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# Beryllium in Antarctic Ultrahigh-Temperature Granulite-Facies Rocks and its Role in Partial Melting of the Lower Continental Crust

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**Final Report for Period:** 01/2001 - 06/2004**Submitted on:** 06/22/2004**Principal Investigator:** Grew, Edward S.**Award ID:** 0087235**Organization:** University of Maine**Title:**

Beryllium in Antarctic Ultrahigh-Temperature Granulite-Facies Rocks and its Role in Partial Melting of the Lower Continental Crust

**Project Participants****Senior Personnel****Name:** Grew, Edward**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Yates, Martin**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Obtained chemical analyses using the electron microprobe

**Post-doc****Graduate Student****Undergraduate Student****Technician, Programmer****Other Participant****Research Experience for Undergraduates****Name:** Roy, Alex**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Alex Roy, now a junior in geological sciences, completed a reading course with me last spring on the phosphate wagnerite and wrote a term paper reviewing the literature on this mineral. Over the summer and into the fall semester Alex prepared separates for X-ray diffraction and electron microprobe analyses of wagnerite from Austria (including the type locality), Bamble, Norway, Santa Fe Mountain, Colorado, and 'Christmas Point' and Mt. Pardoe, Enderby Land. Alex assisted Martin Yates, who is in charge of the electron microprobe laboratory at U Maine, in installing the new Cameca SX-100, preparing a web site for the laboratory, and other tasks. Alex has learned to run the new probe and has obtained preliminary analyses of wagnerite and associated minerals. He found isokite, CaMgPO<sub>4</sub>F, with the Bamble wagnerite, a new locality. Alex was supported largely by REU funds; he also received some work-study support from U Maine.

**Years of schooling completed:** Sophomore**Home Institution:** Same as Research Site**Home Institution if Other:****Home Institution Highest Degree Granted(in fields supported by NSF):** Doctoral Degree**Fiscal year(s) REU Participant supported:** 2003 2002**REU Funding:** REU supplement**Organizational Partners**

### Other Collaborators or Contacts

Charles K. Shearer, University of New Mexico  
 Justin J. Hagerty, University of New Mexico  
 Michael Sandiford, University of Melbourne  
 Masao Asami, Okayama University  
 Kazuhiro Suzuki, Nagoya University  
 A. T. Rao, Andhra University  
 K.K.V.S. Raju, Andhra University  
 John W. Sheraton, Lydney, UK  
 Andrew G. Christy, Australian National University  
 John Moore, Rhodes University  
 Liudong Ren, Institute of Geology, Chinese Academy of Geological Sciences  
 David Waters, Oxford University

### Activities and Findings

#### **Research and Education Activities:**

##### Summary of Objectives

The proposed research is a study of the Napier Complex (Enderby Land, Antarctica) pegmatites with an emphasis on the minerals and geochemistry of beryllium. Structural, geochronological and mineralogical studies will be carried out to test the hypothesis that the beryllium pegmatites resulted from anatexis of their metapelitic host rocks during the ultrahigh-temperature metamorphic event in the late Archean. Host rocks will be analyzed for major and trace elements. Minerals will be analyzed by the electron microprobe for major constituents including fluorine and by the ion microprobe for lithium, beryllium and boron. The analytical data will be used to determine how beryllium and other trace constituents were extracted from host rocks under ultrahigh-temperature conditions and subsequently concentrated in the granitic melt, eventually to crystallize out in a pegmatite as beryllian sapphirine and the related beryllium mineral khmaralite, neither of which have been found in pegmatites elsewhere.

##### Major research activities

- Analyses of sapphirine, orthopyroxene, sillimanite and other minerals in 17 samples of metapelite and anatectic melt from the Napier Complex, Enderby Land, Antarctica for Li, Be and B using secondary ion mass spectroscopy with the ion microprobe in collaboration with C.K. Shearer and J.J. Hagerty. This is a continuation of research begun in 2001, but involves a larger number of analyses
- Analyses of sapphirine, orthopyroxene, garnet, sillimanite, biotite, K-feldspar, plagioclase, spinel, cordierite, wagnerite, apatite and accessory minerals in about 30 samples, including the 17 above, for major constituents using the newly acquired Cameca SX-100 electron microprobe. Profiles of orthopyroxene and garnet and various maps of Pb-bearing potassium feldspar and thorian monazite-(Ce) have also been done.
- Dating of monazite-(Ce) in several pegmatite samples using the newly acquired Cameca SX-100 electron microprobe.
- Analyses of 24 granulite-facies metasediments and pegmatites for major and trace elements by standard methods used in bulk-rock geochemistry

#### **Findings: (See PDF version submitted by PI at the end of the report)**

#### **Training and Development:**

Alex Roy, a junior in geological sciences, completed a reading course with me in 2002 on the phosphate wagnerite and wrote a term paper reviewing the literature on this mineral. Alex has learned to prepare clean mineral separates that can be used for analyses. Alex assisted Martin Yates, who is in charge of the electron microprobe laboratory at U Maine, in installing the new Cameca SX-100 probe, preparing a web site for the laboratory, and other tasks. Alex has learned to run the new Cameca electron microprobe, and used this skill to analyze wagnerite and associated minerals in pegmatites and a granulite from Enderby Land under the direction of Martin Yates. In addition, he has been gaining experience in studying thin sections of rocks with the petrographic microscope. He prepared a poster and presented it at the annual meeting of the Geological Society of America, November, 2003.

#### **Outreach Activities:**

### Journal Publications

Grew, E.S., Rao, A. T., Raju, K.K.V.S., Yates, M.G., "A reexamination of quartz-sillimanite-hypersthene-cordierite gneisses from the Vijayanagaram district: Does surinamite occur in the Eastern Ghats Belt?", *Current Science*, p. 1353, vol. 82, (2001). Published

Grew, E.S., Halenius, U., Kritikos, M, Shearer, C. K., "New data on welshite, e.g.,  $\text{Ca}_2\text{Mg}_3.8\text{Mn}_{2+0.6}\text{Fe}_{2+0.1}\text{Sb}_{5+1.5}\text{O}_2[\text{Si}_{2.8}\text{Be}_{1.7}\text{Fe}_{3+0.65}\text{Al}_{0.7}\text{As}_{0.17}\text{O}_{18}]$ , an aenigmatite-group mineral.", *Mineralogical Magazine*, p. 665, vol. 65, (2001). Published

Grew, E.S., Suzuki, K. and Asami. M., "CHIME Ages of xenotime, monazite and zircon from beryllium pegmatites in the Napier Complex, Khmara Bay, Enderby Land, East Antarctica.", *Polar Geoscience*, p. 99, vol. 14, (2001). Published

Barbier, J., Grew, E.S., Halenius, E., Halenius, U. and Yates, M.G., "The role of iron and cation order in the crystal chemistry of surinamite,  $(\text{Mg},\text{Fe}_{2+})_3(\text{Al},\text{Fe}_{3+})_3\text{O}[\text{AlBeSi}_3\text{O}_{15}]$ : A crystal structure, Mossbauer spectroscopic, and optical spectroscopic study.", *American Mineralogist*, p. 501, vol. 87, (2002). Published

Asami, A., Suzuki, K. and Grew, E.S., "Chemical Th-U-total Pb dating by electron microprobe analysis of monazite, xenotime and zircon from the Archean Napier Complex, East Antarctica: Evidence for ultra-high-temperature metamorphism at 2400Ma", *Precambrian Research*, p. 249, vol. 114, (2002). Published

Ren, L., Grew, E.S., Xiong, M., and Ma, Z., "Wagnerite-Ma5bc, a new polytype of  $\text{Mg}_2(\text{PO}_4)(\text{F},\text{OH})$  from granulite-facies paragneiss, Larsemann Hills, Prydz Bay, East Antarctica", *Canadian Mineralogist*, p. 393, vol. 41, (2003). Published

Grew, E.S., Rao, A.T., Raju, K.K.V.S., Hejny, C., Moore, J.M., Waters, D.J., Yates, M.G., Shearer, C.K., "Prismatine and ferrohoegbomite-2N2S in granulite-facies Fe-oxide lenses in the Eastern Ghats Belt at Venugopalapuram, Vizianagaram district, Andhra Pradesh, India: do such lenses have a tourmaline-enriched lateritic precursor?", *Mineralogical Magazine*, p. 1081, vol. 67, (2003). Published

Asami, A., Suzuki, K. and Grew, E.S., "Th-U-total Pb monazite and zircon ages from Alasheyev Bight to the Sor Rondane Mountains, East Antarctica: Constraints on the position of the Mozambique suture in eastern Queen Maud Land", *Journal of Geology*, p. , vol. , ( ). Submitted

Christy, A.G., Tabira, Y., H=Ischer, A., Grew, E. S., and Schreyer, W., "Synthesis of beryllian sapphirine in the system  $\text{MgO}-\text{BeO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$  and comparison with naturally occurring beryllian sapphirine and khmaralite. Part 1: Experiments, TEM and XRD", *American Mineralogist*, p. 1104, vol. 87, (2002). Published

Christy, A.G. & Grew, E. S., "Synthesis of beryllian sapphirine in the system  $\text{MgO}-\text{BeO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$  and comparison with naturally occurring beryllian sapphirine and khmaralite. Part 2: A chemographic study of Be content as a function of P, T, assemblage and FeMg-1 exchange.", *American Mineralogist*, p. 327, vol. 89, (2004). Published

EDWARD S. GREW, MARTIN G. YATES, CHARLES K. SHEARER, JUSTIN J. HAGERTY, JOHN W. SHERATON, MICHAEL SANDIFORD  
 , "BERYLLIUM IN PSAMMO-PELITIC GRANULITES AND ANATECTIC PEGMATITES OF THE ULTRAHIGH-TEMPERATURE NAPIER COMPLEX, ENDERBY LAND, EAST ANTARCTICA: THE ROLE OF SAPPHIRINE", *Journal of Petrology*, p. , vol. , ( ). Submitted

Grew, E.S., Barbier, J., Britten, J., Yates, M.G., Polyakov, V.O., Shcherbakova, E.P., Hålenius, U. and Shearer, C.K., "Makarochkinite,  $\text{Ca}_2\text{Fe}_{2+4}\text{Fe}_{3+}\text{TiSi}_4\text{BeAlO}_{20}$ , a new berylliosilicate member of the aenigmatite-sapphirine-surinamite group from the Il'men Mountains (southern Urals), Russia, and the Ti-dominant analogue of høgтуvaite", *American Mineralogist*, p. , vol. , ( ). In preparation

### **Books or Other One-time Publications**

Grew, E.S., "Mineralogy, petrology and geochemistry of beryllium: An introduction and list of beryllium minerals", (2002). Book, Published  
 Editor(s): Grew, E.S.

Collection: Beryllium: Mineralogy, Petrology, and Geochemistry

Bibliography: *Reviews in Mineralogy and Geochemistry*, Mineralogical Society of America, no. 50, p. 487-549

Grew, E.S., "Beryllium in metamorphic environments (emphasis on aluminous compositions)", (2002). Book, Published  
 Editor(s): Grew, E.S.  
 Collection: Beryllium: Mineralogy, Petrology, and Geochemistry  
 Bibliography: Reviews in Mineralogy and Geochemistry, Mineralogical Society of America, no. 50, p. 487-549

### Web/Internet Site

### Other Specific Products

### Contributions

#### **Contributions within Discipline:**

The formation of granitic liquids by partial melting deep in the Earth's crust is one of the major topics of research in igneous and metamorphic petrology today. One aspect of this sphere of research is the beginning of the process, specifically, the geochemical interaction between melts and source rocks before the melt has left the source area. In 1973 it was first suggested that there is a close relation between formation of granulites and partial melts deep in the Earth's crust, an idea that has become increasingly popular. The Napier Complex of East Antarctica offered an exceptional opportunity to study partial melting of rocks of sedimentary origin (specifically, mixtures of sands, silts and clays, or psammo-pelites) because of localized good exposure, extensive prior study that provided a context for the present study, and a distinctive magnesium bulk composition of the metamorphosed psammopelites that is more readily modeled by experimental systems. The focus of the present research was the lithophile element beryllium, which is rarely analyzed in either rocks or minerals, although, in some cases, significant amounts are present, for example, in some anatectic pegmatites of the Napier Complex. In the present study, beryllium has given geochemical insight complementary to that obtained from other trace elements.

In brief, the localized enrichment of beryllium in the anatectic pegmatites is attributed to the absence of potential host minerals for beryllium, sapphirine and cordierite, in the metamorphosed psammo-pelites at the time of melting. Instead, trace-element distributions suggest that melting was associated with crystallization of garnet and orthopyroxene. The rocks were melted before peak temperatures were reached, and it appears that melting so depleted the rocks in water, that further heating resulted in temperatures in excess of 1000°C. Melting relatively early in the metamorphic evolution is consistent with available geochronologic data. In summary, we can view the present anhydrous condition of the Napier Complex where the metasedimentary rocks show several characteristic element depletions (for example, lithium, boron, tin, cesium) as a result of partial melting followed by marked temperature increase because temperatures were no longer buffered by partial melting. Many of the world's Precambrian granulite-facies terrains appear to be the products of this process.

A contribution to theoretical metamorphic petrology is the development of phase diagrams for beryllian sapphirine in model systems (iron-magnesium-aluminum-silicon-oxygen + beryllium). These can explain the distribution of beryllian sapphirine and its beryllium-enriched analogue khmaralite in the Napier Complex, and have predictive value for petrologists, for example, the variation of sapphirine beryllium content with temperature and pressure and the stability range of beryllian sapphirine relative to other beryllium minerals, that is, the results of this theoretical work could be used to estimate pressures and temperatures of metamorphism, a major goal of petrologists.

Phosphate minerals are of petrologic interest, which is evidenced by the 2002 publication of a Reviews in Mineralogy and Petrology volume on phosphates by the Mineralogical Society of America. Our study concerns the ferromagnesian fluorophosphate wagnerite and its relationship to apatite. Wagnerite may be a more common mineral in granulite-facies rocks that generally thought, if our discoveries in the Napier Complex and Larsemann Hills (Prydz Bay, Antarctica), as well as in India and Algeria, are any guide. The relative importance of host-rock composition, halogen activity and pressure-temperature conditions of formation in wagnerite-apatite relations is now being worked out.

#### **Contributions to Other Disciplines:**

A major contribution to crystallography was the discovery of polytypism in the ferromagnesian fluorophosphate wagnerite. In collaboration with Chinese petrologist Liudong Ren, I found a new 'crystallographic form' of wagnerite, which the Swiss crystallographer Thomas Armbruster recognized as one of four polytypes of this mineral. As a result, two groups of phosphate minerals (triplite and triplodite) turn out have a polytypical relationship, and their crystallographic nature is now much better understood. Prior to our work, these two groups had deterred the best minds in crystallography, for example, one famous crystallographer characterized the structure of the triplodite group as 'extremely complicated' and wrote that it 'is not easily related to any other structure, except at a trivial level'.

Study of beryllium minerals, including khmaralite, a beryllium-enriched analogue of sapphirine, and the structurally related makarochkinite, welshite and h<sup>o</sup>gtuvaite, has given insight into the siting of beryllium in the crystal structures of silicate minerals, specifically, that beryllium is more often miscible with aluminum than silicon at a given site, and that beryllium-oxygen-beryllium bridges are avoided because the bridging oxygen is undercharged.

**Contributions to Human Resource Development:**

The present study contributed to the education of U Maine undergraduate Alex Roy by giving him an opportunity to do literature research on a scientific topic, learn the use of the electron microprobe (except for the microscope, the instrument most used and needed by mineralogists and petrologists), and to present a poster of his research at a national meeting (Geological Society of America). It is expected Roy will write up his results in a paper for publication in a refereed journal during his senior year (academic year 2004-2005), thereby completing the full cycle of carry out a scientific research project.

**Contributions to Resources for Research and Education:**

In carrying out the analyses connected with this project, both Martin Yates and Charles Shearer have perfected analytical techniques, respectively, on the electron microprobe at U Maine and ion microprobe at the University of New Mexico. In particular, the present project was one of the first to make use of U Maine's recently acquired Cameca SX 100 electron microprobe, so Yates developed analytical protocols to process the analytical data.

**Contributions Beyond Science and Engineering:**

Through collaboration with Liudong Ren (Institute of Geology, Chinese Academy of Geological Sciences, Beijing, PRC), A.T. Rao (Andhra University, Visakhapatnam, India), Elena P. Shcherbakova (Natural Science Museum of the Ilmen State Reserve, Miass, Russia), Thomas Armbruster (University of Bern, Switzerland), Jacques Barbier (McMaster University, Canada), Andrew Christy (Australian National University), and others, this research has fostered international cooperation and understanding, as well as a stimulating exchange of ideas on both sides.

**Categories for which nothing is reported:**

Organizational Partners

Activities and Findings: Any Outreach Activities

Any Web/Internet Site

Any Product

--- **Beryllium and other trace elements in Napier Complex minerals and**

**metasediments.** The new ion microprobe data confirm that sapphirine (Spr) concentrates Be by two orders of magnitude relative to associated orthopyroxene (Opx) and sillimanite (Sil), and that the distribution is regular, particularly between sapphirine and secondary orthopyroxene (Opx II) in coronas formed by reaction of sapphirine and quartz (Figure 1).

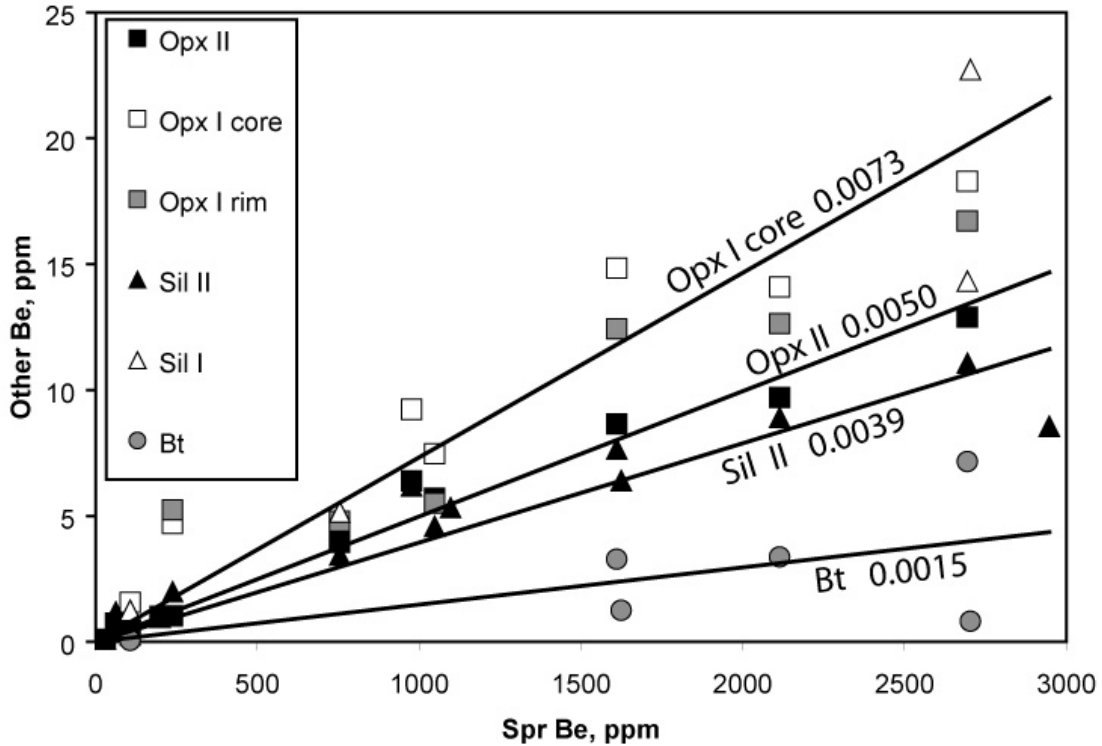


Figure 21

**Figure 1.**

Coarse-grained, presumably primary orthopyroxene (Opx I) contains more Be and Al than secondary orthopyroxene, with cores (Opx Ic) having the highest contents of both constituents; similarly, coarse sillimanite (Sil I) is richer in Be than secondary sillimanite (Sil II) in coronas formed from sapphirine reaction with quartz. Plagioclase (Pl) generally incorporates more Be than associated orthopyroxene and sillimanite, whereas biotite (Bt) incorporates less; quartz (Qtz) and garnet (Grt) contain negligible Be (Figure 2).

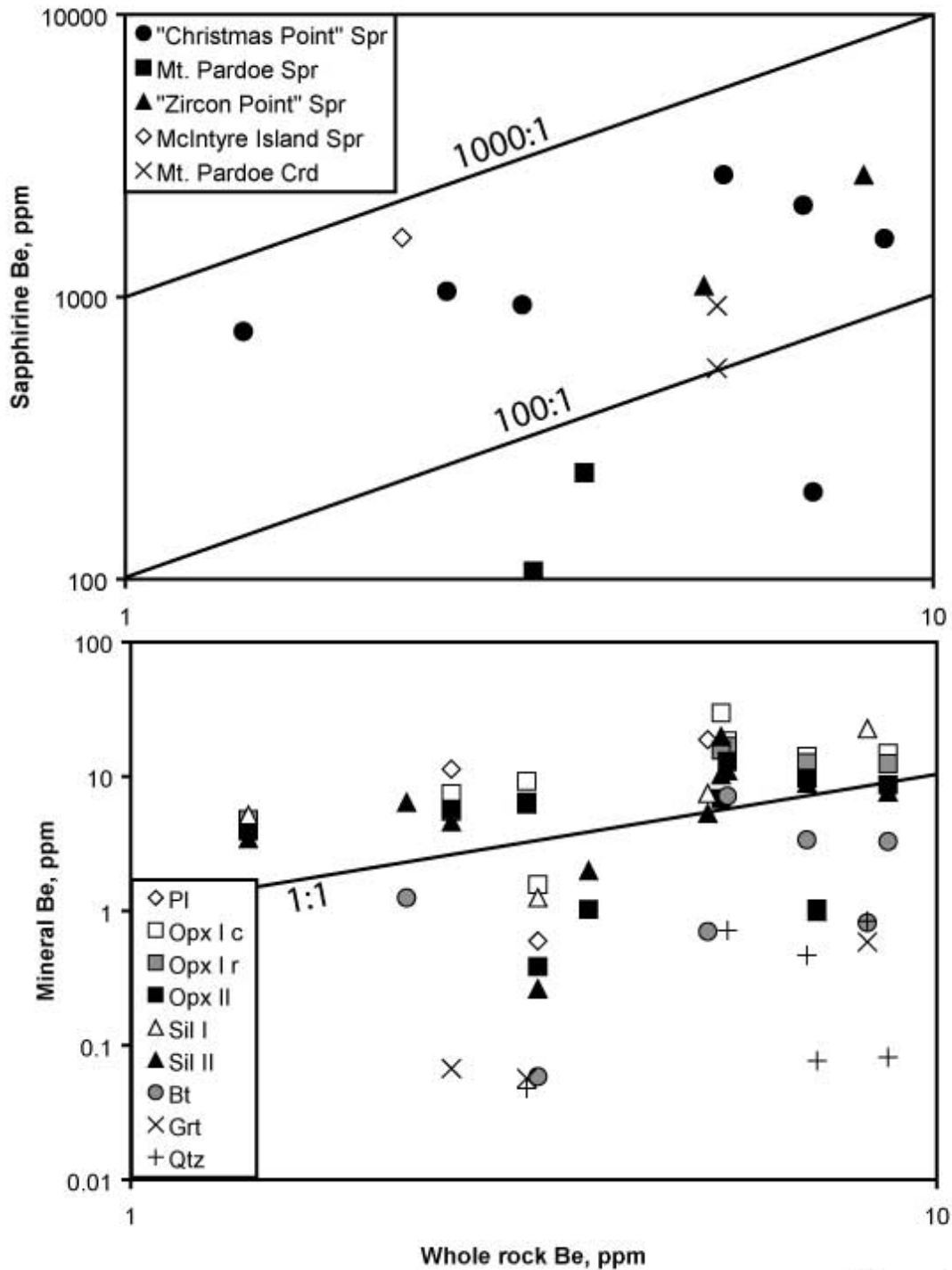


Figure 13

Figure 2.

In the paper now under review with the *Journal of Petrology*, we are suggesting that anatexis at the four studied localities in the Napier Complex did not involve either sapphirine or cordierite, but more likely biotite, orthopyroxene, and possibly sillimanite.



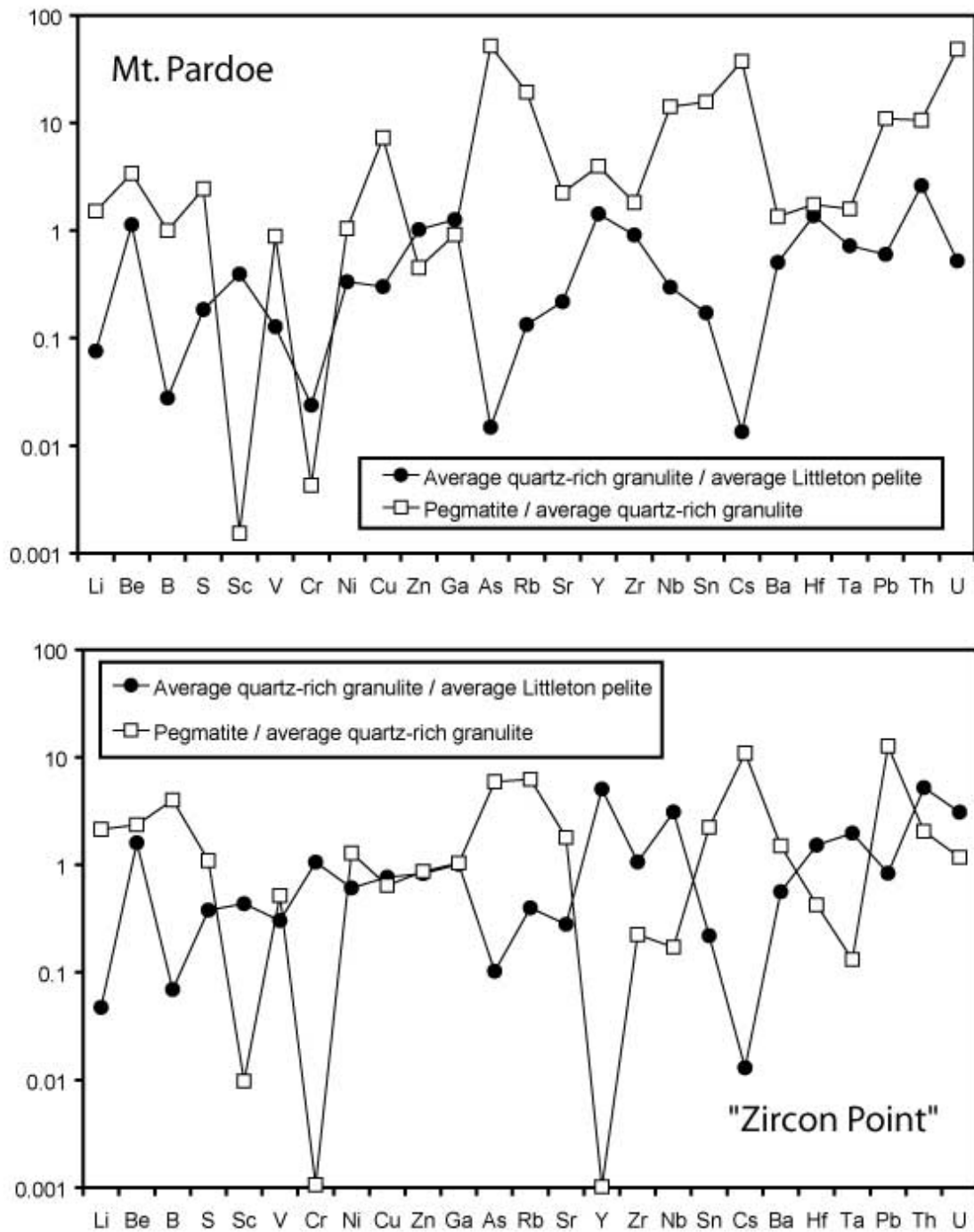


Figure 7

Figure 3.

Major constraints from light elements and certain other trace elements are as follows; the cited depletions are illustrated in Figure 3:

(1) Depletion in Li, Sn and Cs is consistent with the breakdown of biotite to orthopyroxene, garnet, K-feldspar, and/or sillimanite because none of these minerals incorporate Li or Cs to anywhere near the extent that biotite does.

(2) If B had been present in amounts characteristic of pelites and semipelites (tens of ppm ñ 200 ppm), it was largely lost prior to the anatexis in question here. Sapphirine was an unlikely product of this earlier anatexis because it would have concentrated B relative to the above listed minerals.

(3) S and As have received much less attention than other trace elements so the implications of their depletions are not obvious. Depletion in S is neither characteristic of granulite-facies metapelites nor a necessary consequence of anatexis, but depletion in As could be: A plausible explanation for As depletion is breakdown of sulfide, the most likely host for As in the metasediments. Subsequent mobilization with a fluid, perhaps the fluid that mobilized Cl, might have introduced As and Cl into the anatectic melts.

(4) Enrichment of the granulites in Sc and Cr is consistent with the formation of orthopyroxene and garnet from biotite breakdown, either product mineral is a favorable host.

(5) That Be is not depleted in the granulites is consistent with orthopyroxene ± sillimanite being likely products of the anatectic reaction. Figures 1 and 2 imply that Be should be nearly equally distributed between orthopyroxene and melt as it is between sillimanite and melt, i.e., orthopyroxene and sillimanite are not a sinks for Be, yet should prevent Be depletion of the restitic assemblage. Had this assemblage been dominated by garnet and K-feldspar instead of orthopyroxene, one might expect some Be to be lost to the melt as garnet, like K-feldspar and quartz, incorporate negligible Be (Fig. 2).

**--- Beryllium content of sapphirine in the model FMAS system + Be: a theoretical approach.** Andrew Christy and I have completed a theoretical study for predicting the conditions of

formation and beryllium content of sapphirine. Part 2 of our study has been published in *American Mineralogist*. Using the stoichiometries of reactions involving sapphirine and associated phases in the MgO-BeO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> (MBeAS) system in conjunction with molar volume data, we have plotted maps of the sapphirine solid solution field in both  $\mu$ - $\mu$  and  $\mu$ -P space, where  $\mu$  is the chemical potential of an exchange component such as (BeSi)(AlAl)<sub>-1</sub>. These maps give a pressure sequence of stable MBeAS univariant reactions and divariant assemblages that are consistent with experimental data. We generated a MBeAS petrogenetic grid for sapphirine-bearing assemblages over the approximate range T = 700-900°C, P = 0 - 2.5 GPa, identify divariant and univariant assemblages containing sapphirine with maximum Be, and determine the sense of variation of maximum Be content with P. At lower T, maximum Be occurs at the low-P limit of surinamite stability, ca. 0.5 GPa. At higher T, maximum Be increases with P, following the MBeAS univariant reactions involving (sapphirine + surinamite + orthopyroxene + chrysoberyl + forsterite or spinel). Natural assemblages containing sapphirine and its Be-rich near-analog khmaralite from the Napier Complex, Enderby Land, East Antarctica formed at higher T (900-1100°C) than the experiments and in bulk compositions containing substantial Fe. Associated minerals include garnet, sillimanite, quartz and magnesiotaaffeite-6Ni3S (i musgravite).  $\mu$ (BeSi)(AlAl)<sub>-1</sub>- $\mu$ FeMg<sub>-1</sub> diagrams show that the stability of magnesiotaaffeite-6Ni3S causes the maximally beryllian khmaralite to shift from a magnesian composition in equilibrium with (orthopyroxene + surinamite + forsterite + chrysoberyl), as in the MBeAS subsystem, to a more Fe-rich composition associated with (garnet + surinamite + magnesiotaaffeite-6Ni3S + chrysoberyl). Khmaralite associated with (sillimanite + garnet + surinamite + magnesiotaaffeite-6Ni3S or chrysoberyl) in a Napier Complex pegmatite from Khmara Bay is predicted to be the most Be-rich possible in the presence of sillimanite, whereas the (sillimanite + quartz ± orthopyroxene ± garnet) associations in quartz granulites requires a sapphirine much lower in both Be and Fe; analyses are roughly in accord with these predictions. The shape of the sapphirine/khmaralite solid solution field is such that there is a positive correlation between high Be and high Fe<sup>2+</sup>, a chemographic effect independent of any crystal chemical effects due to the clustering of Fe and Be in the crystal structure of khmaralite. The diagram for FMBEAS shows that (Spr + Qtz), which is often cited as evidence for ultrahigh temperatures (e.g., ≥ 1040°C), is stabilized to lower T and higher P than in the corresponding Be-free system. Hence, this minimum T may be valid only in rocks with relatively abundant Spr and/or very low bulk Be content so that what Be is present in the system is not concentrated in Spr.'

--- **Wagnerite polytypes.** Liudong Ren (Institute of Geology, Chinese Academy of Geological Sciences), Ming Xiong and Zhesheng Ma (China University of Geosciences) discovered a new polytype of wagnerite, a fluorophosphate of composition, (Mg,Fe)<sub>2</sub>(PO<sub>4</sub>)(F,OH) from the Larsemann Hills, Prydz Bay, East Antarctica, and invited me to collaborate with them in writing up this find. The

main difference among the wagnerite polytypes is ordering of (F,OH) positions. The results of this study were presented at annual meeting of the Geological Society of America in Denver in October, 2002, and a paper has been published in *Canadian Mineralogist*. The results of this study have direct bearing on the Napier Complex study as the phosphate  $(\text{Mg,Fe})_2(\text{PO}_4)(\text{F,OH})$  is an important constituent of the beryllium pegmatites and the subject of Alex Roy's research (next topic). The primary difference between the newly discovered wagnerite-Ma5bc polytype and standard wagnerite-Ma2bc polytype (e.g., type locality) is ordering of the (F,OH) positions. F can occupy one of two positions resulting in two distinct configurations along the *a* direction. In magniotriplite the sequence of configurations in the *b* direction is disordered, whereas in wagnerite-Ma2bc the sequence is ordered 121212 $\bar{0}$  and in wagnerite-Ma5bc, 12112... Magniotriplite and the wagnerite polytypes do not overlap in composition: minerals richer in Fe and Mn (average ionic radius exceeding 0.76 Å) crystallize as the disordered minerals in the triplite group, whereas highly magnesian minerals (average ionic radius less than 0.73 Å or exceeding 86% of the Mg end member) crystallize as the ordered wagnerite polytypes. Magniotriplite formed at moderate temperatures (e.g., amphibolite-facies), whereas wagnerite-Ma2bc is found in rocks formed under a wide range of P-T conditions. Compositional and/or kinetic factors, rather than P-T, could play the leading role in determining the extent of F order; possibly many  $\text{M}^{2+}_2\text{PO}_4\text{F}$  compounds originally crystallized in the disordered state, the Mabc polytype, and only magnesian varieties subsequently ordered on cooling, i.e.,  $\text{Mn}^{2+}$  and  $\text{Fe}^{2+}$  inhibit ordering.'

--- **Wagnerite in the Napier Complex.** U Maine undergraduate student Alex Roy presented the results of his study of wagnerite and associated minerals in pegmatites and granulites as a poster at the annual meeting of the Geological Society of America in November, 2003. This study is based on the discovery of wagnerite in Late Archean pegmatite pods and veinlets at four localities in the ultrahigh-temperature Napier complex and in a phlogopite-enstatite-sapphirine-cordierite granulite reworked in the Early Cambrian (i Rayneri Complex), western Enderby Land, Antarctica. Associated minerals in the pegmatites include biotite, apatite, sillimanite, quartz, garnet, perthite, beryllian sapphirine-khmaralite, surinamite, cordierite, ilmenite-hematite intergrowths, and rutile. Textural relationships suggest that wagnerite is a primary phase that formed at temperatures of ~900°C (granulite) and possibly ~1000°C (pegmatite) at ~1GPa. Apatite shows complex textures, in most cases it armors or rims the wagnerite grains. Three generations of apatite are evident (1) a primary chlorapatite to Cl-rich fluorapatite that appears to be coeval with wagnerite (i Christmas Point only), (2) rims of chlor-fluorapatite that surround wagnerite in most samples and (3) late F-rich apatite (possibly carbonato-apatite) that has partially replaced the apatite rims. Electron microprobe analysis shows wagnerite Fe/(Fe+Mg) ratio ranging from 0.026 to 0.073, which is roughly correlated with Fe/(Fe+Mg) ratio in

contiguous biotite grains. F and Fe contents in the biotite vary inversely; which is attributed to F-Fe avoidance. Biotite F/(F+Cl) ratios do not vary systematically with apatite F/(F+Cl) ratios, instead there is an increase of apatite F+Cl with increasing wagnerite F amounts. Since OH is assumed to be (1-F) in wagnerite and (1-F-Cl) in apatite, this suggests a possible regular distribution of OH between the two minerals. Overall, the distribution of the halogens and Mg-Fe among biotite, apatite and wagnerite is not particularly regular, and so there is little evidence for chemical equilibrium, possibly as result of multiple events. This disequilibrium is also reflected in the complex apatite textures and variable chemical compositions of biotite. The presence of significant Cl in pegmatitic apatite and biotite, and the near absence of Cl in these minerals within the granulite support evidence obtained from bulk analyses of other Napier complex pegmatites for Cl enrichment in the pegmatites relative to their host rocks.

### **--- Lead aureoles in K-feldspar: implications for electron microprobe age dating of monazite.**

Martin Yates discovered the presence of substantial lead in potassium feldspar surrounding monazite in pegmatites in the Napier Complex, a finding that has led to a study of the relationship between U-Pb-Th ages of monazite obtained from electron microprobe data and diffusion of lead in monazite and feldspar. The results were presented as a poster at the annual meeting of the Geological Society of America in November, 2003, and have been accepted for poster presentation at the 32nd International Geological Congress in Florence, Italy, August, 2004. The results are best summed up in the IGC abstract:

Text: Geologic evolution of the Napier Complex began in the Early Archean (3800 Ma) prior to a regional ultrahigh temperature metamorphic event (up to 7-11 kbar, 1050-1120°C) sometime between 2550 and 2480 Ma, after which metamorphic and igneous activity was largely confined to mafic dike emplacement and amphibolite to granulite-facies events at 1600 Ma, ~1000-900 Ma and 540-520 Ma along the periphery and in highly localized shear zones. U-Pb isotopic data reported in the literature for zircon from a pegmatite (sample #2233) and for monazite from a paragneiss at Zircon Point, Khmara Bay, gave upper and lower intercept ages of 2400-2500 Ma and ~1100 Ma, respectively. Electron microprobe age determinations from monazite-(Ce) in pegmatites and quartz granulites show considerable  $\mu\text{m}$ -scale age heterogeneity. Monazite-(Ce) grains in the pegmatites are coarse (1 to 5 cm) and exhibit considerable chemical variation (up to 28 wt%  $\text{ThO}_2$ ). Th, U, and Pb compositional maps of these coarse monazites show sector and growth zoning, but apparent age maps exhibit no consistent age domains. Apparent age variations are continuous with a few scattered, slightly older domains. Chemical ages from 5  $\mu\text{m}$  spots vary from 2352  $\pm$  85 Ma to 800  $\pm$  40 Ma and are observed to vary as much as 400 Ma in apparent age over a 30  $\mu\text{m}$  distance. Alkali feldspars in contact with monazite-(Ce) grains are strongly enriched in Pb. An aureole 2 to 4 mm thick surrounding the

monazite-(Ce) contains 0.2 to 2.0 wt% PbO, and K-feldspar included in monazite-(Ce) contains up to 9.9 wt% PbO. Monazite-(Ce) grains from quartz granulites range from 20 to 100  $\mu\text{m}$  and tend to be more uniform in composition (6  $\pm$  8 wt% ThO<sub>2</sub> and 0.6 to 1 wt% PbO). They have higher Y and have measurable HREE contents. Apparent age maps exhibit scattered, uniformly old apparent age domains (~2400  $\pm$  100 Ma). They also have both linear and irregular, variable apparent age domains, varying from 1650 to 2010 Ma. We attribute the chronological heterogeneity to partial lead loss during a late-Proterozoic event at ~1100 Ma that resulted in partial lead loss. Lead from the pegmatitic monazite-(Ce) diffused into contiguous alkali feldspar. Where there are linear zones of low apparent age, lead loss may have been controlled by fractures, whereas irregular micron-scale heterogeneity suggests recrystallization. TEM investigations of monazite-(Ce) at the sub-micron scale are underway to evaluate these two alternatives.

--- **Makarochkinite, a new beryllosilicate mineral of the aenigmatite group.** Together with J. Barbier, E.P. Shcherbakova and others I have succeeded in obtaining approval of makarochkinite,  $\text{Ca}_2\text{Fe}^{2+}_4\text{Fe}^{3+}\text{TiSi}_4\text{BeAlO}_{20}$ , as new mineral species from the Commission on New Minerals and Mineral Names, International Mineralogical Association (number 2002-009). Validation of makarochkinite as a mineral distinct from  $\text{h}^-$  gtuvaite is part of a larger crystallographic study of beryllosilicate members of the aenigmatite group and related minerals, including beryllian sapphirine, khmaralite, surinamite and welshite. A manuscript is currently presently being written up; a portion of this study has been accepted for oral presentation at the 32nd International Geological Congress in Florence, Italy, August, 2004. In both makarochkinite and  $\text{h}^-$  gtuvaite, the one Be per formula unit is evenly divided between the T1 and T4 (Q3) sites so that Be-O-Be bridges are minimized. Ca and Na occupy the 7-coordinated M8 and M9 sites, and Mg together with Fe occupy the M1-6 octahedral sites without evidence of strong ordering in either case. The shorter average M7-O distances ( $2.03 \approx$ ) and the associated  $U_{\text{eq}}$  displacement parameters led to assign all Ti to the M7 octahedral sites in both structures, together with  $\text{Fe}^{3+}$  and other minor high-valent elements. As a result, the M7 site occupancy in makarochkinite (59% Ti + 37% Fe) establishes it as a distinct mineral and also distinguishes it from  $\text{h}^-$  gtuvaite (70% Fe + 24% Ti). In contrast to makarochkinite and  $\text{h}^-$  gtuvaite, surinamite has only one T site joined to three others (so-called Q3 site), and this T site is fully occupied by Be, with negligible Be on other T sites. Welshite contains more Be than either makarochkinite or  $\text{h}^-$  gtuvaite, and we are currently trying to refine Be occupancy of this complex mineral.

--- **Beryllium and boron minerals in Indian granulite-facies rocks.** The Eastern Ghats belt of southeastern India is an ultrahigh-temperature granulite-facies terrain having many similarities

to the Napier Complex; moreover, these two terrains are believed to have been juxtaposed in Gondwana reassemblies. For these reasons, a report of surinamite, a beryllosilicate found in Napier Complex anatectic pegmatites, attracted my interest. A study of the Eastern Ghats surinamite paragenesis would be highly relevant to my project on beryllium and its minerals in the Napier Complex. However, no surinamite was found either by me or by one co-author of the original report. My conclusion that the reported surinamite was misidentified hypersthene was published in *Current Science*. In the course of studying rocks from the locality where surinamite was reported to occur, I discovered prismatine, a new locality for India, and this find was published in *Mineralogical Magazine*.