence of four anorogenic, intrusive centers, approximately 1.52 Ga, consisting of the Stettin, Wausau, Rib Mountain, and the Nine Mile plutons, from oldest to youngest (Myers *et al.* 1984). Mirolitic pegmatites abound in all plutons, with the best-exposed examples in the Nine Mile (Falster 1987) and Stettin plutons (Falster 1986). Within the Nine Mile pluton, a group of more evolved F-enriched pegmatites (Koss pegmatite group) has recently been found. WSC pegmatites commonly contain bastnäsite-group, monazite-group, xenotime-(Y), and pyrochlore-group minerals, as well as minor columbite-tantalite-group minerals.

With the exception of TCP biotite, which is notably depleted in Li and F, these elements exhibit a strong positive correlation in all other samples (Fig. 1). Samples from each location plot as distinct populations, with the exception of the WSC samples. The group of WSC samples associated with the Nine Mile and Stettin plutons have low Li and high F contents, whereas the Koss pegmatite pocket micas have high Li and very high F. In the WSC, SP, WWC, and the LGR, a trend of increasing Li and F is evident, with LGR and WWC zinnwaldite most enriched in both Li and F.

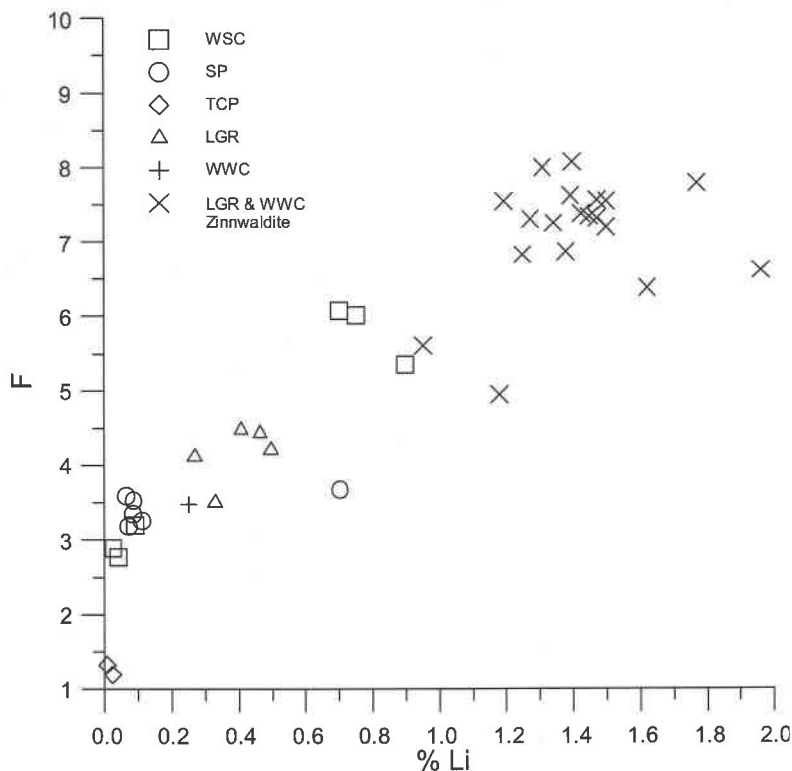


FIG. 1. Proportion (wt.%) of F (electron-microprobe data) versus Li (DCP analysis) in biotite in the samples studied.

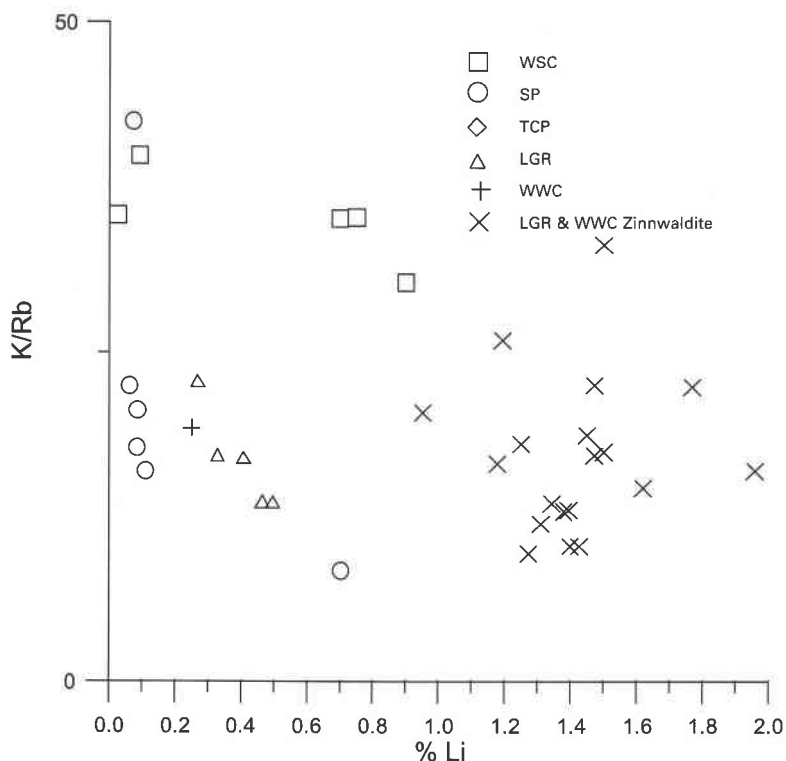


Fig. 2. K/Rb versus concentration of Li (wt.%) in biotite in the samples studied. The concentration of K was established by electron-microprobe analysis, and that of Li and Rb, by DCP analysis.

In a plot of K/Rb versus Li (Fig. 2), the K/Rb values of the TCP biotite are so high (>100) that they plot off scale. In general, biotite from the Nine Mile pluton (WSC) has slightly elevated K/Rb values. The remaining samples show little variation in K/Rb. Similar to the previous trend, the Nine Mile and Stettin samples are notably different (lower Li) than samples from the Koss pegmatite group (higher Li).

A plot of Ga/Al versus Li (Fig. 3) exhibits considerable scatter, although there is a crude trend of decreasing Ga/Al with increasing Li. Here also, TCP biotite is distinct, with lower Ga/Al values. Generally, WSC samples show elevated Ga/Al contents compared to the other districts.

The trace-element levels in biotite appear to be strongly dependent on ultimate origin of the suite. Biotite in the orogenic TCP suite is quite different from that in anorogenic plutons. Thus the higher K/Rb and the low Ga/Al, Li, and F values for TCP biotite may reflect the fact that it is the only representative of orogenic to post-orogenic pegmatites in the dataset. Micas from the anorogenic WSC and Pikes Peak plutons show similar ranges of composition, yet their most primitive micas are more evolved than those from TCP. Differences in biotite composition from these plutons may reflect the fact that the degree of fractionation is increasing as the system evolves. This is represented by the presence of the late Li-rich micas (zinnwaldite in LGR and WWC) and lithian biotite to zinnwaldite in the Koss pegmatite group (WSC).

#### REFERENCES

- FALSTER, A.U. (1986): Minerals of the Stettin Pluton. *Rocks & Minerals* **61**, 74-78.
- \_\_\_\_\_ (1987): Minerals of the pegmatitic bodies in the Wausau pluton. *Rocks & Minerals* **62**, 188-193.
- FOORD, E.E., ČERNÝ, P., JACKSON, L.L., SHERMAN, D.M. & EBY, R.K. (1995): Mineralogical and geochemical evolution of micas from miarolitic pegmatites of the anorogenic Pikes Peak batholith, Colorado. *Mineral. Petrol.* **55**, 1-26.

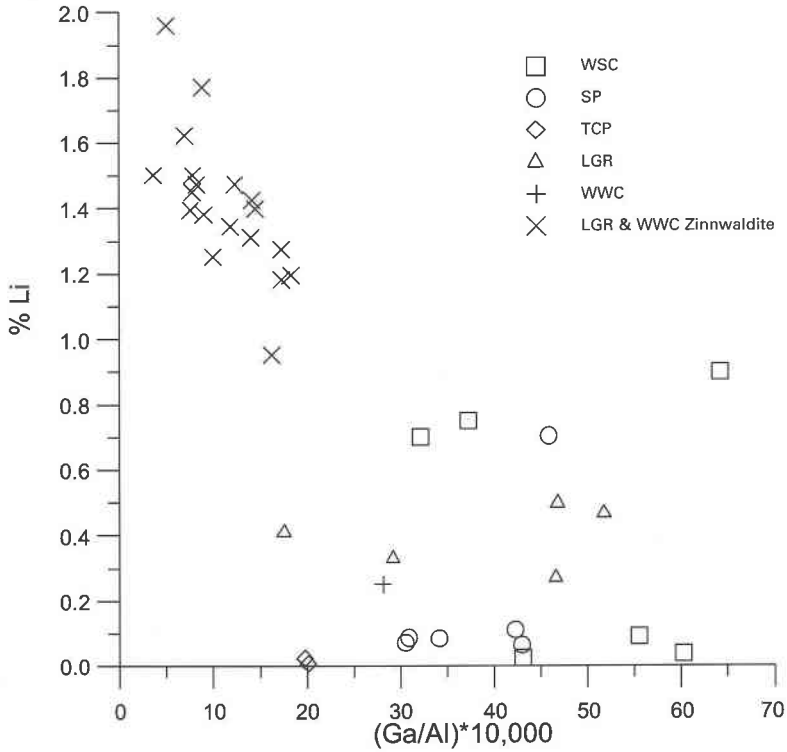


FIG. 3. Proportion of Li (wt.%) versus (Ga/Al)\*10,000 in biotite in the samples studied. The concentration of Al was established by electron-microprobe analysis, and that of Li and Ga, by DCP analysis.

HANSON, S.L., SIMMONS, W.B., WEBBER K.L. & FALSTER, A.U. (1992): Rare-earth-element mineralogy of granitic pegmatites in the Trout Creek Pass district, Chaffee County, Colorado. *Can. Mineral.* **30**, 673-686.

MYERS, P.E., SOOD, M.K., BERLIN, L.A. & FALSTER, A.U. (1984): The Wausau Syenite Complex, central Wisconsin. *Thirtieth Annual Inst. on Lake Superior Geology, Field Trip Guidebook 3*.

SIMMONS, W.B. & HEINRICH, E.W. (1980): Rare-earth pegmatites of the South Platte District, Colorado. *Colorado Geol. Surv., Dep. Natural Resources, Resource Ser. 11*.

\_\_\_\_\_, LEE, M.T. & BREWSTER, R.H. (1987): Geochemistry and evolution of the South Platte granite-pegmatite system, Jefferson County, Colorado. *Geochim. Cosmochim. Acta* **51**, 455-471.

**PHOSPHATE MINERALOGY OF NYF-, LCT- AND MIXED-TYPE GRANITIC PEGMATITES**JAMES W. NIZAMOFF<sup>§</sup>, ALEXANDER U. FALSTER, WILLIAM. B. SIMMONS AND KAREN L. WEBBER*Department of Geology and Geophysics, University of New Orleans, New Orleans, Louisiana 70148, U.S.A.*<sup>§</sup> E-mail address: jnizamoff@hotmail.com

The relative abundance and chemical composition of phosphate minerals from granitic pegmatites of LCT-, NYF- and mixed-type geochemical affiliation vary greatly. A review of phosphate mineralogy from granitic pegmatites follows, with special focus on a few "problem" areas, notably why NYF-type pegmatites are deficient in P in comparison with LCT-type pegmatites, and why certain phosphate species are present in only NYF- or LCT-type pegmatites.

Many LCT-type (typically enriched in Li, Cs and Ta) pegmatites are known to possess significant amounts of phosphate minerals, and a few localities exhibit a tremendous wealth of species (Palermo #1, New Hampshire; Hagendorf-Süd, Bavaria; Tip Top, South Dakota). In contrast, pegmatites of NYF (typically enriched in Nb, Y and F) affiliation rarely contain appreciable amounts of phosphates (South Platte district, Colorado; Wausau Complex, Wisconsin; Sawtooth batholith, Idaho). Pegmatites of mixed geochemical signature may display varying amounts of phosphate minerals typical of LCT- or NYF-type pegmatites (Lord Hill, Maine; Morefield, Virginia).

The chemical composition of pegmatitic phosphate minerals is dependent on the bulk chemical composition of the pegmatite. Primary phosphates of LCT-type pegmatites normally incorporate large amounts of Ca, Fe, Mn and Li with lesser amounts of Al, Na, Mg and F/OH. Typical primary phosphate species of LCT-type pegmatites include: apatite, triphylite–lithiophilite, graffonite–beusite, sarcopside, triplite–zwieselite, amblygonite–montebrasite, arrojadite–dickinsonite, natromontebrasite, wyllieite and monazite. In addition, LCT-type pegmatites commonly exhibit some of the many secondary phosphates that can result from metasomatic or hydrothermal alteration of primary phosphate phases. Over one hundred secondary phosphate species have been identified from LCT-type pegmatites. In contrast, phosphates occurring in NYF pegmatites are typically *REE*-bearing: monazite-(Ce, Nd and La species), xenotime-(Y) and cheralite-(Ce, Nd and La). Minor amounts of apatite with elevated levels of *REE* are also found in many NYF pegmatites. However, secondary phosphates are exceedingly rare in NYF pegmatites. Pegmatites of mixed geochemical signature may exhibit phosphates typical of both NYF- and LCT-type assemblages. Primary and secondary phosphates are generally more abundant than in NYF-type pegmatites, although fewer species are present in comparison to LCT-type pegmatites. Zwieselite–triplite, triphylite–lithiophilite, apatite, monazite and xenotime are typical of mixed-type pegmatites.

If the bulk chemical composition of NYF pegmatites is considered (NYF pegmatites contain significant amounts of Fe and F), it is interesting to note that members of the zwieselite–triplite series  $(\text{Fe,Mn})_2\text{PO}_4(\text{F,OH})$  do not appear in NYF pegmatites. Watson (1976) and Ryerson & Hess (1980) have demonstrated that P has an affinity for cations of comparatively high charge (*REE*, Ca). The formation of *REE* phosphates and apatite may exhaust all of the available P, thereby inhibiting crystallization of zwieselite–triplite. Phosphates of U and Th are virtually absent (with the exception of autunite) in NYF pegmatites, owing in part to the fact that U and Th commonly form oxide minerals that crystallize in the early stages of pegmatite consolidation, preventing the formation of late-stage U and Th phosphates.

The relative paucity of phosphate species in NYF pegmatites suggests that their parental granitic melts might be depleted in P. Černý (1991a) has shown that A-type granites that spawn NYF-type pegmatites are deficient in P, H<sub>2</sub>O, Li and B compared to the I- and S-type granitic melts that generate LCT-type pegmatites. There are several factors that may be important in explaining why NYF pegmatite-generating granites are depleted in P relative to granites parental to LCT-type pegmatites: 1) Metamorphic protoliths of A-type granites are deficient in rare alkalis and other mobile elements (Collins *et al.* 1982, Jackson *et al.* 1984, Whalen *et al.* 1987). 2) Peraluminous fertile granitic melts parental to LCT-type pegmatites are derived from metamorphic country rocks that are generally undepleted in mobile elements (Černý & Meintzer 1988, Černý 1991b). 3) Phosphorus content of pegmatites and parental granites increases with bulk peraluminosity (London 1990). LCT-type pegmatites and fertile granites, which are generally more aluminous than those of the NYF type, display elevated bulk P contents. However, peraluminous NYF pegmatites appear to be as depleted in P as sub- or metaluminous NYF pegmatites, suggesting that other factors influence the bulk P content of granitic melts. 4) *REE* phosphates have low solubility in felsic melts (Rapp & Watson 1986). The low solubility of *REE* phosphates buffers the P content of the residual melt at low values (London 1990).

Thus it appears that A-type granites parental to NYF-type pegmatites originate from rocks poor in P, resulting in a melt with relatively low P that in turn evolves to pegmatites that also are depleted in P. The P that is present in NYF pegmatites tends to form *REE* phosphates rather than apatite since *REE* are preferentially partitioned into the pegmatites from the parental granitic melts. The *REE* present in the granitic melt may form complexes with F (Richardson & Holland 1979) that are incompatible and therefore are transferred to the pegmatite-generating melt. The relative abundance of *REE* phosphates in the more highly evolved zones and replacement units in the pegmatites suggests that the *REE*-F complexes become destabilized in the later stages of pegmatite consolidation. The newly liberated *REE* scavenge the available P and form *REE*-bearing phosphates. Apatite exhibits no pronounced enrichment from granite to pegmatite, as indicated by the presence of minor amounts of apatite in granites and commonly throughout the pegmatites. The apparent lack of Ca-complexes allows for the continuous crystallization of apatite from the available Ca and P in granite to derivative pegmatite, which causes an even greater P deficiency in the residual pegmatite-forming melt.

## REFERENCES

- Černý, P. (1991a): Rare-element granitic pegmatites. II. Regional to global environments and petrogenesis. *Geosci. Canada* **18**, 68-81.
- \_\_\_\_\_ (1991b): Fertile granites of Precambrian rare-element pegmatite fields: is geochemistry controlled by tectonic setting or source lithologies? *Precambrian Res.* **51**, 429-468.
- \_\_\_\_\_ & MEINTZER, R.E. (1988): Fertile granites in the Archean and Proterozoic fields of rare-element pegmatites: crustal environment, geochemistry and petrogenetic relationships. In *Recent Advances in the Geology of Granite-Related Mineral Deposits* (R.P. Taylor & D.F. Strong, eds.). *Can. Inst. Mining Metall., Spec. Vol.* **39**, 170-207.
- COLLINS, W.J., BEAMS, S.D., WHITE, A.J.R. & CHAPPELL, B.W. (1982): Nature and origin of A-type granites with particular reference to southeastern Australia. *Contrib. Mineral. Petrol.* **80**, 189-200.
- JACKSON, N.J., WALSH, J.N. & PEGRAM, E. (1984): Geology, geochemistry and petrogenesis of late Precambrian granitoids in the central Hijaz region of the Arabian Shield. *Contrib. Mineral. Petrol.* **87**, 205-219.
- LONDON, D. (1990): Phosphorus in alkali feldspars of rare-element granitic pegmatites. *Can. Mineral.* **28**, 771-786.
- RAPP, R.P. & WATSON, E.B. (1986): Monazite solubility and dissolution kinetics: implications for the thorium and light rare earth chemistry of felsic magmas. *Contrib. Mineral. Petrol.* **94**, 304-316.
- RICHARDSON, C.K. & HOLLAND, H.D. (1979): The solubility of fluorite in hydrothermal solutions; an experimental study. *Geochim. Cosmochim. Acta* **43**, 1313-1325.
- RYERSON, F.J. & HESS, P.C. (1980): The role of P<sub>2</sub>O<sub>5</sub> in silicate melts. *Geochim. Cosmochim. Acta* **44**, 611-624.
- WATSON, E.B. (1976): Two liquid partition coefficients: experimental data and geochemical implications. *Contrib. Mineral. Petrol.* **56**, 119-134.
- WHALEN, J.B., CURRIE, K.L. & CHAPPELL, B.W. (1987): A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contrib. Mineral. Petrol.* **95**, 407-419.

## ZIRCON, VARIETY CYRTOLITE: A REVIEW

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Conflicting published mineralogical descriptions make the correct recognition of zircon in NYF (niobium–yttrium–fluorine-bearing) granitic pegmatites (Černý 1991) difficult. Starting with Breithaupt in 1825, fifteen researchers have misleadingly described amorphous, radioactive zircon as a new mineral species. The resulting varietal names are ostranite (Breithaupt 1825), oerstedite (Forchhammer 1835), malacon (Scheerer 1844), calyptolite (Shepard 1851), tachyaphalite (Weibye 1853), alvite (Forbes & Dahll 1855), auerbachite (Hermann 1858), cyrtolite (Knowlton 1867), anderbergite (Nordenskiöld 1876), naegite (Wada 1904), orvillite (Lee 1917), hagatalite (Kimura 1925), oyamalite (Kimura 1925), yamaguchilite (Kimura 1933), and gelzircon or arshinovite (Razumnaya *et al.* 1957). In the United States, cyrtolite has become the preferred varietal name to denote zircon that possesses a characteristic habit. Zircon crystals with this habit are usually radioactive and metamict, with physical properties more characteristic of metamict minerals than normal zircon. In Norway, alvite (for the rare-earth-bearing metamict zircon) and malacon (for the radioactive metamict zircon) are the preferred names (Neumann 1985). Investigators in other countries seem to have used one of these three: cyrtolite, alvite or malacon.

Cyrtolite usually forms multiple, intergrown crystals representing many radiating individual crystals from one common origin (resembling a “root”). These aggregates of intergrown crystals, typically with curved {111} faces, have been described as rosette-like, pineapple-like, thorn-like cones or as having a “rhombohedral-dodecahedral” appearance. In most cases, cyrtolite exhibits earthy (rarely lustrous) crystal faces of various shades of brown. These crystals of zircon are typically “rooted” in large biotite crystals, although they have also been found rooted in beryl, triphylite and albite.

Ideal zircon consists of 67.1% zirconium dioxide and 32.9% silicon dioxide, with the formula  $ZrSiO_4$ . The cyrtolite variety contains other elements that have been incorporated into the structure during magmatic crystallization. These include hafnium (commonly up to 15%), the radioactive elements uranium and thorium (up to 4%), various rare-earth elements (less than 2%), Fe, Al, Be, Nb, Ta, and Sc. Because of the destruction of the crystal structure by the alpha particles emitted from uranium and thorium atoms (Mitchell 1973), cyrtolite crystals have a lower specific gravity (average 3.6) than crystalline zircon (4.7), as the structure expands to an amorphous glass. The broken bonds and resultant charge-imbalance allow for the bonding of highly variable amounts of  $H_2O$  and possibly mobile elements such as Ca, Mg, Na, K and Mn to satisfy the charge imbalance. Published chemical compositions of metamict zircon indicate the presence of other elements, such as P and the rare-earth elements (such as Yb, Y, and Dy) in percentages greater than 2%. Robinson (1979) showed that the anomalous concentration of these elements in alvite, naegite, hagatalite, oyamalite and yamaguchilite is caused by the epitactic intergrowth at a microscopic scale of metamict zircon and xenotime. Whereas crystalline zircon has a hardness of 7.5, the hardness of amorphous cyrtolite decreases toward 5.0. Crystalline zircon is uniaxial, with indices of refraction approximately 1.923 ( $\omega$ ) and 1.968 ( $\epsilon$ ). Completely metamict cyrtolite is isotropic, with an approximate index of refraction of 1.82. Hydrochloric acid will mildly etch metamict cyrtolite, but does not affect crystalline zircon.

Cyrtolite is particularly common in rare-earth-bearing granitic pegmatites (or NYF pegmatites), which are usually associated with anorogenic granites. The best localities in North America that will continue to produce cyrtolite are the pegmatites associated with the Pikes Peak Granite, Colorado, granites in the Llano Uplift, Mason and Llano Counties, Texas, and the Ontario–Quebec pegmatites, in the Grenville Province of eastern Canada. Other well-known areas containing cyrtolite are southern Norway pegmatites (Hydra – Iveland – Arendal – Kragero), Madagascar and northern Karelia, Russia.

## REFERENCES

BREITHAUPT, A. (1825): Ostranite. *Poggendorfs Annalen* **5**, 377.

ČERNÝ, P. (1991): Rare-element granitic pegmatites. 1. Anatomy and internal evolution of pegmatites deposits. *Geosci. Canada* **18**, 49-67.

- FORBES, D. & DAHL, T. (1855): Mineralogiske Iagttagelser omkring Arendal og Kragero (Mineralogical survey around Arendal and Kragero). Part 1. *Nt. Mag. F. Naturvidensk* **8**, 213-229.
- FORCHHAMMER, J.C. (1835): Oerstedit, ein neues minerak. *Ann. D. Phys. Chem.* **35**, 630.
- HERMANN, R. (1858): Auerbachite. *J. prakt. Chem.* **73**, 209.
- KIMURA, K. (1925): Hagatalite. *Japanese J. Chem.* **2**, 81.
- \_\_\_\_\_ (1933): Yamaguchilite. *Rep. Japanese Assoc. Advancement of Science* **8**, 157.
- KNOWLTON, W.J. (1867): On a new mineral from Rockport, Massachusetts. *Am. J. Sci.* **94**, 224-226.
- LEE, T.H. (1917): Orvillite – a new mineral. *Revista Soc. Brasileira Sci.* **1**, 31.
- MITCHELL, R.S. (1973): Metamict minerals: a review. *Mineral. Rec.* **4**, 177-182, 214-223.
- NEUMANN, H. (1985): Norges mineraler. *Norges Geologiske Undersokelse Bull.* **68**.
- NORDENSKIOLD, A.E. (1876): Meddelanden i mineralogi. *Geol. Fören. Stockholm Förh.* **3**, 229.
- RAZUMNAYA, E.G., SMELYANSKAYA, G.A., KOROLEV, K.G. & POKULNIS, G.V. (1957): *Methods of Study of Raw Materials*. Gosgeoltekhizdat, Moscow, Russia (45).
- ROBINSON, G.W. (1979): *The Occurrence of Rare-Earth Elements in Zircon*. Ph.D. thesis, Queen's Univ., Kingston, Ontario.
- SCHEERER, T. (1844): Polykras und Malakon, zwei neue Mineralspecies. *Poggendorfs Annalen* **62**, 429-443.
- SHEPARD, C.U. (1851): Calyptolite, a new mineral. *Am. J. Sci.* **62**, 210.
- WADA, T. (1904): *Minerals of Japan*.
- WEIBYE, P.C. (1853): Tachyaphaltite. *Poggendorfs Annalen* **88**, 160.

## COMPOSITION AND STRUCTURAL STATE OF POTASSIUM FELDSPARS FROM MIAROLITIC PEGMATITES

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Voluminous new and published data on the composition and structural state of potassium feldspars (Kfs) from various miarolitic pegmatites have been summarized in the context of a new classification of granitic pegmatites (Zagorsky *et al.* 1999a).

The albite component (Ab) in Kfs ranges from 7 to 56%. Maximum Ab contents are typical for Kfs from the syngenetic intragranite rock-crystal-bearing pegmatites, whereas the minimum concentrations of this component are common for Kfs from the epigenetic rare-metal and rare-metal – muscovite miarolitic pegmatites (Fig. 1). Within pegmatite bodies, the lowest Ab contents are found in crystals from pockets. Kfs contain up to 0.2 wt% Ca, up to 0.06% Mg and up to 0.07% Fe as minor components.

The contents of Li, Rb, and Cs increase in Kfs as miarolitic pegmatites are gradually enriched in rare elements within the succession of pegmatitic formations (corresponding to the classes of P. Černý), from the crystal-bearing to the rare-metal ones (Fig. 2). Relatively low Li contents are common for Kfs from the rock-crystal-bearing, subrare-metal, topaz–beryl, and rare-metal – rare-earth amazonite pegmatites. Consistently low Li concentrations (<5 ppm) are typical only for Kfs from rare-metal – rare-earth amazonite pegmatites (Pikes Peak, Colorado and Ilmeny, Urals). An insignificant increase of Li contents is observed in Kfs of some rock-crystal-bearing and

subrare-metal topaz–beryl pegmatites, containing Li-bearing biotite and, occasionally, amazonite. Maximum Li contents (up to 550 ppm) are characteristic of Kfs from the rare-metal and some subsrare-metal miarolitic pegmatites (California, Transbaikalia, Middle Urals). Rb and Cs concentrations increase in Kfs within the succession from the fluorite – rock-crystal-bearing to the subsrare-metal topaz–beryl, and further to the rare-metal – rare-earth miarolitic pegmatites. Amazonite contains the highest concentrations of these elements (up to 8900 ppm Rb and up to 2580 ppm Cs) independent of mineragenetic specialization and pegmatitic formation (class).

Average Ba and Sr contents in Kfs from miarolitic pegmatites of the various formations are nearly identical. Ba and Sr concentrations in Kfs from highly productive pegmatite bodies (in terms of crystal raw material) show a striking decrease in abundance compared to those from non-productive ones. The significant accumulation of Ba and Sr in residual fluids and, correspondingly, an enrichment of these elements in the rim of Kfs crystals, are observed in pockets (Prince *et al.* 1973, Foord & Martin 1979, Peretyazhko *et al.* 1999).

According to the available data, the difference among pegmatites of various pegmatitic formations in terms of Pb, Ge, Sn, Ga, B and Zn concentrations is not evident. Kfs of rare-metal miarolitic pegmatites is distinguished by elevated Tl contents in comparison with pegmatites of other formations. Concentrations of Tl and Ge in Kfs of miarolitic pegmatites of any formation (class), like those of Rb and Cs, show a progressive enrichment from barren to the most evolved pegmatite bodies and from early to late generations in the latter. Pb concentrations in Kfs typically decrease from early to late generations, with the exception of amazonite from the central zones of pegmatite bodies and pockets, where Pb concentrations reach maximum values.

The structural state of Kfs from miarolitic pegmatites correspond to monoclinic orthoclase ( $0.73 < \Sigma t_1 \leq 1.0$ ) or triclinic Kfs ( $0.1 < \Delta t_1 \leq 1.0$ ). The majority of orthoclase samples have  $\Sigma t_1$  values ranging from 0.8 to 0.9. Samples of orthoclase with  $\Sigma t_1$  ranging from 0.73 to 0.80 are scarce, as are cases of highly ordered orthoclase, with  $\Sigma t_1 > 0.9$ . Maximum orthoclase, with  $0.95 < \Sigma t_1 \leq 1.0$ , occur only in miarolitic cavities of tourmaline-bearing subsrare-metal pegmatites of California (Himalaya, Little Three) (Stern *et al.* 1986). Triclinic Kfs fall into two groups, with  $\Delta t_1$  values of 0.1–0.4 and 0.7–1.0, with intermediate microcline being rare. The structure of Kfs is complicated by solid-phase transformations (variable obliquity, sub-X-ray twinning, *etc.*). If such processes are not completed, mixtures of monoclinic and triclinic phases are preserved. Such Kfs is described in pegmatites from

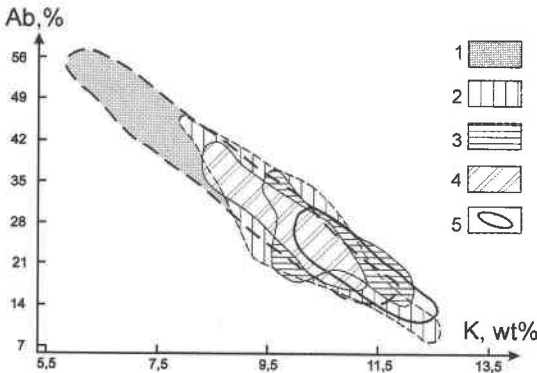


FIG. 1. K (wt%) versus proportion of the Ab component plot for Kfs from miarolitic pegmatites. 1–5: Various miarolitic pegmatites: 1: rock-crystal-bearing, in some cases with fluorite (131 samples: Mongolia, Transbaikalia, Kazakhstan, Middle Urals); 2: subsrare-metal topaz–beryl (142 samples: Middle Urals, Transbaikalia, Pamirs); 3: subsrare-metal tourmaline (488 samples: Transbaikalia, Pamirs, California); 4: rare-metal – rare-earth (33 samples: Ilmeny, Pikes Peak); 5: rare-metal (42 samples: Transbaikalia, California) and rare-metal – muscovite (29 samples: Azad Kashmir, Pakistan).

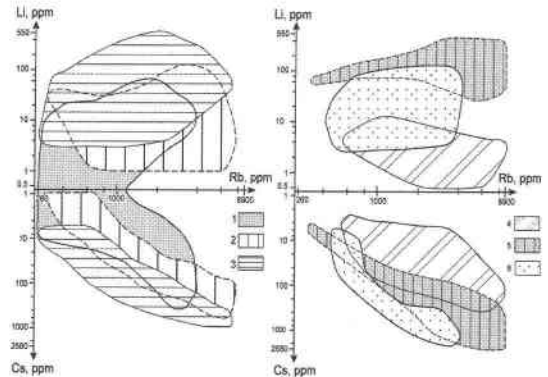


FIG. 2. Li versus Rb and Rb versus Cs plots for Kfs from miarolitic pegmatites. 1–4: see Figure 1; 5 and 6: rare-metal (42 samples: Transbaikalia, California) and rare-metal – muscovite (29 samples: Azad Kashmir, Pakistan) miarolitic pegmatites.



the Ukraine (Volyn), central Pamirs (Kukurt gemstone area) and Pakistan (Azad Kashmir) (Peretyazhko *et al.* 1999, Zagorsky *et al.* 1999b). Structurally heterogeneous Kfs seems to be more common, as the majority of miarolitic pegmatites have been formed under conditions of crystallization where both primary monoclinic (stable or metastable) and triclinic Kfs can form.

Even though several structural variations of Kfs exist, there are common features of their distribution in miarolitic pegmatites. Orthoclase is typical of non-productive and poorly productive pegmatite bodies (in terms of crystal raw material), independent of age and pegmatitic formation (class). Primary zones of productive pegmatites contain monoclinic Kfs as well as minimally triclinic and intermediate microcline. The amount of highly ordered Kfs, including maximum microcline, increases with proximity to pockets. Within pockets, Kfs crystals are commonly less ordered, consisting of orthoclase and minimally triclinic Kfs. In some cases, intermediate and maximum microcline also have been observed. The formation of Kfs in miarolitic cavities was accompanied by a significant change in pressure, temperature, composition of mineral-forming fluids, and rate of crystal growth (Peretyazhko *et al.* 1999). Non-equilibrium conditions of crystallization as well as isolation of miarolitic cavities result in a range of structurally different Kfs in miarolitic pegmatites.

#### REFERENCES

- FOORD, E.E. & MARTIN, R.F. (1979): Amazonite from the Pikes Peak batholith. *Mineral. Rec.* **10**, 373-384.
- PERETYAZHKO, I.S., ZAGORSKY, V.YE., PROKOF'EV, V.YU. & GANTIMUROVA, T.P. (1999): Miarolitic pegmatites of the Kukurt Group of gemstone deposits, central Pamirs: the evolution of physical conditions in the Amazonitovaya vein. *Geochem. Int.* **33**, 1108-1127.
- PRINCE, E.P., DONNAY, G. & MARTIN, R.F. (1973): Neutron diffraction refinement of an ordered orthoclase structure. *Am. Mineral.* **58**, 500-507.
- STERN, L.A., BROWN, G.E., BIRD, D., Jr., JAHNS, R.H., FOORD, E.E., SHIGLEY, J.E. & SPAULDING, L.B., Jr. (1986): Mineralogy and geochemical evolution of the Little Three pegmatite–aplite layered intrusive, Ramona, California. *Am. Mineral.* **71**, 406-427.
- ZAGORSKY, V.YE., MAKAGON, V.M. & SHMAKIN, B.M. (1999a): The systematics of granitic pegmatites. *Can. Mineral.* **37**, \_\_\_\_\_.
- \_\_\_\_\_, PERETYAZHKO, I.S. & SHMAKIN, B.M. (1999b): *Granitic Pegmatites. 3. Miarolitic Pegmatites*. Nauka, Siberian Enterprise, Russian Academy of Sciences, Novosibirsk, Russia (in Russ.).

## GEOCHEMICAL EVALUATION OF THE DEGREE OF DIFFERENTIATION AND ECONOMIC POTENTIAL OF THE PEGMATITES OF THE EASTERN BRAZILIAN PEGMATITE PROVINCE

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The Eastern Brazilian Pegmatite Province (EBPP), as defined by de Paiva (1946) and Putzer (1976), is found in northeastern Brazil in the states of Minas Gerais, Bahia, Espírito Santo and Rio de Janeiro. It is one of the most important pegmatite provinces of the world for the production of outstanding colorful and flawless tourmaline, aquamarine, kunzite, and brazilianite, as well as for columbite–tantalite, cesium and lithium resources. Rumors about the very rich occurrences of precious stones induced the Portuguese Bandeirantes around 1500 to explore the area that is now the central part of the EBPP in search of the fabulous “Serra das Esmeraldas”. The main pegmatite districts of the EBPP are Itambé, Araçuaí, Safira, Nova Era, Aimorés and Espera Feliz (Morteani *et al.*, in press). In the large majority of the occurrences, mining of the pegmatites is done by garimpeiros (diggers) for precious stones, and subordinately for tin and columbite–tantalite. In some of the larger pegmatites, feldspar is produced by small mining enterprises in partly mechanized open pits.

On the basis of the literature (*e.g.*, Correia Neves *et al.* 1986) and our own data, the degree of differentiation and the potential for Nb, Ta and Sn mineralization of individual pegmatites and pegmatite districts within the EBPP has been examined. Our database consists of results of approximately 530 analyses of feldspar, 550 of mica, and 25 of country rock, from 82 occurrences of granitic pegmatite. The pegmatites were intruded at the very end of the Brasiliano tectonometamorphic event (450 to 650 Ma), as indicated by radiometric dating and the sharp contacts and brittle behavior of the country rocks. Metasomatic reactions between the country rocks and the pegmatites, which led to the formation of tourmaline and biotite, are ubiquitous, but macroscopically limited to a zone of several cm to a maximum of 30 cm.

This study focuses on the chemical composition of pegmatitic feldspar and muscovite. Beus (1966), Černý (1991a, b, 1994), Trueman & Černý (1982), Gaupp *et al.* (1984) and London (1990) all have demonstrated that trace-element contents of K-feldspar and muscovite are very useful geochemical indicators with which to assess the degree of differentiation of a pegmatite and its potential for economic Nb, Ta and Sn mineralization.

Discrimination diagrams for K-feldspar and muscovite, such as Cs *versus* K/Rb, Cs *versus* Nb/Ta, Zn *versus* K/Rb and Li *versus* K/Rb, show that the pegmatites of the EBPP cover the whole range of differentiation, from poorly differentiated muscovite-bearing pegmatite to extremely evolved Li-, Cs-, Be-, and Ta-enriched varieties. A comparison of the different pegmatite districts shows not only the wide range of degree of differentiation, but also reveals that the most differentiated pegmatites are found in the Araçuaí district, closely followed by the Safira district (C. Preinfalk, G. Morteani & G. Huber, in prep). Both districts are the largest producers within the EBPP of multicolored tourmaline, aquamarine and Morganite. In addition, Araçuaí contains the most Li-enriched pegmatites of the EBPP. The pegmatite districts of Espera Feliz, closely followed by those of Aimorés and of Itambé, contain less differentiated pegmatites. A Cs *versus* Ta plot for muscovite shows a rather good positive correlation for the whole dataset, as well as for the individual districts. Most muscovite samples have Ta contents above 20 ppm, indicating a potential for Ta mineralization according to Beus (1966). However, only a few data points lie above the much more restrictive limit for economic Ta mineralization (65 to 75 ppm) set by Gordiyenko (1970).

The degree of pegmatite differentiation seems to be primarily related to the level of erosion. Pegmatites that occur at the deepest levels, exposing granulitic to charnockitic rocks, are in fact less differentiated than pegmatites found in rocks that equilibrated in the greenschist and amphibolite facies.

#### REFERENCES

- BEUS, A.A. (1966): Distribution of tantalum and niobium in muscovites from granitic pegmatites. *Geokhimiya* **10**, 1216-1220 (in Russ.).
- ČERNÝ, P. (1991a): Rare-element granitic pegmatites. I. Anatomy and internal evolution of pegmatite deposits. *Geosci. Canada* **18**, 49-67.
- \_\_\_\_\_ (1991b): Rare-element granitic pegmatites. II. Regional to global environments and petrogenesis. *Geosci. Canada* **18**, 68-81.
- \_\_\_\_\_ (1994): Evolution of feldspars in granitic pegmatites. In *Feldspars and their Reactions* (I. Parsons, ed.). *NATO ASI Series, C: Math. Phys. Sci.* **421**, 501-540. Kluwer Academic Publishers, Dordrecht, The Netherlands.
- CORREIA NEVES, J.M., PEDROSA SOARES, A.C. & MARCIANO, V.R.P. da R.O. (1986): A província pegmatítica oriental do Brasil à luz dos conhecimentos atuais. *Rev. Bras. Geoc.* **16**, 106-118.
- GAUPP, R., MÖLLER, P. & MORTEANI, G. (1984): Tantal-Pegmatite; geologische, petrologische und geochemische Untersuchungen. *Monograph Series on Mineral Deposits*, Borntraeger, Berlin, Germany.
- GORDIYENKO, V.V. (1970): *Mineralogy, Geochemistry and Genesis of the Spodumene Pegmatites*. Nedra, Leningrad, Russia (in Russ.).
- LONDON, D. (1990): Internal differentiation of rare-element pegmatites; a synthesis of recent research. In *Ore-Bearing Granite Systems; Petrogenesis and Mineralizing Processes* (H.J. Stein & J.L. Hannah, eds.). *Geol. Soc. Am., Spec. Pap.* **246**, 35-50.
- MORTEANI, G., PREINFALK, C. & HORN A.H. (in press): Classification and mineralisation potential of the pegmatites of the Eastern Brazilian Pegmatite Province. *Mineral. Deposita*
- DE PAIVA, G. (1946): Províncias pegmatíticas do Brasil. *DNPM (Rio de Janeiro), Boletim* **78**, 13-21.

- PUTZER, H. (1976): *Metallogenetische Provinzen in Südamerika*. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany.
- TRUEMAN, D.L. & ČERNÝ, P. (1982): Exploration for rare-element granitic pegmatites. In *Granitic Pegmatites in Science and Industry* (P. Černý, ed.). *Mineral. Assoc. Can., Short Course Handbook* 8, 463-493.

## THE EVOLUTION AND PARAGENESIS OF URANIUM MINERALS FROM THE PALERMO NO.1 GRANITIC PEGMATITE, NEW HAMPSHIRE

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A study of the evolution and paragenesis of the uranium minerals at the Palermo No. 1 granitic pegmatite, Grafton County, New Hampshire (Korzeb *et al.* 1997, Foord *et al.* 1997), reveals four stages of secondary mineralization. A total of eight uranium minerals constitute the four stages. The first stage, "gummite", consists of a mixture of schoepite-group minerals and related uranyl oxide-hydroxide, hydrated compounds referred to as mineral "A" by Frondel (1956). This first stage surrounds and replaces a uraninite core. The second stage is a carbonate stage represented by rutherfordine. The third stage is represented by beta-uranophane. The fourth and final stage involves the phosphates phosphuranylite and meta-autunite. Hydrothermal and meteoric processes were responsible for the development of the first three stages. With dropping temperatures, hydrothermal fluids likely reached the temperature of meteoric water. The pH shifted from acidic (pH less than about 6 at 1000°C) to alkaline (pH > 7 at 250°C). Since mineral "A" contains hydroxyl and low amounts of molecular water, it probably formed at a temperature greater than 1000°C in an acidic environment. After the first stage, the hydrothermal fluids cooled to temperatures of meteoric water. The initial pH of the meteoric water was acidic (pH less than about 6 at 250°C) and then slowly shifted to alkaline. The mineralizing fluids became oversaturated in CO<sub>3</sub>, Ca, K, and Si. Uraninite, mineral "A", and "gummite" became unstable and were replaced by rutherfordine and beta-uranophane. The phosphate stage developed from the introduction of groundwater. The uranyl phosphate minerals precipitated from an acidic fluid (pH ≈ 7 at 250°C) that was oversaturated with Ca, K, U, and P. Analysis of "gummite" by LAM-ICP-MS showed the presence of radiogenic lead; the <sup>206</sup>Pb/<sup>207</sup>Pb ratio is 0.053, yielding a calculated age of 329 Ma. Uraninite was analyzed by LAM-ICP-MS and shows the presence of Th, Pb, K and Ca. All the lead is radiogenic, and the <sup>206</sup>Pb/<sup>207</sup>Pb ratio is 0.0533, which gives an age of 342 Ma.

### REFERENCES

- FOORD, E.E., KORZEB, S.L., LICHTÉ, F.E. & FITZPATRICK, J.J. (1997): Additional studies on mixed uranyl oxide-hydroxide hydrate alteration products of uraninite from the Palermo and Ruggles granitic pegmatites, Grafton County, New Hampshire. *Can. Mineral.* 35, 145-151.
- FRONDEL, C. (1956): Mineral composition of gummite. *Am. Mineral.* 41, 539-568.
- KORZEB, S.L., FOORD, E.E. & LICHTÉ, F.E. (1997): The chemical evolution and paragenesis of uranium minerals from the Ruggles and Palermo granitic pegmatites, New Hampshire. *Can. Mineral.* 35, 135-144.

## **REE-BEARING MINERALS IN OHRO GRANITIC PEGMATITE, JAPANESE ISLAND ARC: CRYSTALLIZATION OF ORTHO- AND PYROSILICATES SUBSEQUENT TO BOWEN'S REACTION SERIES**

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One of the greatest enigmas of igneous mineralogy at the present time concerns the mechanism of crystallization of SiO<sub>2</sub>-poor minerals at the ultimate stages of magmatic evolution. The factors controlling the crystallization of Si-poor minerals relative to quartz, alkali feldspar and nonsilicates subsequent to Bowen's reaction series in granitic pegmatites are complex and poorly understood.

*REE* (rare-earth-element)- and *RE* (rare-element)-bearing accessory minerals occur in the 50–65 Ma Ohro granitic pegmatite of the Miyazu granitic belt, Kyoto Prefecture, Japan. Pseudorutile, radioactive zircon, thortveitite and metamict pyrochlore-like minerals from this pegmatite were studied by EPMA, MXRD, XPS, MPMS and other methods. The pegmatite is up to 20 m wide and consists of two zones: a quartz core accompanying fluorine-bearing muscovite (XPS detection of F) and an outer zone of alkali feldspars (including albite). Accessory minerals include zircon, pseudorutile, thortveitite, and pyroxferroite. The absence of tourmaline, spodumene, lepidolite and beryl emphasizes the very low concentrations of B, Li, and Be in the pegmatite. Furthermore, the lack of fluorite and apatite suggest that the melt was also very poor in Ca. High levels of *REE* are indicated by the minerals bastnäsite-(Ce): (Ce,La)(CO<sub>3</sub>)F, fluorocerite-(Ce): (Ce,La)F<sub>3</sub>, xenotime-(Y): YPO<sub>4</sub> and monazite: (Ce,La,Nd,Th)PO<sub>4</sub>, (Sakurai *et al.* 1960, Yamada *et al.* 1990). In addition to these, we have recently discovered pseudorutile in quartz fractures. This is the first occurrence of this mineral in Japan. Unique *RE* minerals such as: 1) Sc- and Nb-bearing pseudorutile from the quartz core (~0.20 wt% Sc<sub>2</sub>O<sub>3</sub> and ~0.90% Nb<sub>2</sub>O<sub>5</sub>); 2) [*HREE* + radioactive elements]- and P-bearing zircon from the feldspar zone (~13.0 wt% *REE* + *RE* oxides and up to 3.85 wt% P<sub>2</sub>O<sub>5</sub>), and 3) Sn-bearing thortveitite crystallized on K-feldspar from the feldspar zone (up to 4.37 wt% SnO<sub>2</sub>). Comparison between pseudorutile occurring in continental and island-arc pegmatites indicates that Nb in the former strongly predominates over Ta (Černý *et al.* 1999). A pyrochlore-like mineral (44.17 wt% Nb<sub>2</sub>O<sub>5</sub>, 12.88% PbO, 10.15% UO<sub>2</sub>, 9.95% As<sub>2</sub>O<sub>3</sub>, *etc.*) is associated with zircon. The paragenetic relationship among these *REE* minerals and their host crystals (quartz or feldspars) affords cogent evidence for crystallization of the former before or after crystal growth of the latter. Chemical characteristics of these four minerals are unique for assemblages of pegmatitic minerals occurring in island arcs. The mineral chemistry of the Ohro pegmatite does not fit Černý's (1992) classification of granitic pegmatites.

Of great significance to *REE*-geochemists is the discovery of zoning in thortveitite from Ohro, Japan and Iveland, Norway. Back-scattered electron images reveal two kinds of chemical regions, one rich in Sc (dark zone), and one rich in Y and Zr (light zone). In contrast, thortveitite from the Kobe pegmatite 10 km northeast of the Ohro pegmatite shows no chemical zonation. Dominance of non-*REE* cations at the octahedral sites and the thermal history may facilitate exsolution of chemically different zones in thortveitite. Chemical differences between dark and light zones may be explained by both electronegativity (West 1994) and the summation of ionic radii of octahedrally coordinated cations in the thortveitite structure. In addition, thortveitite has paramagnetic susceptibility that is more than 100 times that of the associated K-feldspar.

Data from this and previous studies suggest that separation of Si- and P-fluorides from the H<sub>2</sub>O-poor silicate melt, subsequent to Bowen's reaction series, exerts a strong control on crystallization of the Si-poor silicate and oxide minerals enriched in *HREE* and *RE*, or nonsilicate minerals enriched in *LREE* at the last stage of magmatism. The geochemical behavior of fluorine and phosphorus helps to explain why silica-poor minerals are common phases at the extreme stage of crystallization of granitic pegmatites (*e.g.*, garnet, fayalite, phenakite, topaz, zircon, thortveitite, allanite and pyroxferroite) and felsic volcanic rocks (*e.g.*, garnet, fayalite, topaz) (Gaines *et al.* 1997). The estimated solidus temperatures for F-bearing granites are 30–60°C lower than in F-free granitic systems

(Swanson & Fenn 1992); this may provide an explanation for pegmatitic crystallization of SiO<sub>2</sub>-poor minerals within the felsic igneous rocks. Pockets in some felsic igneous rocks afford abundant evidence for the growth of large SiO<sub>2</sub>-poor crystals associated with a vapor phase. However, the crystallization of Si-poor or nonsilicate minerals following Bowen's (1928) reaction series has provoked little controversy. Paragenetic relationships with the REE minerals examined confirm a new principle underlying the genesis of minerals: *Si-poor minerals crystallize from a silicate melt enriched in fluorine and phosphorus, subsequent to the "reaction series", which ends by returning to the crystallization of silica-poor minerals.* At the end of Bowen's reaction series, the melt satisfies five constraints: (1) Ca-poor and alkali-rich aluminosilicate, (2) H<sub>2</sub>O-poor or anhydrous content, (3) enrichment of fluorine, (4) small quantities of CO<sub>2</sub>, and (5) high REE- and RE-concentration. The present principle may provide a fresh insight into the mechanism of pegmatite petrogenesis posterior to Bowen's reaction principles.

#### REFERENCES

- BOWEN, N.L. (1928): *The Evolution of the Igneous Rocks*. Princeton University Press, Princeton, New Jersey.
- ČERNÝ, P. (1992): Geochemical and petrogenetic features of mineralization in rare-element granitic pegmatites in the light of current research. *Appl. Geochem.* **7**, 393-416.
- \_\_\_\_\_, CHAPMAN, R., SIMMONS, W.B. & CHACKOWSKY, L.E. (1999): Niobian rutile from the McGuire granitic pegmatite, Park County, Colorado: solid solution, exsolution, and oxidation. *Am. Mineral.* **84**, 754-763.
- GAINES, R.V., SKINNER, C.H., FOORD, E.E., MASON, B. & ROSENZWEIG, A. (1997): *Dana's New Mineralogy* (8th ed.). John Wiley & Sons, Inc., New York, N.Y.
- SAKURAI, K., NAGASHIMA, K. & KATO, A. (1960): Thortveitite from Kobe-Shiroishi, Ohmiya-cho, Kyoto prefecture. *Chigakukennkyu* **13**, 49-51 (in Japanese).
- SWANSON, S.E. & FENN, P.M. (1992): The effect of F and Cl on the kinetics of albite crystallization: a model for granitic pegmatites? *Can. Mineral.* **30**, 549-559.
- WEST, A.R. (1994): *Basic Solid State Chemistry*. John Wiley & Sons, Ltd. New York, N.Y.
- YAMADA, S., OKAMOTO, A., TAKADA, M., FUJIWARA, T. & TAKEMURA, M. (1990): On the thortveitite, fluocerite, pyroxferroite and other minerals from Isanago mine, Oro, Nakagun, Kyoto prefecture. *Chigakukennkyu* **31**, 205-222 (in Japanese).

## SUCCESSFUL APPLICATION OF GROUND-PENETRATING RADAR IN EXPLORATION FOR GEM TOURMALINE

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Application of ground-penetrating radar has been successful in delineating gem-bearing zones in the Himalaya pegmatite mine of the Mesa Grande district of southern California. The high frequency of the electromagnetic signal allows features as small as a few cm to be resolved within 1–2 meters of the surface of a mine wall. The first documented success was recorded in a part of the Himalaya dike that was no longer actively mined and where the dike exhibited few features that indicated the presence of pockets (Fig. 1). Based on this success, additional work led to the discovery of seven more gem-bearing pockets and 25 more gem-bearing vugs in the subsequent few weeks. Careful setup, data processing, and application of geological information have so far allowed us to distinguish between gem-bearing cavities, non-gem bearing cavities, and barren dike (dike with no pockets). If carefully used, this method promises to provide an important tool for mapping the internal structures of pegmatites and thus assisting mining activities in the future.

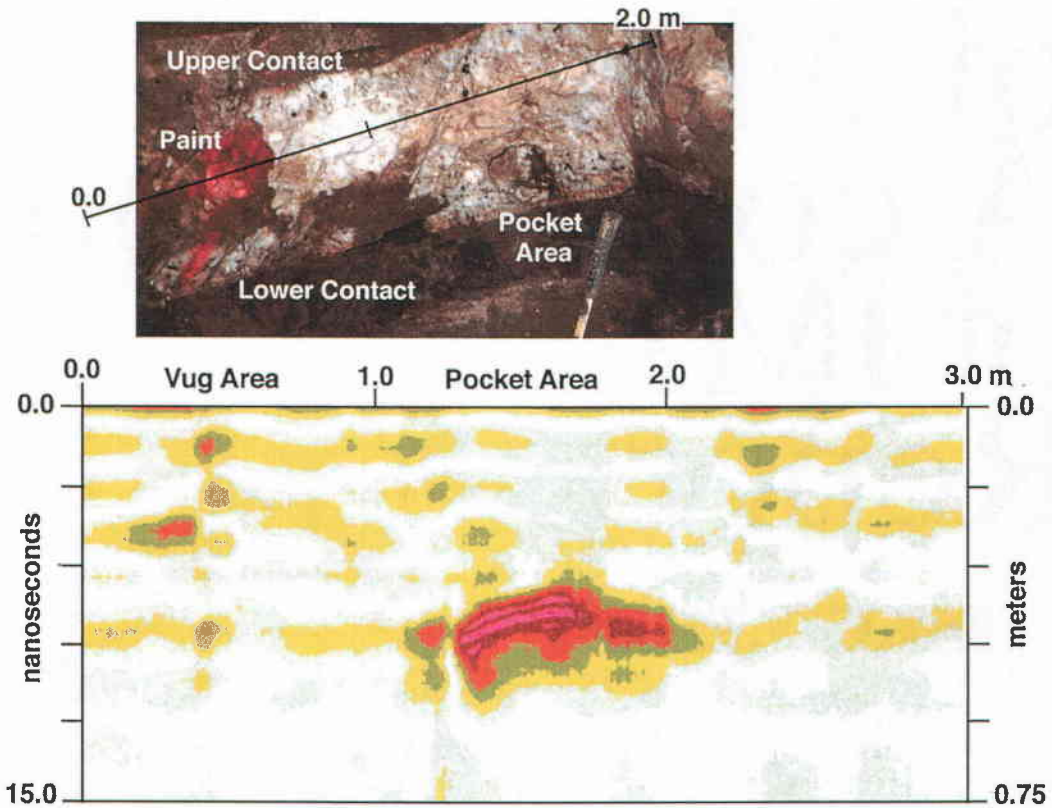


FIG. 1. A section of dike in the region of the discovery pocket before excavation (upper). Here the dike is about 0.45–0.50 cm thick, and has few signs of pocket development. The line with 0.0–2.0 m marks is the line of traverse along the dike made with radar antennas; meter marks correspond to those on the scan below. Preliminary interpretations identified two promising areas: 1) a small set of anomalies (location indicated by red paint on the dike) at about 3–5 nanoseconds near 0.5 m on the scan, or about 0.15–0.25 m depth, and 2) a more prominent anomaly at longer travel time (7–8 nanoseconds, or about 0.35–0.40 m depth) near 1.5 m on the scan. The prominent anomaly was associated with a pocket 10 cm in diameter containing three moderately sized crystals of gem tourmaline.