



## COMPACT SCANNING ELECTRON MICROSCOPES: IMPRESSIVE ANALYTICAL TOOLS

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I have been working with ion microprobes for over three decades now, and I have witnessed major technological advances over that period. For example, the isotope ratio repeatability for major elements that are now possible for a modern secondary ion mass spectrometer (SIMS) is down to  $\pm 0.1\%$  on a fairly routine basis, perhaps a factor of five better than was the case just two decades ago. However, one aspect that has seen little improvement for most SIMS machines is the challenge of sample viewing. The fundamental problem is one of simple geometry for the large-radius instruments that are used for both isotope ratio and geochronology applications: secondary ions must be extracted perpendicular from the sample surface, meaning that the objective for the sample viewing microscope cannot be positioned where it really needs to be. Two possible solutions exist that enable real-time viewing: the first is by employing a Schwarzschild lens with a central hole in each of its mirrors; the second is to use oblique viewing. Neither of these solutions are really satisfactory because spatial resolution remains limited to no better than 2–3  $\mu\text{m}$ . This leaves plenty of opportunity for the SIMS analyst to position his/her analysis on small cracks, scratches, or micron-sized inclusions which remain invisible to even the best trained eye.

Back in the late 1980s while doing my PhD research using the original sensitive high-resolution ion microprobe (SHRIMP) instrument in Canberra (Australia), the U–Pb dating of zircons meant photographing each crystal and then bicycling downtown to a camera shop carrying rolls of 35 mm film that took around three days to develop and print. With this strategy, having amassed perhaps 75 detailed reflected-light images and a low magnification map made from photos pasted to a poster board, one was ready to run.

Nowadays, things have changed somewhat. We now have digital reflected-light mosaics of the entire 1-inch [2.54 cm] sample mount that can be calibrated to a SIMS sample stage position to within a few microns. We commonly augment this sample documentation with backscattered electron images and panchromatic (i.e. black and white) cathodoluminescence (CL) images made of key locations using a field-emission scanning electron microscope (SEM) housed in a neighboring section of my institute. Such images provide crucial information for targeting the best domains for isotope ratio or U–Pb analyses, and such images can be extremely helpful in understanding subsequent data sets that turn out to be more complex than anticipated. However, this routine use of SEM documentation is not without its problems. Waiting times for accessing such high-end analytical equipment can run into many weeks, if not months. And, if due care is not taken, the extremely high current densities that a field emission source delivers can damage the epoxy resin. Image mosaics of the entire surface of a 1-inch SIMS mount are time consuming. Samples need to be coated with a conductive film in order to achieve the imaging performance of a field-emission SEM. Finally, it just seems like a misuse of analytical resources to use a machine that delivers 2 nm imaging resolution when 200 nm spatial resolution would more than suffice for my needs.

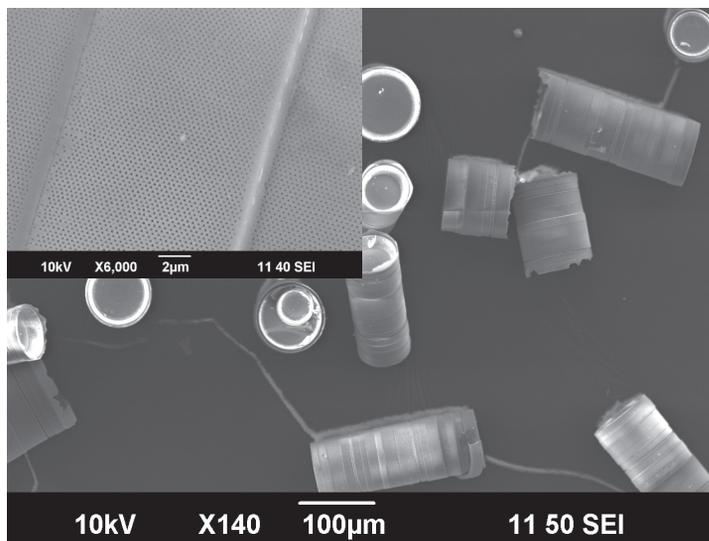
I have long been on the lookout for an alternative sample documentation strategy. This is the background as to why I contacted the company JEOL Germany to inquire about the JSM-IT200, the newest in their line of compact SEM instruments. The information that I received convinced me that this technology was worth a more detailed look. Such compact scanning electron microscopes have been around for more than two decades, and, during this period, the performance capabilities have advanced greatly. My first stop was a visit across town



**FIGURE 1** The small format scanning electron microscope (SEM) at the Hochschule für Technik und Wirtschaft (University for Applied Sciences), Berlin (Germany).

to Berlin's University of Applied Sciences (Hochschule für Technik und Wirtschaft) where Klaus Heinrich showed me his two-year-old JSM-IT100 system (FIG. 1). His laboratory is a very practical one where student users with little to no microanalytical experience can quickly understand the basics of the instrumentation in order to generate images for their research projects. I believe that Klaus' enthusiasm for his SEM is well justified, both in terms of instrument design and the highly intuitive software layout. Just imagine a system where clicking on the button labeled "Focus" results in the image on the computer screen instantly sharpening. Clicking on the button labeled "Magnification" produces a drop-down menu where the present magnification is clearly shown and all the other options are obvious. These and the other software features really seem designed with the machine-human interface at the forefront. Another feature that impressed me was that the JSM-IT100 site requirements consisted of (1) an electric socket, and (2) an RJ45 internet socket. That's all there was. And the internet socket itself was actually extraneous if one doesn't wish to run the instrument remotely. Small footprint. Simple to learn. Simple to operate. Truly impressive.

The needs of the Potsdam SIMS laboratory that I manage derive from large-area backscattered electron mosaic images that cover an entire 1-inch sample mount, to secondary electron images with <100 nm spatial resolution, to color CL imaging. For further help, I turned to JEOL and requested that a demonstration session be arranged on a suitably configured instrument. Two weeks later, I took the 230 km drive to the University of Jena where Sven Schönherr at the Institute for Solid State Physics had agreed to show me his JEOL system, which

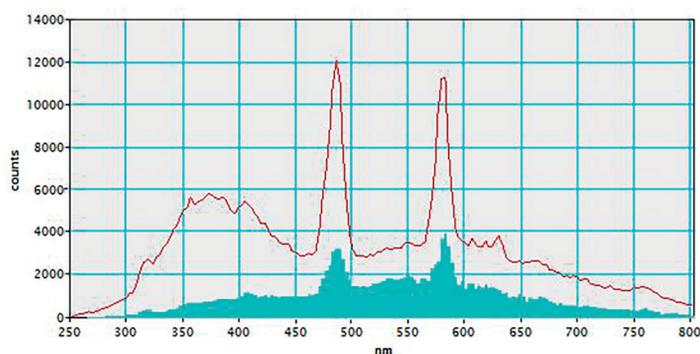


**FIGURE 2** Secondary electron images of diatoms. The inset image is a high-magnification image of a horizontal surface. Features smaller than 100 nm are clearly visible. IMAGE CREDIT: SVEN SCHÖNHERR

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was based on an eight-year-old JEOL compact system augmented with a high-end Gatan spectrometer for acquiring both CL spectra and for narrow waveband image acquisition. Such a system should be able to provide a 50 nm spatial resolution, so one test that I requested was that a fine-structured sample should be imaged. I had brought with me a vial of diatoms which I had obtained from Hanno Meyer, a colleague of mine at the Alfred Wegner Institute in Potsdam. These 100  $\mu\text{m}$  structures were sprinkled onto a sticky carbon film prior to being carbon coated. The images, acquired in a matter of minutes (Fig. 2), lived up to expectations. The spatial resolution was well below 100 nm, and this was achieved with little effort in terms of tuning and optimization. Nicer still, I was assured that fairly similar results could be achieved using low vacuum mode and without sample coating.

My key motivation for travelling to Jena was to get an impression of the color CL capabilities of a compact SEM. What is important to understand here is that CL photon spectrometers are always mounted on a port on the side of the SEM's sample chamber, and this means that a mirror with a central hole must be placed into the electron beamline; all CL images are acquired in a scanning imaging mode. For the Jena machine, the mirror was placed near the surface of the sample, which is advantageous for their spectroscopic applications but means that CL and backscatter modes cannot be operated concurrently (though other system geometries don't suffer this limitation). Another constraint of the arrangement in Jena was that the presence of the mirror in the electron beamline leads to shadow artifacts when scanning more than  $\sim 100\ \mu\text{m}$  off axis. This would be a major problem with regards to my needs in the Potsdam SIMS lab, but I have been assured that other CL detector geometries suffer much less from this issue. That said, for spectroscopic applications, the Jena system yielded high-quality results. An example that I present here (Fig. 3) shows the spectra from two zircon samples that include Temora2 (blue filled area) (Black et al. 2003) and a second material currently being investigated in Potsdam (red line). Clearly, there is a lot of valuable information in such data sets. Equally clear is that there are decisions that need to be made when configuring a system so that it is optimized to one's specific analytical needs.



**FIGURE 3** Cathodoluminescence photon emission spectra from two different zircon samples. In both cases, the data were acquired over an  $\sim 50 \times 50\ \mu\text{m}$  area with a spectral resolution of 4 nm. A single spectrum needs  $\sim 10$  minutes to acquire. IMAGE CREDIT: SVEN SCHÖNHERR

I was still keen to get an impression of the color CL imaging capability of the Jena instrument. For this, we used a large quartz crystal provided by Axel Müller (University of Oslo), which he had previously been imaged in panchromatic CL (Fig. 4A) (Müller et al. 2018). The largest area that we could scan without excessive shadowing from the in-line mirror was  $125 \times 125\ \mu\text{m}$ , and we conducted such a scanning image for two wavelengths centered on 411 nm and 640 nm using a 4 nm spectrometer slit. Each such scan took but a few minutes to complete,



**FIGURE 4** (A) Panchromatic cathodoluminescence (CL) mosaic of a large quartz crystal from central Norway. The red arrow indicates the location for the detailed color CL image. IMAGE CREDIT: A. MÜLLER. (B) Two-frequency, false color CL image of a small area of the quartz crystal in FIGURE 4A. Purple color  $\lambda = 411\ \text{nm}$ ; Orange color  $\lambda = 640\ \text{nm}$ . IMAGE CREDIT: SVEN SCHÖNHERR

after which software constructed an integrated false-color image from these two monochromatic images (Fig. 4B); see Götze and Möckel (2012) for an overview of trace elements and CL emission in quartz. There is a wealth of information evident in such images. However, the Jena system, which is optimized for spectroscopy, was not well suited for color CL imaging over large areas. That said, a simpler CL detector system that is configured more toward imaging would fit the task better.

Considering all of the points discussed above, it should be clear that the JEOL line of compact SEMs does impress me. And there is one more important thing that I have yet to mention. The purchase price of such a compact system is perhaps 80% below that of a top-end field-emission SEM! For researchers wanting to invest in scanning electron technology there is now a fundamental question: Do you really need nanometer-scale resolution? If not, then the JSM-IT200 from JEOL, or a similar product from another company, such as Hitachi, Phenom or Zeiss, might be a better choice.

I would like to finish this discussion by thanking everyone who contributed towards my understanding of the true capabilities of compact SEM instrumentation. Alex Müller of the University of Oslo provided the quartz sample for CL imaging, and Hanno Meyer of the Alfred Wegner Institute in Potsdam provided the diatom sample for testing imaging performance. I would also like to express my particular thanks Klaus Heinrich at Berlin's Hochschule für Technik und Wirtschaft for giving me a tour of his JEOL lab and to Sven Schönherr of the University of Jena for a very interesting day devoted to a detailed demonstration of his SEM, including his patience in producing the wide variety of test images I proposed. Finally, Leon Hütsch from JEOL Deutschland GmbH is gratefully acknowledged for having arranged these contacts for me and for his tireless willingness to answer my many questions.

Best Regards from Potsdam,  
**Michael Wiedenbeck**

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## LITHIUM – 200 YEARS: SYMPOSIUM AND FIELD TRIP JUNE 14–16, 2018

Edward S. Grew<sup>1</sup>, Erik Jonsson<sup>2,3</sup>, and Jörgen Langhof<sup>4</sup>

Lithium was discovered in 1818 in petalite from pegmatites on Utö (Sweden), an island in the Stockholm archipelago, by Johan August Arfwedson (1792–1841), a student working in the laboratory of Jacob Berzelius (1779–1848), the famous Swedish chemist. To commemorate the 200<sup>th</sup> anniversary, the Swedish Mineralogical Society (SMS), with the support of the Swedish Museum of Natural History, organized a symposium held at the museum (FIG. 1) followed by a two-day field trip to Utö Island, where it is still possible to collect petalite and other lithium minerals and to study the geological context of the lithium–cesium–tantalum (LCT) pegmatites in which the lithium minerals occur.



**FIGURE 1** Attendees of the symposium “Lithium 200 years” on the front steps of the Swedish Museum of Natural History. PHOTO: BENGT OLOFSSON.

The symposium opened on 14 June 2018 before an audience of more than 40 with a welcome and introduction by Erik Jonsson (Geological Survey of Sweden and Uppsala University), who also touched upon the economics of lithium as a potentially critical commodity in Europe. The keynote talk was delivered by Edward Grew (University of Maine, USA) on lithium mineral evolution and ecology, i.e. the increasing diversity of lithium minerals as reported in the geologic record, the history of discovery of these minerals, and estimating Earth’s endowment of these minerals. Andreas J. Korn (Uppsala University, Sweden) discussed lithium in the cosmos. This talk was followed by reviews of lithium mineralization in Norway, by Roy Kristiansen (amateur mineralogist from Norway, delivered by Alf Olav Larsen), and in Swedish pegmatites, by Erik Jonsson. Joakim Mansfeld (University of Stockholm, Sweden) reported on the metamorphic evolution of the rocks that host the LCT pegmatites at Utö, and Jörgen Langhof (Swedish Museum of Natural History) summarized studies of these pegmatites. Magnus Leijd reported on Sweden’s most recently discovered LCT pegmatites at Bergby, and Thomas Zack (University of Gothenburg, Sweden) concluded the symposium with a re-evaluation of Swedish pegmatite ages using in situ Rb/Sr dating.

Following the symposium, 18 participants attended a field trip to Utö Island to view the famous Swedish iron-ore mines and the LCT pegmatites at the type locality for petalite and spodumene. Participants gathered at Årsta havsbad (a port on the coast south of Stockholm) for

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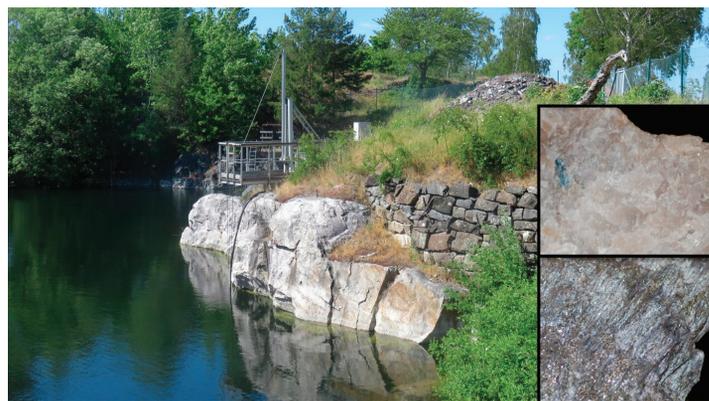
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4 Department of Geosciences  
Swedish Museum of Natural History  
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**FIGURE 2** Field trip participants, including Erik Jonsson (khaki shirt) in front of Edward Grew (in red shirt, pointing), examine the contact of a lithium–cesium–tantalum pegmatite with its iron-rich host rock exposed in the southern side of the Nyköpingsgruvan mine on Utö Island (Sweden). PHOTO: JÖRGEN LANGHOF.

the ferry to Utö and enjoyed a picnic lunch in splendid weather at the first stop in Rävstavik. Here, participants observed glacially polished coastal outcrops of metagreywacke intercalated with metaconglomerate at the base of the sedimentary–volcanic sequence that hosts the LCT pegmatites. After a brief examination of metasedimentary and metavolcanic rocks higher in the section, participants admired the Nyköpingsgruvan and Långgruvan mines. From at least as early as the 12<sup>th</sup> century, and only ending in 1879, iron ore was extracted from these mines, which are now partially filled with water. The LCT pegmatites located within these mines are where several lithium-bearing minerals were discovered: spodumene and petalite (in 1800) and holmquistite (in 1910). The largest LCT pegmatite is, for the most part, submerged, but a smaller dyke to the south afforded views of the contact in situ between host rock and pegmatite (FIG. 2). This part of the pegmatite shows patches of amazonite and there are spodumene cleavages up to several centimeters across. The day’s field activities concluded with a stop at the most differentiated part of the bigger Nyköpingsgruvan pegmatite where pollucite, a cesium-rich zeolite, has been reported. The final “stop” was the small mining museum in the “Spruthuset” building, which was specially opened for our benefit. At 18:00, participants were treated to a lecture by Jan Trofast on a re-evaluation of the history of the lithium discovery based on his latest research on J. Berzelius. The second day was largely devoted to collecting on the main mine dump, where participants succeeded in finding several of Utö’s specialties – fresh petalite, fibrous holmquistite (FIG. 3), chiavennite, and elbaite tourmaline.



**FIGURE 3** The main lithium–cesium–tantalum pegmatite exposed on the north wall of the Nyköpingsgruvan mine (Utö Island). Most likely, the type material of petalite and spodumene originated from this pegmatite. (INSET TOP) Light-gray petalite (field of view 6 cm), collected on the field trip. (INSET BOTTOM) Fibrous holmquistite (field of view 3 cm), also collected on the field trip. PHOTO: EDWARD GREW; INSET PHOTOS: JÖRGEN LANGHOF.

## 2018

**July 30–August 2** Summer School: Reactive Transport Modeling in Geochemical Systems, Edinburgh, Scotland, UK. Web page: <https://www.gwb.com/workshops.php>

**August 5** Pre-meeting Congress: Standards and Reference Materials for Microanalysis, Baltimore, MD, USA. Web page: [www.microscopy.org/MandM/2018/program/congress\\_X61.cfm](http://www.microscopy.org/MandM/2018/program/congress_X61.cfm)

**August 5–9** Microscopy & Microanalysis 2018, Baltimore, MD, USA. Web page: [www.microscopy.org/events/future.cfm](http://www.microscopy.org/events/future.cfm)

**August 5–10** Gordon Research Conference: Geochemistry of Mineral Deposits: Mineralizing Processes Across All Scales, Waterville Valley, NH, USA. Web page: [www.grc.org/geochemistry-of-mineral-deposits-conference/2018/](http://www.grc.org/geochemistry-of-mineral-deposits-conference/2018/)

**August 10–12** Short Course: High Temperature Gas – Solid Reactions in Earth and Planetary Processes, Boston, MA, USA. Web page: forthcoming

**August 10–12** Magma Chamber Simulator Workshop, Boston, MA, USA. Web page: [mcs.geol.ucsb.edu/](http://mcs.geol.ucsb.edu/)

**August 12–17** 2018 Goldschmidt Conference, Boston, MA, USA. Web page: [www.geochemsoc.org/programs/goldschmidtconference/](http://www.geochemsoc.org/programs/goldschmidtconference/)

**August 13–17** XXII Meeting of the International Mineralogical Association, Melbourne, Australia. Web page: [www.ima2018.com](http://www.ima2018.com)

**August 13–17** 20th International Sedimentological Congress, Quebec, QC, Canada. Web page: [www.isc2018.org](http://www.isc2018.org)

**August 19–23** 256th ACS National Meeting & Exposition, Boston, MA, USA. Web page: [www.acs.org](http://www.acs.org)

**August 19–24** Gordon Research Conference: Rock Deformation: Integrated Approaches to Rock Deformation: Observations, Experiments, and Models, Andover, NH, USA. Web page: [www.grc.org/rock-deformation-conference/2018/](http://www.grc.org/rock-deformation-conference/2018/)

**August 22–27** 31st European Crystallography Meeting, ECM-31 Oviedo, Spain. Web page: [ecanews.org/mwp/meetings/](http://ecanews.org/mwp/meetings/)

**August 27–30** Comparative Climatology of Terrestrial Planets III (CCTP-3), Houston, TX, USA. Web page: [www.hou.usra.edu/meetings/climatology2018/](http://www.hou.usra.edu/meetings/climatology2018/)

**August 28–31** 15th Quadrennial IAGOD Symposium, Salta, Argentina. Web page: [15iagods.org/](http://15iagods.org/)

**September 2–6** GEOBONN 2018: Annual Conference of DGGV, DMG and PalGes, Bonn, Germany. Web page: [www.geobonn2018.de/imprint.html](http://www.geobonn2018.de/imprint.html)

**September 3–7** Magmatism of the Earth and Related Strategic Metal Deposits, Moscow, Russia. Web page: [emsmdu.ru/](http://emsmdu.ru/)

**September 4–7** European Microbeam Analysis Society (EMAS) 2018 Workshop, Bristol, UK. Web page: [www.microbeamanalysis.eu](http://www.microbeamanalysis.eu)

**September 9–14** 19th International Microscopy Congress (IMC-19), Sydney, Australia. Web page: [imc19.com/](http://imc19.com/)

**September 12–14** 89th Congress: SGI-SIMP (Italian Society of Mineralogy and Petrology), Catania, Italy. Web page: forthcoming

**September 16–21** 16th International Conference on Thermochronology, Quedlinburg, Germany. Web page: [www.thermo2018.de/#/](http://www.thermo2018.de/#/)

**September 30–October 3** Bombardment: Shaping Planetary Surfaces and Their Environments, Flagstaff, AZ, USA. Web page: [www.hou.usra.edu/meetings/bombardment2018/](http://www.hou.usra.edu/meetings/bombardment2018/)

**October 1–3** Late Mars Workshop, Houston, TX, USA. Web page: [www.hou.usra.edu/meetings/latemars2018/](http://www.hou.usra.edu/meetings/latemars2018/)

**October 1–5** Short Course: Application of Diffusion Studies to the Determination of Timescales in Geochemistry and Petrology, Bochum, Germany. Web page: forthcoming

**October 7–9** GIA International Gemological Symposium, Carlsbad, CA, USA. Web page: [gia.eventsair.com/QuickEventWebsitePortal/gia-symposium-2018/gia-symposium](http://gia.eventsair.com/QuickEventWebsitePortal/gia-symposium-2018/gia-symposium)

**October 14–18** Materials Science & Technology 2018, combined with ACerS 120th Annual Meeting (MS&T18), Columbus, OH, USA. Details forthcoming

**October 25–28** 25th Session of the Petrology Group of the Polish Mineralogical Society, Brunów, Sudetes, Poland. Web page: [www.ptmin2018.uni.wroc.pl](http://www.ptmin2018.uni.wroc.pl)

**November 4–7** Geological Society of America Annual Meeting, Indianapolis, IN, USA. E-mail: [meetings@geosociety.org](mailto:meetings@geosociety.org); Web page: [www.geosociety.org/meetings](http://www.geosociety.org/meetings)

**December 3–7** Short Course, Introduction to Secondary Ion Mass Spectrometry in the Earth Sciences, Potsdam, Germany. Web page: [sim.gfz-potsdam.de/short-course/](http://sim.gfz-potsdam.de/short-course/)

**December 10–14** AGU Fall Meeting, Washington, DC, USA. [fallmeeting.agu.org/2018/welcome/](http://fallmeeting.agu.org/2018/welcome/)

## 2019

**January 27–February 1** 42nd International Conference and Expo on Advanced Ceramics and Composites (ICACC'19), Daytona Beach, FL, USA. Web page: [ceramics.org/meetings/acers-meetings](http://ceramics.org/meetings/acers-meetings)

**February 18–22** DTTG workshop: Qualitative and Quantitative Analysis of Clays and Clay Minerals, University of Greifswald, Germany. Information: [www.dttg.ethz.ch/workshop2019.html](http://www.dttg.ethz.ch/workshop2019.html)

**March 10–14** TMS (Minerals, Metals & Materials Society) 2019 148th Annual Meeting & Exhibition, San Antonio, TX, USA. Web page: [www.tms.org/tms2019](http://www.tms.org/tms2019)

**March 18–22** 50th Lunar and Planetary Science Conference, Houston area, USA. Web page [www.hou.usra.edu/meetings/lpsc2019/](http://www.hou.usra.edu/meetings/lpsc2019/)

**March 31–April 4** 257th ACS National Meeting & Exposition, Orlando, FL, USA. Web page: [www.acs.org/](http://www.acs.org/)

**May 12–15** GAC–MAC 2019, Quebec City, QC, Canada. Webpage: forthcoming

**May 19–22** AAPG 2019 Annual Convention & Exhibition, San Antonio, TX, USA. Web page: [www.aapg.org/events/conferences/ace](http://www.aapg.org/events/conferences/ace)

**June 20–21** Mineralogical Society of America Centennial Symposium, Washington, DC, USA. Details forthcoming.

**July 8–12** 82nd Annual Meeting of the Meteoritical Society, Sapporo, Japan. Web page: [meteoriticalsociety.org/?page\\_id=18](http://meteoriticalsociety.org/?page_id=18)

**July 20–24** American Crystallographic Association Meeting, Covington, KY, USA. Web page: forthcoming

**July 22–26** Ninth International Conference on Mars, Pasadena, CA, USA. Web page: [www.hou.usra.edu/meetings/ninthmars2019/](http://www.hou.usra.edu/meetings/ninthmars2019/)

**August 4–8** Microscopy & Microanalysis 2019, Portland, OR, USA. Web page: [www.microscopy.org/events/future.cfm](http://www.microscopy.org/events/future.cfm)

**August 18–23** Goldschmidt 2019, Barcelona, Spain. Web page: [Goldschmidt.info/2019](http://Goldschmidt.info/2019)

**August 18–23** 32nd European Crystallography Meeting (ECM-32), Vienna, Austria. Web page: [ecm2019.org/home/](http://ecm2019.org/home/)

**August 25–29** 258th ACS National Meeting & Exposition, San Diego, CA, USA. Web page: [www.acs.org/](http://www.acs.org/)

**September 11–14** European Conference on Mineralogy and Spectroscopy 2019, Prague, Czech Republic. Web page: [ecms2019.eu/](http://ecms2019.eu/)

**September 22–25** Geological Society of America National Meeting, Phoenix, AZ, USA. Web page: [www.geosociety.org/GSA/Events/Annual\\_Meeting/GSA/Events/gsa2019.aspx](http://www.geosociety.org/GSA/Events/Annual_Meeting/GSA/Events/gsa2019.aspx)

**December 9–13** AGU Fall Meeting, San Francisco, CA, USA. Details forthcoming

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol (more meetings are listed on the calendar she maintains at <https://sites.google.com/a/udayton.edu/akoziol1/home/mineralogy-and-petrology-meetings/>). To get meeting information listed, please contact her at [akoziol1@udayton.edu](mailto:akoziol1@udayton.edu)

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## WHAT'S YOUR NEXT DREAM?

Gerhard Wörner<sup>1</sup>

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While working on extinct volcanoes in Germany, I always wanted to see Hawaii. This dream came true in 1984 when I was on my way to study volcanoes in Antarctica when we passed through Hawaii ... and I got the thrill of seeing Pu'u 'Ō'ō erupt. Later, over a beer, I was telling my friend, Russ Harmon, how my fieldwork adventures had fulfilled a long-held dream. "So, what's your next dream?", he asked. "I want to work on the volcanoes of the Atacama in South America", was my answer, not realizing that he and his colleagues were planning a field campaign to work on Parinacota Volcano in northern Chile the next year. I was invited to join.

This was 1986 and Chile's dictator, Augusto Pinochet, was still in power. The shaggy border town of Arica, our departing spot to the high Andes, had just one lonely place to hang out before departing to the field: Café 21 on calle 21. The café was the center of town, an uneasy place where students would protest and police would arrest them, and where dollar-dealers with big pockets would be the only ones to change your currency. In the early mornings, a snarling voice offered daily newspapers telling stories of terrorist attacks against the regime and questionable weapons finds in the desert. These stories gave Pinochet all the reason he needed to violently crack down on protesters.

Going into the field meant climbing a winding desert road that had the biggest potholes imaginable. We drove from sea level to 4,500 m in one day, into the winter of the Cordillera at  $-18\text{ }^{\circ}\text{C}$  at night. We had to pass four police stations on the way, and each time the police recorded the numbers of all our documents into thick books.

**Disputed Land**

Arica, and the Atacama, is a disputed border land. Land mines can be found at every road crossing between Chile, Peru, and Bolivia (Fig. 1). Chile took this territory during the "War of the Pacific" (1879–1884) in a sweeping advance to Lima (Peru). With the help of the British, Chile had fought and won this war, which was all about natural resources: nitrates, gold, copper, and other riches to fill the pockets of the wealthy and treasuries of the European empires. The Bolivians lost their access to the ocean, but they still threaten to take it back at any time. They even have a navy for that purpose, sailing on Lake Titicaca.



**FIGURE 1** Minefield alert at a small road near the Chilean town of Ollagüe, close to the border with Bolivia. PHOTO: G. WÖRNER.

The nitrates of the Atacama were a precious commodity, the source for the explosives that killed millions during World War I. Workers were lured into the desert mines with promises of paying off their debts, which only increased because workers had to pay for their shovels and other equipment in the company store. Regular punishments further increased worker debts. The mine company controlled the railway and even the money (Fig. 2). There was no escape from the treacherous conditions. Late in December 1907, ~18,000 mine workers, many with families, marched the >100 km from the mines in the desert to the coastal town of Iquique to protest against the difficult working conditions and low pay. Workers in the harbor, where the nitrate was shipped, joined them. The dispute ended in tragedy. Thousands were killed, and



**FIGURE 2** Two-peso coins 'minted' by the nitrate mine company, Compañía de Salitre de Antofagasta. These coins are made from bakelite (the first plastic made from synthetic components). These coins could only be spent in the company's store. PHOTO: G. WÖRNER.

the surviving workers were forced to return to the mines. The military colonel who was responsible for this massacre was even awarded for restoring order. Those mines became ghost towns after the synthetic fixation of nitrogen from air (the Haber–Bosch process) was invented. Later, Pinochet's torturers used the abandoned mines as prisons for those who opposed his regime.

This border region of the Atacama is today crossed by many trucks that deliver and export goods to and from Bolivia. Can you imagine old, unsafe trucks overloaded with timber from the Bolivian rainforest of the Amazon basin, crossing the Andes to make their way down this treacherous road to the Pacific harbor at Arica? In 1986, this road was Bolivia's only connection to the world's markets. And, unfortunately, drug dealers and smugglers abound.

**Unique Geology and Ecology**

But what magnificent volcanic geology! The road from Arica to the high Andes climbs along the flanks of deep canyons and arrives at vast plains covered with extensive ignimbrites. Tectonic forces have thrust the Cordillera up to 5,500 m. Incision by rivers, fed from glacial waters from peaks on the horizon, cut canyons almost 2,000 m deep. The combined tectonic and erosional processes have produced oversteepened slopes and frequent earthquakes have caused slope failures. Gigantic landslides have displaced rock sections that are more than 600 m thick up to 40 km downslope.

Arriving on the Altiplano, the views are breathtaking: volcanoes right and left, snow-capped glaciated peaks rising from the Altiplano to well above 6,000 m. Parinacota is the highest volcano in Lauca National Park (Fig. 3). The little streams from these glaciated volcanoes feed the "bofedales", wetlands in the desert, that are rich in green pasture for the alpacas and llamas that provide wool and meat to the Aymara Indians (Fig. 4). The elegant vicuñas and endemic (and monogamous) Andean geese live here. Coots build their nests in shallow lake waters, and giant condors circle overhead.

Little jumping rabbit-like animals, with a long tail, that nurse their babies in a belly pocket, are the viscachas, marsupials similar to chinchillas. Viscachas enjoy the andesitic block lavas that provide ideal hiding spaces for rest and breeding. Their nesting material and feces are an archive for pollen, which tell stories of past climates. Wetter climate conditions during past ice ages (and even deeper in geological time) have left their traces on this land. Lake sediments and shorelines are evidence of vast lakes and changing climates on the Altiplano. The extensive salt flats (salars) are their remnants. The salars and their saline pools are home to the several species of flamingos, some endemic, that breed here.

Lake Chungará, near the border of Bolivia, at 4,518 m, is the highest lake for its size (21 km<sup>2</sup>) on our planet. Lake Chungará developed after a small river was blocked by a flank collapse between growing Parinacota Volcano and Ajoya Volcano, its much older glaciated neighbor. This blockage severed the connection to the surrounding outflowing rivers

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**FIGURE 3** Parque Nacional de Lauca (Lauca National Park) in northernmost Chile with the twin volcanoes Parinacota (FRONT CENTER) and Pomerape (REAR). PHOTO: G. WÖRNER.



**FIGURE 4** Alpacas and llamas are the economic base of Aymara Indians on the Altiplano. The animals feed on the swampy grasslands known locally as “bofedales”, which themselves receive water from higher snow melt. PHOTO: G. WÖRNER.

Lake Chungará therefore still has its original livestock of small endemic killfish. Biologists once told me the story of these fish: the genetic code of the endemic fish indicates their origin in the salt waters of the Atlantic Ocean where their closest relatives now live. They adapted to the freshwater rivers that drained the Amazon and lived happily until tectonic forces changed and displaced the drainage systems. With the formation of the endorheic basin of the Altiplano at about 10 Ma, some rivers (and some fish, apparently) were caught up between the eastern and western cordilleras. Increasing aridity, due to blockage of rain from the west coast, created large salars that are fed by small freshwater rivers. The killfish had to adapt and retreat to the upper reaches of these rivers where they encountered fresh glacial meltwaters, such as the small river south of Parinacota Volcano. When Parinacota’s flank failed, these fish were isolated from the rest of their native waters on the Altiplano. Since then, their genetic code has deviated from populations beyond the lake. This is a striking example of geological and biological coevolution.

This place is full of wonders. The llareta (yareta) cushion plant, for example, can grow for hundreds of years at altitudes of between 4,400 m and 4,800 m, forming bulges more than a meter high (FIG. 5). The

indigenous Aymara Indians know their varied uses. Llareta extracts have antibacterial effects, its resin can be used as glue or as a fragrance, and the dried plant is the only fuel to be found at such elevations.

The Lauca National Park with the old town of Parinacota at its center, and the Vicuñas National Reserve have been set up to preserve the natural wonders of the region. Plans to lower the level of the lake to feed water to an electrical power plant were abandoned and mining activities have been restricted. Consequently, many animals thrive here. In contrast, across the border in Bolivia, the viscachas and vicuñas are hunted down and eaten.



**FIGURE 5** An example of the llareta (*Azorella compacta*) plant growing more than a meter thick. PHOTO: G. WÖRNER.

Global climate change and globalization have taken their toll. Glaciers have retreated dramatically over the past 27 years that I have conducted fieldwork in the region. The level of Lake Chungará has dropped, exposing tens of meters of muddy ground along its shallow shores (FIG. 6). Climate change combined with excessive borax mining in the National Reserve has lowered the water level of Salar de Surire and now threatens the endemic Andean flamingos. Road traffic has exploded with globalization. The new tarmac road from Arica to La Paz has litter everywhere, plastic bags and bottles being tossed out by truck drivers.



**FIGURE 6** The water levels of Lake Chungará (Chile) have dropped markedly over the past few decades. The formerly pristine lake shore is now littered with plastic, and the coots use the plastic bags to make their nests. PHOTO: G. WÖRNER.

This arid Atacama ecosystem has not had the same level of support and the attention as that of our planet’s rain forests or Antarctic jewels. But, it is just as precious, unique, and vulnerable. It should not need a geologist’s view and almost 30 years of observation to recognize the true value and beauty of these arid lands. Working there has become my life’s true dream and it is saddening to realize that such beauty will soon be gone.

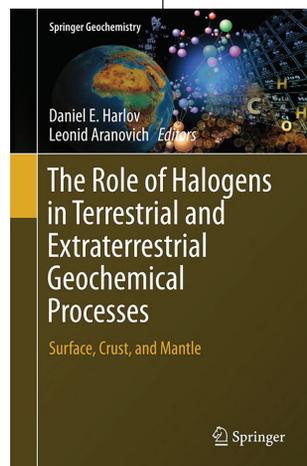
What’s your next dream?

## THE ROLE OF HALOGENS IN TERRESTRIAL AND EXTRATERRESTRIAL GEOCHEMICAL PROCESSES: SURFACE, CRUST, AND MANTLE<sup>1</sup>

The halogens—F, Cl, Br, I—are an incredibly reactive group of elements named for their ability to form a salt (*hal*) and to produce (*gen*) ionic compounds with metals (e.g. Na) by accepting outer-shell electrons from the metal to fill the outer shell of the halogen atom. Many of you may remember performing simple salt and water dissolution–evaporation–precipitation experiments, used to explore how the halogens bond with metal cations and how the resultant metal-chloride complexes are transported during geologic processes. Most readers here, I'm sure, have advanced far beyond a grade/primary-school understanding of ionic bonding. However, if your research program is as narrowly focused as mine, whereby I study the mobility of metals in aqueous fluids to understand the formation of mineral deposits, it is probably safe to assume that your breadth of knowledge regarding the importance of halogens during geologic processes is limited to your specific area of research.

To expand your knowledge base, I strongly recommend reading *The Role of Halogens in Terrestrial and Extraterrestrial Geochemical Processes* (Springer, 2018). This remarkably comprehensive compilation of papers

<sup>1</sup> Harlov DE, Aranovich L (eds) (2018) *The Role of Halogens in Terrestrial and Extraterrestrial Geochemical Processes: Surface, Crust, and Mantle*. Springer, 1,030 pp, ISBN 978-3-319-61665-0, doi: 10.1007/978-3-319-61667-4, ebook US\$ 339.00, hardcover US\$ 429.00



has been edited by Daniel E. Harlov (GFZ Potsdam, Germany) and Leonid Aranovich (IGEM RAS, Russia) and has opened my eyes to the many roles that halogens play in geochemical processes across a wide range of geologic environments. What makes this collection of papers unique is the diversity of subject matter, all focused on halogens, but with contributions from authors whose paths never likely cross at scientific meetings. I particularly enjoyed the chapter on terrestrial and cosmic geochemical systems, which concisely presents an overview of the distribution of halogens among Earth's terrestrial geologic reservoirs, as well as halogens on/within the Moon, Mars, and asteroid Vesta. The book also includes tables that compile seminal references for the wide variety of analytical techniques used to quantify halogen abundances. Several chapters focus on the behavior of the halogens in magmatic systems across the compositional spectrum, from

basalt to rhyolite, and two chapters connect magmatic processes to the formation of hydrothermal mineral deposits. The crystal chemistry of halogen-bearing minerals—including the common minerals apatite, amphiboles, and micas, as well as many of the nearly 700 minerals in which halogens are an essential structural constituent, including rare-earth fluorides, copper chlorides, mercury halides and halogenates—are comprehensively described in a chapter that includes a large number of eye-catching crystal structures in full color. Chapters on the behavior of the halogens in sedimentary systems, seawater and other marine systems, metamorphic systems, Earth's mantle, and extraterrestrial systems, including chondritic meteorites and oceans on the moons of Jupiter and Saturn, are wonderfully informative.

While each paper represents the state-of-the-art understanding of halogens in a particular environment, each provides an appropriate level of background that makes the material easily accessible for the nonexpert. The papers are incredibly rich in data, and the majority of the figures (many in color) are available online, which is great for teaching purposes. This volume would be a fantastic resource around which to scaffold an upper-level undergraduate or graduate seminar focused on the halogens. Importantly, in academia, where we often have minimum enrollment requirements for courses, such a course would be a wonderful way to draw students from multiple subdisciplines where the halogens can be used to build connections between seemingly disparate research programs. It is amazing how much one can learn from stepping outside the comfort zone of one's own research program to explore the magic that is happening in the research fields of our colleagues. This book does just that and is a must read for anyone interested in the halogens.

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