Elements
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Tourmaline

BARBARA L. DUTROW and DARRELL J. HENRY, Guest Editors

A Geologic DVD

From Atomic Arrangement to Viking Navigation

Tourmaline Isotopes: No Element Left Behind

Recorder of Ore-Forming Processes

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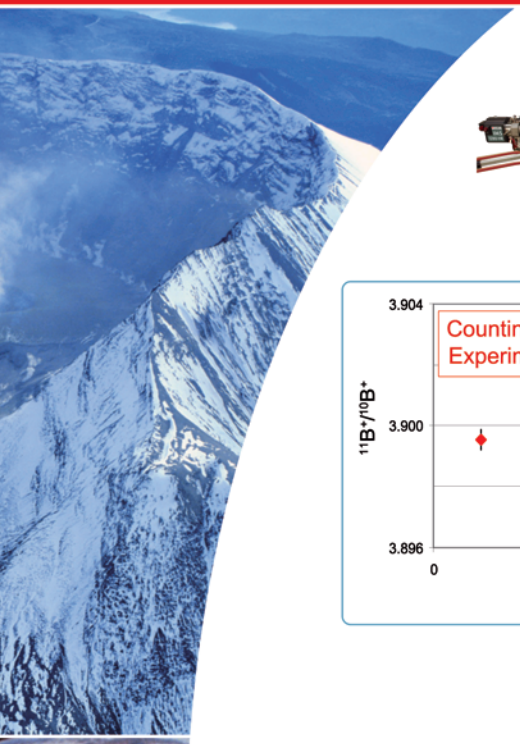

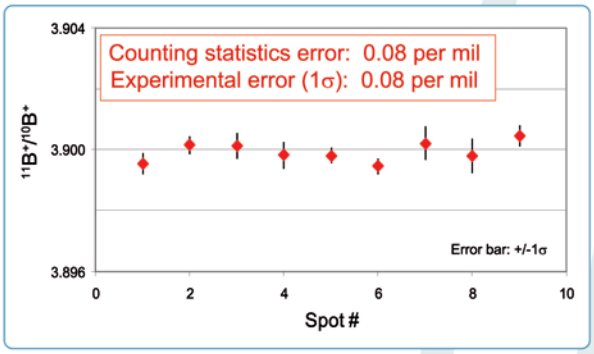

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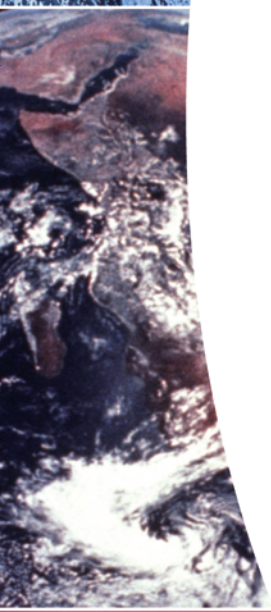

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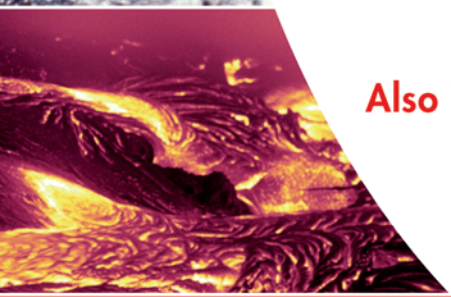

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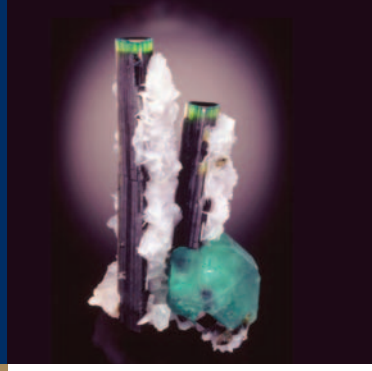
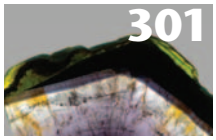


About the Cover:
These elongate tourmaline crystals, probably an elbaitic species, display a common color change toward the top of the crystal. Tourmaline is associated with plates of albite (white) and a crystal of fluorite (green). The specimen is from Stak Nala, Pakistan, and is 10.6 cm high. However, tourmaline is more than just another pretty mineral—it can be a single-mineral thermometer, a provenance indicator, and a recorder of *P–T–X* conditions.
Photo © courtesy of Jeffrey Scovil

Tourmaline

Guest Editors: **Barbara L. Dutrow and Darrell J. Henry**



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Barbara L. Dutrow and Darrell J. Henry

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Frank C. Hawthorne and Dona M. Dirlam

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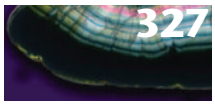
Tourmaline as a Recorder of Ore-Forming Processes
John F. Slack and Robert B. Trumbull



Tourmaline as a Petrologic Forensic Mineral: A Unique Recorder of Its Geologic Past
Vincent J. van Hinsberg, Darrell J. Henry, and Barbara L. Dutrow

Tourmaline: The Kaleidoscopic Gemstone
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The Mineralogical Association of Canada was incorporated in 1955 to promote and advance the knowledge of mineralogy and the related disciplines of crystallography, petrology, geochemistry, and economic geology. Any person engaged or interested in these fields may become a member of the Association. Membership benefits include a subscription to *Elements*, reduced cost for subscribing to *The Canadian Mineralogist*, a 20% discount on short course volumes and special publications, and a discount on the registration fee for annual meetings.

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The Clay Minerals Society (CMS) began as the Clay Minerals Committee of the US National Academy of Sciences – National Research Council in 1952. In 1962, the CMS was incorporated with the primary purpose of stimulating research and disseminating information relating to all aspects of clay science and technology. The CMS holds an annual meeting, workshop, and field trips, and publishes *Clays and Clay Minerals* and the CMS Workshop Lectures series. Membership benefits include reduced registration fees to the annual meeting, discounts on the CMS Workshop Lectures, and *Elements*.

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The Association of Applied Geochemists is an international organization founded in 1970 that specializes in the field of applied geochemistry. It aims to advance the science of geochemistry as it relates to exploration and the environment, further the common interests of exploration geochemists, facilitate the acquisition and distribution of scientific knowledge, promote the exchange of information, and encourage research and development. AAG membership includes the AAG journal, *Geochemistry: Exploration, Environment, Analysis*; the AAG newsletter, *EXPLORE*; and *Elements*.

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The Deutsche Mineralogische Gesellschaft (German Mineralogical Society) was founded in 1908 to "promote mineralogy and all its subdisciplines in teaching and research as well as the personal relationships among all members." Its great tradition is reflected in the list of honorary fellows, who include M. v. Laue, G. v. Tschermak, P. Eskola, C.W. Correns, P. Ramdohr, and H. Strunz. Today, the Society especially tries to support young researchers, e.g. to attend conferences and short courses. Membership benefits include the *European Journal of Mineralogy*, the DMG Forum, *GMit*, and *Elements*.

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The Società Italiana di Mineralogia e Petrologia (Italian Society of Mineralogy and Petrology), established in 1940, is the national body representing all researchers dealing with mineralogy, petrology, and related disciplines. Membership benefits include receiving the *European Journal of Mineralogy*, *Plinius*, and *Elements*, and a reduced registration fee for the annual meeting.

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The International Association of Geoanalysts is a worldwide organization supporting the professional interests of those involved in the analysis of geological and environmental materials. Activities include the management of proficiency testing programmes for bulk rock and micro-analytical methods, the production and certification of reference materials and the publication of the Association's journal, *Geostandards and Geoanalytical Research*.

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The Polskie Towarzystwo Mineralogiczne (Mineralogical Society of Poland), founded in 1969, draws together professionals and amateurs interested in mineralogy, crystallography, petrology, geochemistry, and economic geology. The Society promotes links between mineralogical science and education and technology through annual conferences, field trips, invited lectures, and publishing. Membership benefits include subscriptions to *Mineralogia* and *Elements*.

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The Sociedad Española de Mineralogía (Spanish Mineralogical Society) was founded in 1975 to promote research in mineralogy, petrology, and geochemistry. The Society organizes annual conferences and furthers the training of young researchers via seminars and special publications. The *SEM Bulletin* published scientific papers from 1978 to 2003, the year the Society joined the *European Journal of Mineralogy* and launched *Macla*, a new journal containing scientific news, abstracts, and reviews. Membership benefits include receiving the *European Journal of Mineralogy*, *Macla*, and *Elements*.

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The Swiss Society of Mineralogy and Petrology was founded in 1924 by professionals from academia and industry and by amateurs to promote knowledge in the fields of mineralogy, petrology and geochemistry and to disseminate it to the scientific and public communities. The Society coorganizes the annual Swiss Geoscience Meeting and publishes the *Swiss Journal of Geosciences* jointly with the national geological and paleontological societies.

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TOURMALINE RESEARCH: UNLOCKING ALI BABA'S CAVE

Georges Calas

Mineralogy is among the scientific fields most accessible to the general public. People dream about the beautiful crystals they see in museums, and they wonder about mineral diversity. Some become passionate about finding exceptional minerals, original colors, and crystal shapes. There is a broad range of mineral fans, from rockhounding teenagers who spend their weekends at old mines and former famous mineralogical sites, to the experienced—sometimes wealthy—collectors who often lead very different professional lives. All these amateurs are eager to share their passion and tell stories about their cherished samples, although their discretion about the place of origin of their specimens is legendary.

Researchers, too, may spend much time and energy in investigating a few single crystals, deciphering the information they bear like messages in a bottle. They now have access to small scales of observation, and they can investigate grains measuring a few micrometers or nanometers—they can even image minerals at the atomic scale. We now have a broad range of analytical equipment providing spatially resolved information, including electron microscopes, ion probes, synchrotron X-ray microprobes and microdiffractometers. Analytical information is also complemented by numerical modeling, constraining the structural and dynamical properties of minerals and their reactivity at mineral–fluid interfaces. All this information provides a continuum of knowledge on Earth materials by linking scientific fields that were once isolated, such as crystallography, crystal chemistry, experimental and field mineralogy and petrology, geochemistry (including isotope geochemistry), mineral physics, mineral deposit studies, etc. The list is long, and a distinction between mineralogy, petrology, and geochemistry is becoming less and less appropriate. Indeed, a forward–backward exchange approach progressively integrates all the information these fields provide, and the concept of disciplines is fading. A few years ago, an editorial by Ian Parsons in *Elements* (3: 3-4) recalled the importance of teaching "the whole wonderful world of imaging techniques that the 21st century provides," to make students understand the real nature of Earth materials. Spatially resolved methods are replacing former approaches that once considered minerals and rocks just as black boxes containing some pertinent parameters. Nowadays, the data obtained on the conditions of formation and evolution of minerals are interrelated, and novel information is arising from this cross-fertilization. And even if all quantitative scaling laws are not available for transferring information from the crystal scale to more global scales, minerals already provide major constraints on the physical and chemical evolution of the Earth.

This issue of *Elements* tells the story of the tourmaline supergroup. Previous issues of the magazine devoted to a single mineral were on diamond, gold, bentonite, and zircon. The first two are minerals well known to the public; but, in addition to their high monetary value, these minerals also contain much information of interest to "serious science." Zircon and bentonite are more complex. Bentonite, well known for its industrial and environmental uses, also provides information on low-temperature alteration processes. And zircon, a "tiny but timely" mineral, has been a major witness to the evolution of our planet since the first cooling events 4.4 billion years ago, and is a superb vector of geochemical information due to its exceptional resistance. These minerals tell us how investigations of key minerals can provide amazing insights into the history of rocks and the evolution of our planet. Tourmaline is well in line with that philosophy. In many respects, tourmaline is even more complex than zircon. Tracking tourmaline is not a common pursuit, notably in the mineral's nonclassic contexts, such as sedimentary and metamorphic environments, and we are probably far from completing our knowledge about this group and from using all the potential information it bears.

> …investigation of key minerals can provide amazing insights into the history of rocks and the evolution of our planet.

As shown in this issue, tourmaline deserves more attention. Lively research activity on this mineral is providing unique information on various aspects of our evolving planet, including crustal evolution, the genesis of ore deposits, and fluid–rock interactions over a broad range of *P*–*T*–*X* conditions. A tourmaline grain is like Ali Baba's cave: you can open it to retrieve its treasures, provided you have the magic formula. Tourmaline's scientific wealth comes from the variety of information it contains. Tourmaline retains information about the formation and evolution of its complex crystals, and it marries mineralogy and geochemistry perfectly. Tourmaline's ability to retain information over time leads to the apt description of this mineral as a "geologic DVD," as shown in the Introduction. We can unravel the conditions of tourmaline crystal growth or the crustal residence time of the isotopes of a broad variety of elements. And now that boron and lithium—important tourmaline components—are becoming strategic elements, there is a need for improving our knowledge on Li- and B-bearing minerals. Tourmaline may be considered uncommon, but most mineralogists are actually familiar with it, from the black schorl tourmaline sampled in a field trip to the incredible specimens displayed in mineral fairs and mineralogical websites. This mineral also recalls stories from our past history, such as the centuries-old presence of tourmaline in our cultural heritage and its historical importance in various technological developments, for example, the tourmaline tongs used by 19th century mineralogists. This issue of *Elements* will help us take this "semiprecious" mineral more seriously, at its true scientific value.

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THIS ISSUE

Tourmaline—a gemstone, a pretty mineral, but also a "garbage-can" mineral, a geothermometer, a provenance indicator, and more. The message is loud and clear: there is a lot more to tourmaline than meets the eye. The guest editors for this issue, Barb Dutrow and Darrell Henry, have studied tourmaline for much of their careers. Along with colleagues, many of whom are authors of articles in this issue or are referenced in the articles, they have been instrumental in moving this field forward. So enjoy!

GOLDSCHMIDT 2011

You can read a full report on the Goldschmidt 2011 Conference on pages 356–357. Prague was a wonderful venue. Participants convened daily at the Prague Conference Center, with its marvelous view of the city. *Elements* had a booth at Goldschmidt for the first time. Many thanks to all who found and stopped by our tucked-away location (a glitch!): your comments and suggestions were most appreciated. A highlight of the conference was the Fukushima special session, and an issue of *Elements* is in preparation for next year, with several speakers at that session as authors.

At our editorial meeting, we reviewed the highlights of the previous year. To us it is always remarkable that we manage to produce six issues a year more or less on time: we have no backup plan and, for each issue, we rely on guest editors and authors to come through with their articles in a timely manner. *Elements* finished 2010 with a net income of about $37,000, which will help reach our goal of having a financial reserve sufficient to cover the cost of producing three issues. A large part of our meeting was devoted to reviewing the theme proposals received and firming up the lineup for 2012, which we will publish in the next issue. One idea we discussed was the possibility of adding supplementary material online to make articles more relevant. More on that in a future issue.

Lunch in Prague for the editors. From left to right, Tim Drever, John Valley (incoming principal editor), Georges Calas, Pierrette Tremblay, and Hap McSween.
Photo by Barb Dutrow

SPIN-OFF

You know you are successful when you are imitated. *Elements* now has a "little brother" called *Animal Frontiers*. After hearing a talk about *Elements* given by the managing editor at the Council of Science Editors meeting in 2009, officers of the American Society of Animal Science set out to create a new magazine based on the concept of thematic issues. Along with two other societies, they launched their first issue in July. Its theme "Fork to Farm: The Carbon Footprint," is particularly relevant, and the articles (PDFs available at www.animalfrontiers.com) are pitched at a good level. For example, it was interesting to read that shipping lamb from New Zealand to the United Kingdom and other countries contributes only 5% of the total carbon footprint of lamb farming.

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WHEN ACCESSORIES ARE ESSENTIALS

Bruce Yardley

In the early days of its development, the petrological microscope's value was far from universally accepted. Pioneers like H. C. Sorby were ridiculed by those who believed that it was impossible to learn anything about mountains by looking down a microscope. Changing scale in this way comes naturally to most Earth scientists today; we have learnt to value the subtle as well as the big and obvious. This *Elements* issue is dedicated to just one mineral, tourmaline, which is almost never in the vanguard of rock-forming minerals but is remarkably common in the background as an accessory phase. One of the most endearing and useful features of tourmaline to me is that it is usually very easy to recognise in hand specimen and under the microscope. This matters because showing tourmaline to a student in a rock or a thin section provides both a boost to their confidence – it is a relatively unusual mineral that should be easy to recognise again – and an opportunity to show that a fascinating range of aspects of geology can be explored just because tourmaline is there. Students often see the major divisions of the Earth sciences as entirely separate topics, delivered by different professors, carried around in different parts of the brain and brought up in different exams. A discussion about how tourmaline in a schist might mean that the parent sediment was marine or how the triangular coordination of boron may be reflected in the mineral's morphology may prod them towards that visionary moment when they suddenly realise that all sorts of different stuff actually fit together. Set against that of course is the painful memory of those intransigent black residues at the bottom of the crucibles when I tried to do wet chemical analyses of tourmaline-bearing rocks!

Like many other accessory minerals, tourmaline is generally left out of consideration when we investigate how the rocks that host it have formed. Our understanding of granites and granitic melts is based mainly on experimental investigations of combinations of quartz, feldspars and perhaps micas, but only pegmatite enthusiasts have considered the effects of the components present in accessory minerals. That was a reasonable starting point when we had no idea about the actual melting points of magmas, but of course where tourmaline is present, there must be boron, and boron is an effective flux.

When rigorous and quantitative experimental petrology blossomed half a century ago, it was obviously more useful to study simple end-member systems from which thermodynamic data could be extracted and applied to a range of natural systems, than to investigate the infinite range of natural systems. The drawback is that minor components which may have an important influence, whether on melting temperatures, solubilities or even conditions of equilibrium between phases, get left out. Fortunately, these are often components, like B, which do not vary randomly in nature but are buffered by the presence of the accessory minerals in which they predominantly reside. Accessory minerals allow us to investigate more complex, and hence more natural, systems in a very measured and controlled way – the number of components increases, but the degrees of freedom do not.

The effects of additional components are particularly marked when it comes to mineral (or rather, rock) solubility. Based on the low solubility of corundum in water, we thought for many years that Al is an element with extremely low solubility in the crust. There is not a geochemical modelling code in existence that will not tell you the same thing. Only very recently have the innovative experiments of Craig Manning and Bob Newton established that although corundum is very insoluble on its own, if you put an Al-silicate with other minerals, Al will form complexes with Si and Na in solution so that its solubility goes up significantly. Thank goodness for that, because how else could those beautiful Al-bearing minerals be forming in hydrothermal veins? And of course, one of the most widespread Al-rich vein minerals is tourmaline, so is it just possible that B also plays a role in enhancing Al solubility?

It is not my place to pre-empt the editors and authors of this issue in extolling the virtues of tourmaline, but it really is a very valuable marker for understanding the environment in which it grew, even if all the possible constraints have not yet been calibrated. Not only is it stable over a wide range of pH and redox conditions, but there are lattice substitutions that will reflect these variables. That is quite a combination – for example, for understanding late-magmatic volatiles – and it has the potential to address issues which would otherwise be completely intractable.

Of course tourmaline is just the latest of a number of accessory minerals to have come in from the cold and be recognised for their contributions to the larger science. The arrival of the microprobe meant that petrologists began to take opaque minerals seriously, instead of referring to them as "ores" (thereby displaying as little knowledge of economics as of reflected-light microscopy). The minerals that can be dated were next to reach prominence. If we understand where they form in the petrogenetic history and can obtain an age for them, minerals such as zircon and monazite take on a front-line role in unravelling the history of metamorphic belts. Apatite also is proving to be another valuable monitor of the behaviour of some of those minor components that are so hard to nail down but can have a profound influence on how a geochemical system behaves.

The Earth sciences, probably more than any others, have advanced by guesswork. Not just any guesswork, but good guesswork founded on observation and an understanding of underlying scientific principles. It made sense to start investigating how rocks form in the deep Earth by looking at simple systems of wide applicability, but having done that, it was inevitable that we would start speculating about all sorts of details of deep-Earth processes. Studies of accessory minerals provide new constraints and tests for those speculations, and we can now move on to a higher level of guessing.

Most of the time, the things that we learn from accessory minerals and the other minutiae beloved of the careful petrographer provide a refinement of our ideas but don't completely overturn them. Just occasionally, however, the minutiae turn out to profoundly change our understanding. The recognition of coesite and diamonds in eclogites has transformed high-pressure petrology and has led to completely new models for the tectonic settings from which eclogites may be derived and the means by which they return to the surface. At an even smaller scale, halite daughter crystals in fluid inclusions have revealed that chloride salts play a fundamental role in fluids from the mantle to the surface, transforming ideas about metal solubility and transport and requiring the development of two-phase flow models to properly address deep fluid flow. Not bad for a mineral that rarely exceeds a few micrometres across in high-*T* rocks, and a great vindication of the faith of H. C. Sorby in the value of thin sections; it was he who first noticed halite in fluid inclusions, in a granite from Aberdeenshire.

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University of Leeds

ROD EWING ON NUCLEAR WASTE TECHNICAL REVIEW BOARD

Rod Ewing has been appointed to the Nuclear Waste Technical Review Board (NWTRB) by President Obama. Rod is the Edward H. Kraus Distinguished University Professor in the Department of Geological Sciences at the University of Michigan, with faculty appointments in the Departments of Nuclear Engineering & Radiological Sciences and Materials Science & Engineering. He was also a visiting professor at the Center for International Security and Cooperation at Stanford University for the 2010–2011 academic year.

The NWTRB (www.nwtrb.gov**)** is an independent agency of the U.S. federal government that provides independent scientific and technical oversight of the Department of Energy's program for managing and disposing of high-level radioactive waste and spent nuclear fuel. The Board evaluates the technical validity of U.S. Department of Energy (DOE) activities and provides objective expert advice on nuclear waste management to Congress and the Secretary of Energy. The Board is made up of 11 members, including two other geoscientists: George M. Hornberger, appointed in 2004, is a Distinguished University Professor at Vanderbilt University, where he is the director of the Vanderbilt Institute for Energy and the Environment. William M. Murphy is a professor in the Department of Geological and Environmental Sciences at California State University, Chico, and was appointed in 2006. His research focuses on geochemistry, including the interactions of nuclear wastes and geologic media.

GEOLOGICAL SOCIETY OF AMERICA AWARDS

Several awards were presented at the Geological Society of America annual meeting, including the following two to members of our community.

Susan L. Brantley, professor of geosciences, Pennsylvania State University, received the Arthur L. Day Medal for her work in the successful application of chemical kinetics to the interpretation and synthesis of observations of geochemical processes in natural systems. She has led efforts to understand why rates of geochemical reactions differ between field and laboratory settings, and she does research to understand biological control on rates of geochemical processes. Brantley's Gold Medal lecture was titled "Back to the future as a geochemist."

The Subaru Outstanding Woman in Science Award was presented to **Naomi E. Levin**, assistant professor, Johns Hopkins University, for her 2008 PhD research, which has had a major impact in the fields of paleoclimate, paleoecology, and human origins. Levin's dissertation, titled "Isotopic Records of Plio-Pleistocene Climate and Environments in Eastern Africa," looks at how landscapes and terrestrial organisms responded to past climate change and provides perspective on the effects of future climate perturbations.

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ANTARCTICA: THE BEST PLACE ON EARTH TO COLLECT METEORITES

Figure 1 Members of the ANSMET team collect a meteorite. Photo credit: Nancy Chabot

One of the questions most commonly asked of a meteoriticist is where the best places are to hunt for meteorites. The answer? The arid deserts of the planet. Unfortunately for the average meteorite enthusiast, many of these deserts are not easily accessible and do not boast overly comfortable weather conditions. They are either extremely hot or, in the case of Antarctica, extremely cold. It turns out, however, that of all the places on the surface of this wet and warm planet, the Antarctic has the best environment for preserving meteorites for as long as it takes to find them—usually many thousands of years. Climate, topography, and glacial processes create an Antarctic meteorite "conveyor belt" that protects meteorites from becoming aqueously weathered and concentrates them in places where they can be collected. Soon after landing, most meteorites get buried by snow and ice and slowly move with the Antarctic ice sheet as it travels downslope toward the Southern Ocean. Luckily for cosmochemists, the Transantarctic Mountains act as a barrier to this gravitational flow, stranding pockets of ice. Dry katabatic winds rush down from the pole and speed the loss of ice through both sublimation and abrasion, leaving regions of compressed, blue ice with its cosmic cargo sitting on the surface, ripe for collection (Fig. 1).

The systematic recovery of meteorites from Antarctica began in 1969 when a Japanese expedition found the first concentration site (the extraordinary Yamato ice field). For 33 of the last 34 years, the United States has sent a team to the Antarctic ice to collect meteorites. As of the latest season (2010–2011), almost 20,000 meteorite specimens have been recovered by the US's Antarctic Search for Meteorites (ANSMET) program. Japanese, German, Italian, Chinese, and, most recently, South Korean meteorite-hunting teams have brought back another 30,000 or so pieces of Solar System material (China, 10,000; Japan, 20,000; Italy, 1200). While the deserts of the southwestern United States, Australia, Chile, and particularly northern Africa have yielded many meteorites, Antarctica remains the best place to find large numbers of fresh meteoritic samples. These teams have found more extraterrestrial material in 30 years than has been collected over recorded time.

Figure 2 Members of the ANSMET team search a blue ice field by snowmobile at the Meteorite Hills. Photo credit: Cari Corrigan

Figure 3 A member of the ANSMET team conducts a search on foot in a glacial moraine in the MacAlpine Hills. Photo credit: Yulia Goreva

As the author knows firsthand, the US-led ANSMET team generally takes between 6 and 12 people per year as volunteers to spend 6 to 7 weeks camping in nine-foot-square Scott tents on the slopes of the Transantarctic Mountains. Teams generally bring back anywhere from 200 to 1400 meteorites per season, depending on the number of team members, the locations searched, prior experience at the site, and, of course, the weather. Weather plays a huge part in determining how many of the 45 or so days are spent in tents, hunkered down playing cribbage, and how many are spent searching blue ice fields (Fig. 2) and glacial moraines (Fig. 3) for the telltale signs of a meteorite. The best visual marker is fusion crust, the melted layer of material that forms on the outside of a rock as it passes through the Earth's atmosphere. For example, the fusion crust on lunar meteorites (Fig. 4) can have an unusual green tint (the color of moldy cheese). Meteorites sometimes reveal features not seen in terrestrial rocks: chondrules or native iron–nickel metal. The study of meteorites recovered from Antarctica has yielded major discoveries in cosmochemistry. Included in this treasure trove are new types of chondritic meteorites from the earliest moments of the Solar System, samples that record the onset of melting of asteroids, and meteorites from the Moon and Mars, including the first meteorite recognized as having come from the Moon.

A photo of a basaltic lunar meteorite as it appeared when collected in the La Paz ice field in Antarctica. Photo credit: ANSMET

For the specialist, Antarctic meteorites offer the chance to study rare and primitive rocks containing, in one case, materials altered by extraterrestrial water and, in another, interstellar grains forged in extrasolar furnaces before our Solar System was born. The coldest continent is home to a dazzling variety of extraterrestrial rocks and has given us a rich harvest. Remarkably, these meteorites are available freely to any qualified scientist, anywhere, who wants to study them. Requests are taken on a rolling basis, although the Meteorite Working Group meets biannually (March and September) to review requests, approximately one month after each new Antarctic Meteorite Newsletter is published. Request forms and newsletters can be found at http://curator.jsc.nasa.gov/antmet/index.cfm. More information on the US's Antarctic Search for Meteorites program can be found at http://geology.case.edu/~ansmet.

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Meet the Authors

Dona M. Dirlam is the director of the Richard T. Liddicoat Gemological Library and Information Center at the Gemological Institute of America (GIA) in Carlsbad, California. She holds a BS in Earth sciences from the University of Minnesota and an MS in geology and geophysics from the University of Wisconsin. She is a GIA Graduate Gemologist (GG) and a Fellow of the Gemmological Association of Great Britain (FGA). She has received GIA's highest honor, the Richard T. Liddicoat Award for Distinguished Achievement.

Barbara L. Dutrow is the Adolphe Gueymard Professor at Louisiana State University. Her studies in fluid–mineral interactions in hydrothermal systems combine field, analytical, and theoretical approaches. After conducting high *P*–*T* experiments as a von Humboldt Fellow at Ruhr Universität, her recent work, as an affiliate of Los Alamos National Laboratory, has focused on computational studies and scientific visualization of heat and mass transfer to understand their impact on mineral nucleation, growth, and chemistry in geothermal to metamorphic systems. She is also a past president of MSA.

Frank C. Hawthorne holds a Canada Research Chair in Crystallography and Mineralogy and is a Distinguished Professor in the Department of Geological Sciences at the University of Manitoba, Winnipeg, Canada. He received an ARSM and a BSc in geology from the Royal School of Mines, Imperial College, London, and a PhD in geology from McMaster University, Hamilton, Canada. He is a Fellow of the Royal Society of Canada and a Foreign Member of the Russian Academy of Sciences. He is interested in the factors affecting the atomic arrangement of atoms in solids and liquids, particularly those of geological and environmental interest.

Darrell J. Henry is a petrologist with interests in the crystal chemistry and petrologic applications of minerals (particularly tourmaline) in metamorphic and sedimentary environments, in the tectonometamorphism of Paleozoic to Archean metamorphic terranes, and in geoscience education. He received his BS (1973), MS (1976), and PhD (1981) from the University of Wisconsin–Madison. He was a postdoctoral fellow at Arizona State University and NASA's Johnson Space Center and a consultant to ARCO Oil and Gas Co. In 1985 he moved to Louisiana State University where he is the Campanile Charities Professor of Geology.

Shao-Yong Jiang is a professor in the Department of Earth Sciences, Nanjing University, China. He is also the director of the State Key Laboratory for Mineral Deposits Research (Nanjing University). He received his BSc from Peking University (China) and his PhD from Bristol University (UK). His areas of interest include the study of mineral deposits, isotope geochemistry and geochronology, and marine geochemistry. He has published more than 120 scientific journal articles. He is on the editorial boards of *Chemical Geology*, the *Journal of Geochemical Exploration*, and the *Chinese Science Bulletin*.

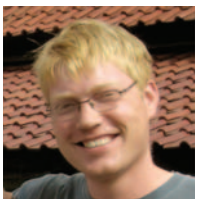
Brendan M. Laurs is an editor and technical specialist for *Gems & Gemology* at the Gemological Institute of America (GIA). He is a gemologist and geologist specializing in the formation of colored-gemstone deposits. Brendan developed an early interest in geology while exploring the gem-bearing pegmatites of San Diego County. He obtained a BS degree in geology from the University of California, Santa Barbara, and an MS degree in geology from Oregon State University. He was an exploration geologist for colored gemstones with Kennecott Exploration Co. before joining GIA in 1997.

Horst R. Marschall was appointed an assistant scientist at Woods Hole Oceanographic Institution in February 2011. His research is focused on the petrology and geochemistry of (ultra)high-pressure metamorphic rocks as probes into physicochemical processes operating at convergent plate margins. Of great importance for these studies are the minerals of the tourmaline supergroup as geochemical and isotopic recorders. He received both his diplom and doctoral degrees from Heidelberg University (Germany) and held a five-year postdoctoral appointment at the University of Bristol (UK).

Federico Pezzotta is the curator of mineralogy at the Natural History Museum of Milan, Italy. He received a PhD in geochemistry and petrology from the University of Milan and the CNR of Pisa in 1994, and in 2003 he was honored with the IMA-approved new mineral (and new gemstone) pezzottaite. He has more than 15 years of experience in gemstone prospecting and mining in Madagascar. His research interests are in the petrology and mineralogy of gemstone-bearing pegmatites and the petrogenesis of gemstone deposits.

John F. Slack is a research geologist at the U.S. Geological Survey in Reston, Virginia. His studies have dealt with the mineralogy and geochemistry of stratabound sulfide deposits, chiefly in the United States, Canada, and Norway. Topics of recent interest include the redox states of Precambrian oceans, the origins of iron formations and phosphorites, and the sources of metals in metalliferous black shales. He earned a PhD from Stanford University in 1976 and has served on the editorial boards of *Geology*, *Economic Geology*, and *The Canadian Mineralogist*. He is a fellow of the Geological Society of America and the Society of Economic Geologists.

Robert B. Trumbull is a senior research scientist at the GFZ German Research Centre for Geosciences in Potsdam. His PhD study of tin-bearing pegmatites in Swaziland was his first exposure to the study of tourmaline and African geology, and these have remained on his active list to this day. In Potsdam since 1994, his research includes a happy mix of field work and laboratory studies, the latter including the microanalysis of trace elements and the measurement of isotope ratios in minerals and glassy inclusions using SIMS. A growing interest is the study of boron isotope systematics in tourmaline, particularly from hydrothermal ore deposits.



Vincent J. van Hinsberg is a Marie Curie Postdoctoral Fellow at the University of Oxford. His main topic of research is the use of minerals to reconstruct physical and chemical conditions within the Earth and on its surface, both at the present and back to the Archean. He worked on tourmaline as an indicator of pressure and temperature in his PhD at the University of Bristol and as an indicator of fluid composition while a Tomlinson Postdoctoral Scholar at McGill University. His present research combines experiments and natural samples with atomistic simulations to understand the partitioning of elements among minerals and fluids.

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Featured images are tourmalinized granite from Roche Rock, near St Austell, Cornwall, UK. The tourmaline exhibits complex oscillatory compositional zoning from schorl varieties (black, red and blue) through to dravite (orange), and is intergrown with quartz (pink) and mica (green).

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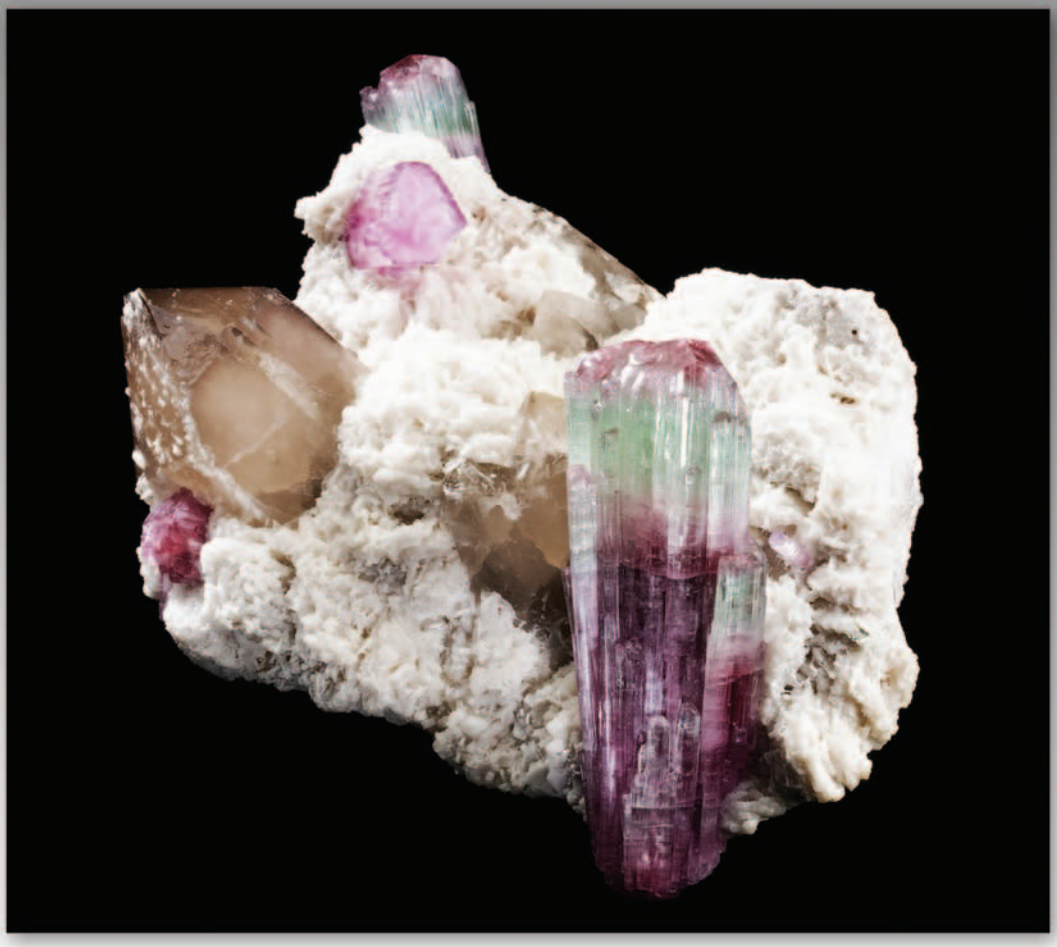

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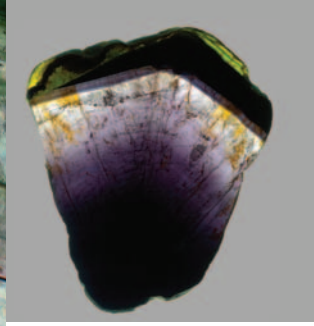
Tourmaline: A Geologic DVD



Optical scans of polished slabs of tourmaline from Madagascar

Barbara L. Dutrow[1] and Darrell J. Henry[1]

1811-5209/11/0007-0301$2.50 DOI: 10.2113/gselements.7.5.301

Tourmaline is an eye-catching mineral, but even more importantly, it has played a significant role in the evolution of scientific thought and, more recently, has been recognized as a medium for recording geologic information, not unlike a DVD. With its plethora of chemical constituents, its wide range of stability from conditions near the Earth's surface to the pressures and temperatures of the upper mantle, and its extremely low rates of volume diffusion, tourmaline can acquire a chemical signature from the rock in which it develops and can retain that signature through geologic time. As a source as well as a sink for boron, tourmaline is nature's boron recorder. Tourmaline can be used as a geothermometer, provenance indicator, fluid-composition recorder, and geochronometer. Although long prized as a gemstone, tourmaline is clearly more than meets the eye.

KEYWORDS: tourmaline, boron, history of science, pressure–temperature stability, crystal chemistry, pyroelectricity

INTRODUCTION

Tourmaline was once considered to be no more than a collectable mineral, a semiprecious gemstone, or a curious accessory mineral in select rock types. But recent advances in the understanding of tourmaline's chemical and crystallographic complexities and isotope systematics have led to new applications of tourmaline in deciphering and interpreting geologic processes. In this issue of *Elements*, advances in knowledge of tourmaline crystal chemistry and structure are reviewed as a necessary background to understanding its geologic importance (Hawthorne and Dirlam 2011 this issue). As a sensitive indicator of fluid composition, tourmaline and its isotopic composition are used to better understand the chemistry of ore-forming fluids (Slack and Trumbull 2011 this issue) and subduction zone processes (Marschall and Jiang 2011 this issue). Its complex and variable chemistry, coupled with low diffusivities, makes it an ideal indicator of its host environment—from salt domes to pegmatites to ultrahigh-pressure (>2.5 GPa) metamorphic rocks (van Hinsberg et al. 2011a this issue). The complete "life cycle" of a tourmaline may be encapsulated in a single grain, which can preserve information on temperatures, pressures, and fluid compositions during the entire history of the rock in which it develops, and, in some cases, the absolute age of the events it undergoes. Although gemmy tourmaline crystals continue to be prized by mineral collectors and gemologists (FIG. 1; Pezzotta and Laurs 2011 this issue), they have had other interesting practical uses. For example, the piezoelectric properties of tourmaline have been used to detect sudden large changes in hydrostatic pressures related to phenomena such as nuclear explosions (Dietrich 1985). In a different and perhaps less-known way, tourmaline has long played a role in science, prompting advances in scientific thinking.

TOURMALINE AND THE HISTORY OF SCIENCE

The term *tourmaline* is thought to have been derived from the Sinhalese word *turmali* (or *thuramali*, *thoramalli*, or *toramalli*), which was used to refer to mixed-colored stones of unknown type by gem dealers in Serendib (later Ceylon and now Sri Lanka). The first known written reference to tourmaline is in *De lapidibus* ("On Stones") by Theophrastus (371–285 BC). Here, a gemstone called *lyngurium* is described that has the color of electrum (shades of yellow; FIG. 2) and attracts straw and ash when heated (Walton 2001). In ancient times, *lyngurium* was thought to be fossilized lynx urine. The variation in color was associated with the sex of the lynx such that "the female is the more transparent and ... paler" (presumably due to a lower content of divalent manganese).

Tourmaline became well known in Europe in the early 18th century as traders started to import varieties of precious stones from the Far East (Pezzotta and Laurs 2011). At the same time, its importance as a gemstone was virtually overshadowed by the discovery of its pyroelectric properties, a phenomenon that caught the attention of the early scientific community. Tourmaline was found to possess the ability to attract (or repel) fine-grained materials. Lang (2004) reports the following 1707 account of this effect by Johann Georg Schmidt:

> "The ingenious Dr. Daumius, chief physician to the Polish and Saxon troops on the Rhine, told me, that, in the year 1703, the Dutch first brought from Ceylon in the East Indies a precious stone called tourmaline, turmale, or trip, which had the property of not only attracting the ashes from the warm or burning coals, as the magnet does iron, but also repelling them again..."

In 1747, Carl von Linné (Linnaeus) provided the first scientific description of the pyroelectric properties of tourmaline, referring to the mineral as *lapis electricus*. Ten years later (in 1756), Franz Aepinus performed the first systematic scientific studies of the electrical properties of tourmaline,

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FIGURE 1 Elbaite tourmaline crystal set in a matrix of muscovite, with an accompanying cut stone. The crystal is 5.2 cm high and came from the Jonas Mine, Minas Gerais, Brazil. The cushion-cut pink tourmaline is from Conselheiro Pena, Governador Valadares, Minas Gerais, Brazil. IMAGE COURTESY © GEMOLOGICAL INSTITUTE OF AMERICA, REPRINTED WITH PERMISSION; PHOTOGRAPHER: ROBERT WELDON

demonstrating that it became "electrified" by being warmed and that the crystals acquired opposite charges at opposite poles (see also Hawthorne and Dirlam 2011). This latter observation was used to support Benjamin Franklin's theory of positive and negative electricity. Other experiments by 18th-century scientists also attempted to link tourmaline's properties to magnetism. In fact, in 1766 Johann Wilcke used the properties of tourmaline to link heat, electricity, and magnetism in an early version of a "grand unification theory" of physics (Dietrich 1985). Later, notable physicists such as Lord Kelvin (in 1878) and Pierre Curie (from 1880 to 1908) published papers concerned with tourmaline's electrical properties (Lang 2004). Since these early days of scientific inquiry, tourmaline has been influential in scientific discourse and has played an important role in the history of scientific reasoning and early scientific advances.

THE CHEMICAL AND STRUCTURAL PALETTE OF TOURMALINE

Tourmaline has long been known for its complex chemistry. John Ruskin, in his 1894 book entitled *The Ethics of the Dust: Ten Lectures to Little Housewives on the Elements of Crystallization,* somewhat derisively states that the composition of tourmaline "is more like a mediaeval doctor's prescription than the making of a respectable mineral." (See box). In fact, tourmaline can incorporate a significant number of the elements in the periodic table in major, minor, or trace amounts (Dietrich 1985; Marschall and Jiang 2011). This may have amused Dr. Ruskin, yet it is this feature that gives tourmaline much of its potential for recording chemical information that can be related to the host environment in which it develops (Henry and Dutrow 1996).

> After a brief discussion on the meaning of "Tourmaline", the 'student' Mary asks "And what is it made of?"
>
> The lecturer replies: "A little of everything; there's always flint, and clay, and magnesia in it; and the black is iron, according to its fancy; and there's boracic acid, … and there's potash, and soda; and, on the whole, the chemistry of it is more like a mediaeval doctor's prescription than the making of a respectable mineral."
>
> —From "Crystal Sorrows" in *The Ethics of the Dust,* Ruskin (1894)

Tourmaline, with a general formula of $XY_3Z_6T_6O_{18}(BO_3)_3V_3W$, is not a single mineral, but a supergroup currently consisting of 18 species approved by the International Mineralogical Association's Commission on New Minerals, Nomenclature and Classification (Henry et al. 2011; see Hawthorne and Dirlam 2011 for details). The best-known species are dravite $[NaMg_3Al_6Si_6O_{18}(BO_3)_3(OH)_3(OH)]$, schorl $[NaFe_3Al_6Si_6O_{18}(BO_3)_3(OH)_3(OH)]$, and elbaite $[Na(Li_{1.5}Al_{1.5})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3(OH)]$. Tourmaline incorporates a wide variety of elements as mono-, di-, tri-, and tetravalent cations as well as mono- and divalent anions. These characteristics led W. L. Bragg (of X-ray crystallography fame) to refer to the chemical diversity of tourmaline as a "garbage-can mineral" (Bragg 1937). The structural building blocks of tourmaline include six TO_4 tetrahedra, which share corners to form a ring structure (cyclosilicate) such that all tetrahedra point in the same direction, with the *T* site occupied primarily by Si with some Al and B (Hawthorne and Dirlam 2011). Boron is an essential constituent of tourmaline, and it completely occupies the triangularly coordinated site. These structural components are linked by two types of 6-fold sites, *Y* and *Z* octahedra that can contain a great diversity of multivalent cations. The [9]-coordinated *X* site is located just out of the plane of the tetrahedral ring, and it typically contains Na and Ca but is commonly partially vacant. There are two types of anion sites, which can contain not only O, but also OH and F (*W* site only). These structural components of tourmaline are linked in such a way that the mineral typically attains the trigonal symmetry that is distinctive of its crystal morphology (Hawthorne and Dirlam 2011).

THE STABILITY RANGE OF TOURMALINE

Tourmaline has an extensive temperature and pressure (*T*–*P*) stability range that covers most of the conditions found in the Earth's crust (FIG. 3), and it can be in equilibrium with a wide range of geologic fluids. This stability is due, in part, to the flexibility of the structure to adjust in composition in response to changing chemical environments and *T*–*P* conditions. Because of its stability and extremely low rates of volume diffusion for major and trace elements in its structure, tourmaline can retain chemical and textural information even at relatively high temperatures (van Hinsberg et al. 2011b).

Tourmaline is not known to form at the Earth's surface conditions (25 °C, 0.0001 GPa), but it can develop during diagenesis and in relatively low-*T*–*P* hydrothermal environ-

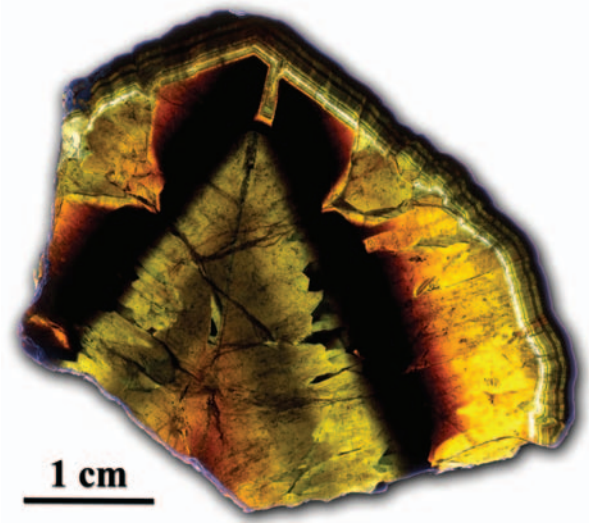

FIGURE 2 Polished slab of Malagasy tourmaline displaying various shades of "yellow"

ments. Under diagenetic conditions, tourmaline typically forms as fine-grained prismatic to equant grains, as overgrowths on detrital tourmaline grains, or, less commonly, as separate delicate crystals (Henry and Dutrow 1996). Authigenic tourmaline has been found in the caprock of salt domes, in diagenetically altered layered evaporite deposits, and in near-surface hydrothermal deposits (Henry et al. 1999, 2008; Moore et al. 2004). It is likely that tourmaline can form below 150°C and 0.06 GPa, although its development would depend on the kinetics of nucleation and growth.

The upper thermal stability of tourmaline has been constrained by experiments and observations of natural occurrences in high-temperature rocks. Experiments show that tourmaline undergoes melting between 725 and at least 950°C, depending on pressure and composition (van Hinsberg et al. 2011b and references therein). Dravite stability, established in experiments, extends to temperatures of at least 950°C (Werding and Schreyer 1996). These experiments are consistent with the location of a "tourmaline-out" isograd at ~725°C and 0.45 GPa, as observed in progressively metamorphosed pelites in the Ryoke metamorphic belt in southwestern Japan (Kawakami 2001). In addition, the presence of abundant tourmaline in granulite facies peraluminous gneisses from locations such as south-central Massachusetts that reached ~775°C at 0.6–0.7 GPa (Thomson 2006) or the Proterozoic Broken Hill complex where maximum metamorphic conditions were 750–850°C and 0.5–0.55 GPa with *P* locally up to 0.8–0.9 GPa (Slack et al. 1993; Slack, personal communication) provides further evidence for the persistence of tourmaline to high temperatures.

Based on experimental and petrologic investigations, tourmaline is stable at ultrahigh-pressure (UHP) conditions (FIG. 4). Dravite breaks down to produce different Al–Mg phases at pressures as high as 6–8 GPa according to experiments by Krosse (1995). In the presence of coesite, experiments show that natural tourmaline is stable to pressures exceeding 4.0 GPa in the temperature range of 800–850°C and at 4.5–5.0 GPa at temperatures of about 700°C (Ota et al. 2008). Tourmaline continues to be stable during subduction of the crust into UHP conditions. Evidence for UHP tourmaline comes from inclusions of coesite from the Erzgebirge in Germany and Lago di Cignano and the Dora Maira massif in the Alps (e.g. Marschall et al. 2009).

The composition of the fluid phase can significantly influence the stability of tourmaline, even within its overall *T*–*P* stability range. In aqueous fluids tourmaline is stable

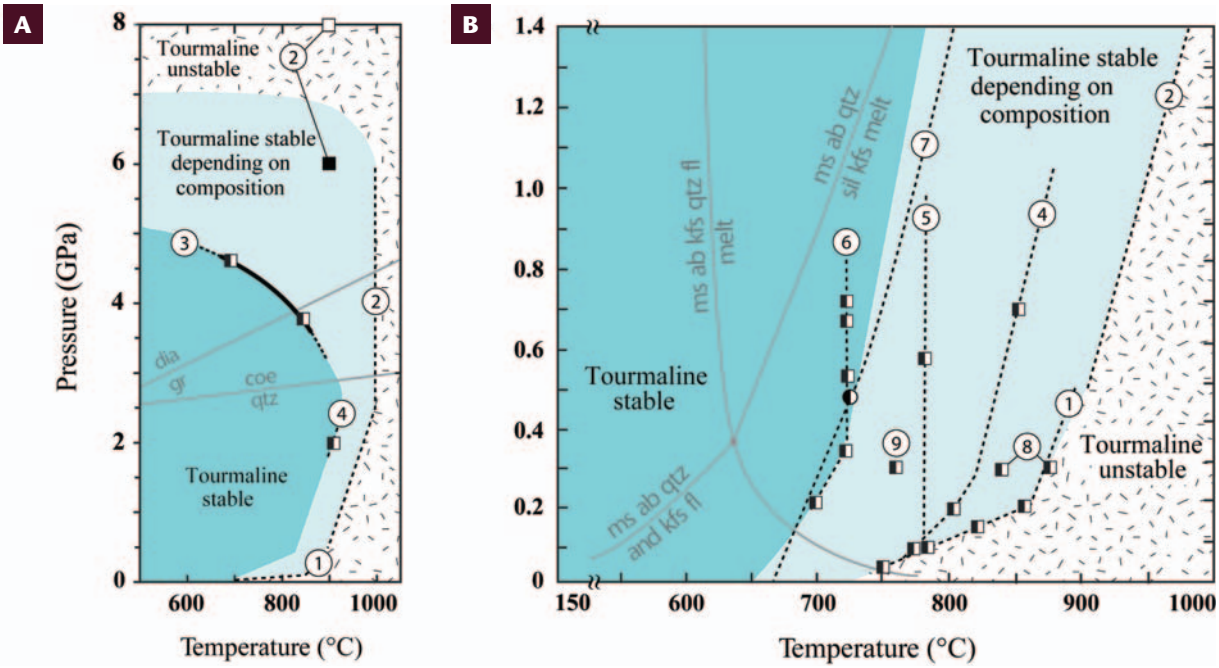

FIGURE 3 Upper *P*–*T* stability estimates for tourmaline of various compositions based on constraints from natural samples (circle) and experimental data (squares), with extrapolations (dashed lines); from van Hinsberg et al. (2011b). Selected reaction boundaries (gray lines) are shown for reference. (**A**) High-pressure and high-temperature stability. (**B**) Lower-pressure and high-temperature stability. **Dravite**: (1) Robbins and Yoder 1962; (2) Krosse 1995; (3) Ota et al. 2008. **Magnesio-foitite**: (4) Werding and Schreyer 1996. **Na-free Mg system** (5) and **Na-bearing Mg system**: (6) von Goerne et al. 1999. **Natural tourmaline**: (7) Kawakami 2001; (8) Spicer et al. 2004. **Schorl**: (9) Holtz and Johannes 1991. Mineral abbreviations: dia = diamond, gr = graphite, coe = coesite, qtz = quartz, ms = muscovite, ab = albite, and = andalusite, kfs = K-feldspar, fl = fluid, sil = sillimanite

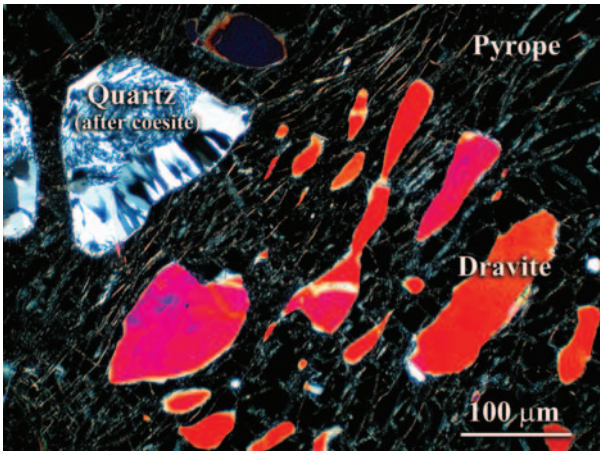

FIGURE 4 Inclusions of optically continuous dravite and associated quartz (after coesite) in pyrope garnet from the Dora Maira massif, Italy. PHOTOMICROGRAPH (CROSSED POLARIZERS) COURTESY OF DR. HANS-PETER SCHERTL, RUHR UNIVERSITÄT, BOCHUM

in highly acidic to neutral solutions (e.g. Henry and Dutrow 1996). This is because high-pH solutions produce boron complexes that are typically tetrahedrally coordinated to oxygen in a $B(OH)_4^-$ anionic complex. However, at neutral-to-low-pH conditions, boron is triangularly coordinated with three oxygens in a $B(OH)_3$ complex that is consistent with the coordination of boron in tourmaline. The amount of boron required to stabilize tourmaline increases with increasing pH, and tourmaline has not been synthesized under alkaline conditions (Morgan and London 1989). In addition, tourmaline growth and dissolution can be influenced by the proportions of the cations and anions in solution (e.g. Dutrow et al. 1999). It is also not uncommon to find early-generation tourmaline partially dissolved and replaced by later generations of tourmaline. For example, tourmaline is such a sensitive indicator of fluid compositions that individual fibers, 50 micrometers thick, can retain three distinct compositional zones representing different stages of tourmaline dissolution and subsequent growth (FIG. 5; Dutrow and Henry 2000).

SOURCES OF BORON

Boron is an essential element for the formation of tourmaline. As such, tracking boron availability in the Earth provides a link to understanding tourmaline development and the timescale of its formation and growth. Tourmaline is, in fact, a major reservoir of boron in the Earth's crust and a key mineral in the cycling of boron (e.g. van Hinsberg et al. 2011a).

Except for beryllium, boron is the least abundant element lighter than Fe in the Solar System (0.775 ppm B in CI chondrite; Lodders 2010), which is reflected in boron's very low concentration of 0.26 ppm in primitive mantle (TABLE 1). Differentiation of the silicate component of the Earth has resulted in substantial concentration of B in the continental crust, particularly at the Earth's surface (TABLE 1). Boron enrichment in crustal rocks is largely attributed to the compatibility of boron in silicic melts. Unmelted residues, such as the Earth's mantle, will be relatively depleted in boron. Today, ocean water is a significant reservoir for boron, which acts as a conservative element with a residence time of ~14 million years (Lemarchand et al. 2000). Its removal from ocean water is dominantly through incorporation into pelagic sediments and through hydrothermal alteration of oceanic crust. Pressure–temperature–fluid conditions in the subducting lithospheric slab stabilize tourmaline, thereby retaining boron in the pelagic (meta) sediments. Consequently, tourmaline controls cycling of boron and boron isotopes in subduction zones (Marschall and Jiang 2011).

At the Earth's surface, boron can be concentrated by evaporative processes in nonmarine and marine evaporite basins where borate minerals are precipitated (Smith and Medrano 1996). Because the isotopic composition of boron dissolved in seawater and nonmarine water differs by 40‰, boron isotopes in tourmaline can be used to infer the sources and proportion of marine and nonmarine boron (e.g. Marschall and Jiang 2011).

In igneous rocks boron is enriched via three primary processes that can lead to the formation of tourmaline: (1) partial melting of boron-bearing protoliths, (2) fractional crystallization of igneous melts, and (3) generation of hydrothermal fluids in association with boron-bearing melts. Partial melting of boron-enriched source rocks has been linked to the development of tourmaline-bearing granitic rocks, e.g. the tourmaline leucogranites of the High Himalayas (Guillot and Le Fort 1995). Melt fractionation resulting in boron enrichment is due to the strongly incompatible nature of boron, which preferentially concentrates in the melt phase. Thus, tourmaline is a common mineral produced in highly evolved melts such as granites, granitic pegmatites, and nodular granites, where it may occur in substantial amounts. In the later stages of magma crystallization, hydrothermal fluids can be generated and they are enriched in boron because of the partitioning of B into the hydrous fluid (cf. silicate melt) at the *P*–*T* conditions near the granitic solidus. When tourmaline crystallizes near the critical end-point in H_2O-rich systems, its composition records the chaotic *P*–*T*–*X* excursions at supercritical conditions (e.g. Norton and Dutrow 2001). Boron concentration and mobilization in magmatic–hydrothermal fluids may result in the metasomatic introduction of tourmaline

TABLE 1 BORON ABUNDANCE IN VARIOUS RESERVOIRS*

Reservoirs	Boron (ppm)
Fluids	
Ocean water	4.4
Fresh and sedimentary water	<~0.2
River water	~10.2 (ppb)
Brines	<2160
Salt and borax lakes	<9000
Crust	
Upper continental	17
Middle continental	17
Pelagic clay	<230
Volcanic arc basalts	2–35
Fresh mid-ocean ridge basalt	<1.5
Within-plate basalts	<3.0
Silicic igneous rocks	~5–1900
Pelitic and metapelitic rocks	<~250
Lower continental crust	2
Mantle	
Primitive mantle	0.26
Upper mantle (average)	<0.1

* Sources of B data include Henry and Dutrow (1996), Leeman and Sisson (1996), and Rudnick and Gao (2003) and references therein.

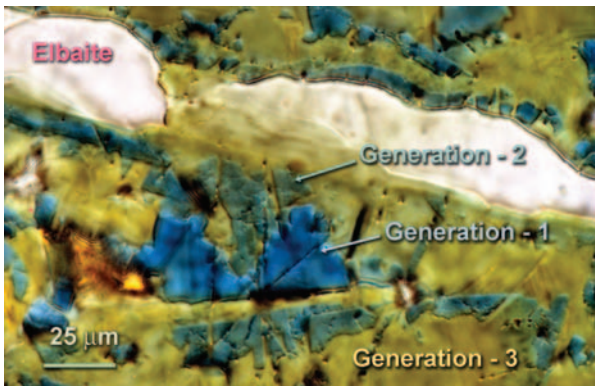

FIGURE 5 Photomicrograph of an elbaite host partially replaced by multiple generations of tourmaline that developed within a single tourmaline fiber. The section is cut perpendicular to the **c** axis and shows four distinct tourmaline compositions; three display dissolution and reprecipitation features: Elbaite (host), Generation 1 = foitite, Generation 2 = schorl/elbaite, and Generation 3 = "fluor-elbaite". AFTER DUTROW AND HENRY (2000)

in diverse settings, forming tourmaline-rich rocks such as tourmalinites in some seafloor hydrothermal systems (Slack and Trumbull 2011) and in the margins of igneous bodies and surrounding country rocks.

In metamorphic environments, the amount of boron available to form tourmaline depends on the initial quantities of boron present in the rocks and when that boron is released (TABLE 1). As temperature increases, boron is generally released from hydrous, lower-temperature minerals (e.g. phyllosilicates), and some portion of this boron may form tourmaline given favorable fluid compositions. With continued boron availability, more tourmaline will form, and its chemistry can be used to provide chemical information about the environment during progressive metamorphism (van Hinsberg et al. 2011a, b). In general, this process tends to deplete metamorphic rocks of boron at the highest metamorphic grades (e.g. Leeman and Sisson 1996), although boron-rich fluids from magma crystallization are known to flux into high-grade metamorphic rocks to produce tourmaline enrichment (e.g. Dutrow et al. 1999). Consequently, tourmaline commonly forms episodically as boron escaping from other phases or incoming fluids is captured. In addition, boron may be reintroduced into metamorphic rocks to form tourmaline on the retrograde path (van Hinsberg et al. 2011a, b).

The concentration and availability of boron began to increase during the Archean, allowing tourmaline to crystallize. Some of the oldest known tourmalines, dravite and schorl, are reported from the Isua Complex in Greenland dated at about 3700 Ma, with other varieties forming later (Grew and Hazen 2010). Clearly tourmaline has sequestered boron since the early stages of crust formation.

SUMMARY: THE CASE FOR TOURMALINE AS A GEOLOGIC DVD

Once merely considered an attractive collectable mineral and gemstone or simply overlooked as an uninteresting accessory mineral, tourmaline has become a focus for geologic and petrogenetic research because we can now extract from it a rich and robust amount of information. It has many of the attributes of modern electronic information storage devices such as the DVD. These include its ability to precisely record information at very small scales in both space and time; its well-understood mineral structure, which is capable of capturing large chemical variations reflective of host-rock composition, fluid composition, and the *P*–*T* conditions under which it formed; and its ability, occasionally, to stamp the date on that information. Because its structure is not prone to chemical degradation or mechanical disintegration, tourmaline is stable over a wide range of geologic conditions, such that the information encoded is retained. Finally, an additional key, analogous to a DVD, is the necessity to have a precise reader to decode the encased information. As shown in this issue (and many previous contributions), our ability to read the chemical, textural, and structural information stored in tourmaline has elevated the mineral to a new status as a geologic powerhouse. Tourmaline's complexity is now an asset because it records abundant information about geologic processes that reveal the story of an evolving Earth.

ACKNOWLEDGMENTS

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Tourmaline the Indicator Mineral: From Atomic Arrangement to Viking Navigation

Tourmaline as a constituent of jewelry. From the tourmaline collection of Dr. E. Sokolova

Frank C. Hawthorne[1] and Dona M. Dirlam[2]

1811-5209/11/0007-0307$2.50 DOI: 10.2113/gselements.7.5.307

Tourmaline *sensu lato* has been known for at least two thousand years, and its unique combination of physical properties has ensured its importance to human society, from technical devices (such as a possible Viking navigational aid and early piezoelectric gauges in the 20th century) to attractive and popular gemstones. The chemical diversity and accommodating nature of its structure combine to make tourmaline a petrogenetic indicator for the wide range of rocks in which it occurs. Recent advances in understanding the structure, site assignments, and substitution mechanisms have led to a new nomenclature for the tourmaline supergroup minerals. Eighteen species have been described to encapsulate the chemical variety found in this intriguing structure.

Keywords: tourmaline, crystal structure, crystal chemistry, pyroelectricity, piezoelectricity, tourmaline nomenclature, gemstone

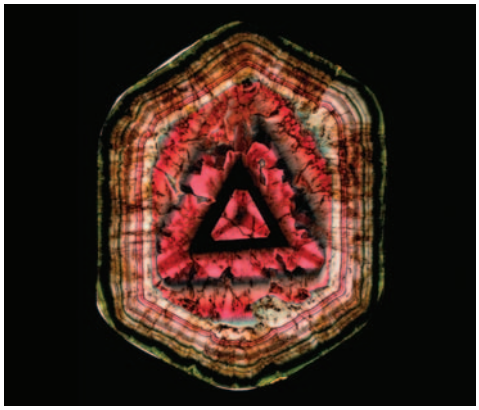

Figure 1 A complexly zoned slice of fluor-liddicoatite cut parallel to (001), from Anjanabonoina, Madagascar. This slice measures approximately 10 cm in its longest dimension, and displays a trigonal star pattern and "aggregate-type" zoning. The outer region consists of fine-scale color zoning roughly parallel to the prism faces. Photo © Harold & Erica Van Pelt

INTRODUCTION

For many years, tourmaline *sensu lato* (i.e. minerals of the tourmaline supergroup) was not taken seriously by mineralogists, petrologists, and geochemists. The problem lay primarily in our lack of understanding of these minerals. They have recondite crystal chemistry, a fairly complicated crystal structure, and a chemical composition that is almost Byzantine in its complexity. Moreover, they can exhibit extremely convoluted chemical zoning, and several of their more important chemical constituents (H, Li, B, Fe^{2+}, Fe^{3+}) were not easily determined by standard analytical techniques (specifically, electron microprobe analysis). Tourmaline was essentially a "Saturday afternoon" mineral, something that was fun to look at but wasn't to be taken too seriously. This situation began to change about 20 years ago, as systematic examination of its crystal chemistry and paragenesis began to illuminate the mysteries of this hitherto exotic mineral. Tourmaline is the epitome of the thesis that the more complicated a mineral, the more information it contains about its crystallization and subsequent evolution, and our increased understanding of its crystal chemistry is turning this mineral into an important petrogenetic indicator (van Hinsberg et al. 2011).

CHEMICAL COMPOSITION

Our first indication of the complexity of the minerals of the tourmaline supergroup arises from their general chemical formula:

$$XY_3Z_6[T_6O_{18}][BO_3]_3V_3W \ ,$$

where X = □ (vacancy), Na, K, Ca, Pb^{2+},
Y = Li, Mg, Fe^{2+}, Mn^{2+}, Cu^{2+}, Al, V^{3+}, Cr^{3+}, Fe^{3+}, Mn^{3+}, Ti^{4+},
Z = Mg, Fe^{2+}, Al, V^{3+}, Cr^{3+}, Fe^{3+},
T = Si, B, Al,
B = B,
V = OH, O, and
W = OH, F, O.

The letters in the general formula correspond to groups of cations or anions that occupy the same sites in the structure. These occupancies are well established, except perhaps for the presence of Fe^{2+} at the Z site where some differences of opinion still exist (e.g. Ertl et al. 2006; Andreozzi et al. 2008). The crystal chemistry of tourmaline has taken a long time to unravel, a result of the combination of a complicated structural arrangement and a flexible structure that can incorporate many different cations and anions. In particular, the above formula can include three light lithophile elements (H, Li, B) that can occur in variable quantities and Fe that can occur as both Fe^{2+} and Fe^{3+}. These constituents cannot be analyzed easily with the more common analytical techniques, and either (often dubious) stoichiometric assumptions are necessary to calculate a chemical formula or less common and more difficult analytical techniques (see below) are required for accurate chemical analysis. These problems are compounded by the fact that tourmaline is often zoned on a fine scale (Fig. 1; see Pezzotta and Laurs 2011 this issue), and bulk analytical

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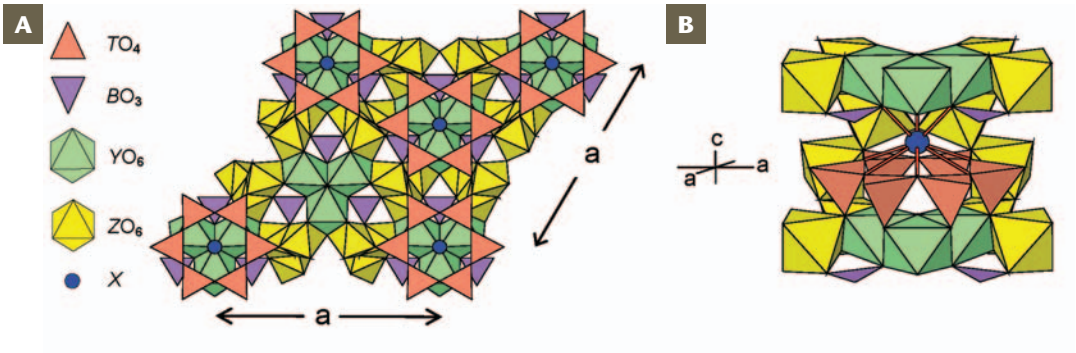

Figure 2 The crystal structure of tourmaline: (**A**) projected onto (001); (**B**) oblique view

techniques are not appropriate. Thus an adequate understanding of the chemical variations in tourmaline minerals has been dependent on the development of suitably advanced milli- and microbeam analytical techniques, accounting for why the tourmaline minerals are perhaps the last of the common silicates to be adequately understood.

THE CRYSTAL STRUCTURE OF TOURMALINE

In the structure of tourmaline (Fig. 2), there is one tetrahedrally coordinated site, labelled *T*, which is predominantly occupied by Si but also can contain Al and B. Six TO_4 tetrahedra join corners to make a $[T_6O_{18}]$ ring, forming a cyclosilicate structure. There is one triangularly coordinated site that is fully occupied by B. There are two octahedrally coordinated sites, labeled *Y* and *Z*, respectively. Three *Y* octahedra share edges to form a $[Y_3\phi_{13}]$ trimer (ϕ = unspecified anion). The *Z* octahedra share edges around the periphery of this trimer, the BO_3 group providing additional linkage (Fig. 2a). The *X* site is [9]-coordinated and lies out of the plane of the $[T_6O_{18}]$ ring.

Tourmaline has point-group symmetry 3*m*, which is both noncentrosymmetric (i.e. does not have a center of symmetry) and polar (i.e. the unit cell of the structure has a net electric dipole moment). Thus tourmaline is both pyroelectric and piezoelectric (see below). The principal atomic-scale contribution to the piezoelectric and pyroelectric effects is the attitude of the tetrahedra in the tourmaline structure. All tetrahedra point along **–c** (Fig. 2b), and the resulting noncentrosymmetry and polar character strongly affect the growth, morphology, internal texture, and chemical zoning of tourmaline (e.g. van Hinsberg et al. 2011).

Much of the chemical complexity of tourmaline arises because of the variety of sites in the structure and the ease with which several of these sites can incorporate a wide variety of chemical species. In particular, H, Li, B, Fe^{2+}, and Fe^{3+} are common variable constituents, and their quantitative analysis can require careful crystal-structure refinement (e.g. Ertl et al. 1997, 2005), SIMS (secondary-ion mass spectrometry: H, Li, B), MAS NMR (magic-angle-spinning nuclear magnetic resonance: $^{[4]}$B and $^{[4]}$Al; i.e. [4]-coordinated B and Al replacing Si at the *T* site), and ^{57}Fe Mössbauer spectroscopy (Fe^{2+} and Fe^{3+} at the *Y* and *Z* sites). ^{11}B and ^{27}Al MAS NMR are sensitive to the coordination numbers of B and Al (Fig. 3a, b). There is a strong signal from $^{[3]}$B at ~13–20 ppm and a well-resolved signal at ~0 ppm (Fig. 3a) due to $^{[4]}$B that replaces Si at the *T* site in the tourmaline structure (Tagg et al. 1999; Lussier et al. 2008), and there is a strong signal from $^{[6]}$Al at ~0 ppm and a well-resolved signal at ~60–70 ppm (Fig. 3b) due to $^{[4]}$Al that replaces Si (Lussier et al. 2009). Thus ^{11}B and ^{27}Al MAS NMR allows detection of low levels (~0.02 *apfu,* atoms per formula unit) of $^{[4]}$B and $^{[4]}$Al in tourmalines that contain only small amounts of (ferromagnetic) transition metals (which tend to quench the NMR signal). ^{57}Fe Mössbauer spectroscopy is sensitive to valence state and coordination of Fe. Figure 3c shows the spectrum of an Fe-bearing elbaite with signals from Fe^{2+}, Fe^{3+}, and a mixed state, $Fe^{2.n}$, which indicates intervalence charge transfer, the dynamic transfer of charge between locally adjacent Fe cations in the structure that gives rise to intense pleochroism in many tourmalines. The relative intensities of the peaks are related to the amounts of the different Fe species, and Fe at the *Y* and *Z* sites gives rise to different doublets in the spectrum (Andreozzi et al. 2008). Consequently, the combination of several analytical methods can give more complete chemical information about tourmaline, but problems still exist with regard to detecting and accurately measuring $^{[4]}$B and $^{[4]}$Al in Fe-rich (FeO > 2 wt%) tourmaline.

Tourmaline shows extensive short-range order (local clustering of specific cations and anions; e.g. Taylor et al. 1995) due to the operation of the local valence-sum rule (Hawthorne 1997; Bosi 2011). As a result, the chemical constituents of tourmaline have extremely slow diffusion rates, and tourmaline from many environments is

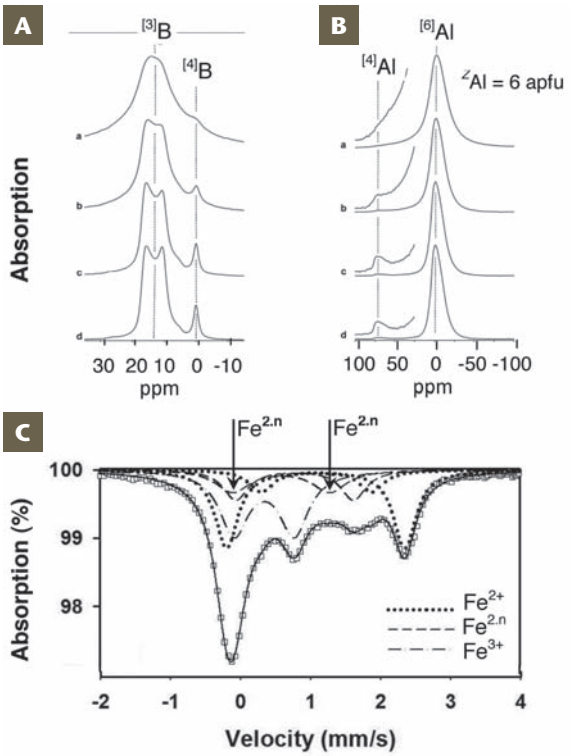

Figure 3 Spectroscopy and site occupancy in tourmaline. (**A**) ^{11}B MAS NMR spectra of a series of tourmalines with the amount of $^{[4]}$B increasing downward (a to d) in accord with the peak at ~0 ppm (**B**) ^{27}Al MAS NMR spectra of a series of tourmalines with the amount of $^{[4]}$Al increasing downward in accord with the peak at ~65 ppm (**C**) ^{57}Fe Mössbauer spectrum of tourmaline (elbaite) showing peaks (doublets) due to Fe^{2+}, Fe^{3+}, and mixed-valence $Fe^{2.n}$. Spectra from Lussier et al. (2008, 2011)

Figure 4 Miner Ailton Barbosa kneeling with a large elbaite tourmaline (variety rubellite) cluster, which he discovered at the Jonas mine, Minas Gerais, Brazil, in 1978. Photo ©Julio Cesar Mendes Mendes

extremely optically, chemically, and isotopically zoned. Such zoning preserves details of the crystallization history of the tourmaline, gives major insight into the petrologic processes affecting the host rocks (e.g. Henry and Guidotti 1985; Henry and Dutrow 1992; van Hinsberg and Marschall 2007; van Hinsberg and Schumacher 2009; van Hinsberg et al. 2011), and provides a record of the evolving fluids from which the tourmaline crystallized (e.g. Dutrow et al. 1999; Marschall et al. 2008; Marschall and Jiang 2011 this issue). In particular, the occurrence of B in both [3]- and [4]-coordination has major ramifications with regard to B isotope signatures in rocks (Marschall and Jiang 2011).

MORPHOLOGICAL CRYSTALLOGRAPHY AND HABIT

Tourmaline is rhombohedral, ditrigonal pyramidal (point group $3m$) and has space-group symmetry $R3m$*. It commonly occurs as large crystals (Fig. 4), typically euhedral and showing a bewildering variety of forms (Goldschmidt 1922). Doubly terminated crystals are common and frequently exhibit *hemimorphic* character, that is, they have different morphological forms at each end of the **c** crystallographic axis (Fig. 5A). Tourmaline is pyroelectric due to the polar character of its symmetry and structure: when the crystal is heated, the *antilogous pole* of the crystal (the end that occurs along the +**c** crystallographic axis; Fig. 5A) acquires a negative charge, and the *analogous pole* (the end that occurs along the –**c** crystallographic axis) acquires a positive charge (Dietrich 1985). The pyramidal faces are much steeper on the antilogous end than on the analogous end, and the pedion (single basal face) at the antilogous end is highly reflective whereas the pedion at the analogous end has a rather matt luster. Crystal growth is much more rapid in the +**c** direction than in the –**c** direction, and authigenic crystals growing on detrital tourmaline cores are extended toward the antilogous end compared to the analogous end (e.g. Henry and Dutrow 1992).

Tourmaline shows extremely diverse habits and is commonly morphologically complicated (Fig. 5B). Crystals are predominantly prismatic, varying from stubby to very acicular or fibrous, but can be tabular. Moreover, prism faces are commonly grooved parallel to the **c** axis, a characteristic feature for the identification of tourmaline in hand specimen. The change from prismatic to fibrous habit can be particularly spectacular when accompanied by a color change (Lussier et al. 2008).

* There are some reports of tourmaline, or sectors within tourmaline crystals, having orthorhombic, monoclinic, or even triclinic symmetry (e.g. Akizuki et al. 2001).

Table 1 COMMON PHYSICAL PROPERTIES OF THE TOURMALINE MINERALS

Color	Commonly black, also brownish, reddish pink to pink, pale green to dark green, yellow, shades of blue, mauve to purple, white, colorless
Streak	White to brown, greyish blue
Luster	Usually vitreous, occasionally resinous
Hardness (Mohs)	7–7½
Cleavage	Indistinct, poor on both {110} and {101}
Fracture	Uneven to conchoidal
Density (g cm^{-3})	2.8–3.3
Morphology	{110}, {111}, {11$\bar{1}$}, {101}, {10$\bar{1}$}, {001}, {00$\bar{1}$} common
Habit	Crystals are frequently prismatic and often form divergent aggregates in granitic pegmatites.
Unit-cell dimensions	$a = b \approx 15.7–16.2$ Å, $c \approx 7.05–7.25$ Å, $\alpha = \beta = 90°$, $\gamma = 120°$
Optic sign	Uniaxial negative
Refractive indices	$\varepsilon = 1.610–1.650$, $\omega = 1.635–1.675$
Birefringence	0.018–0.040
Pleochroism	Colored tourmaline minerals can be strongly pleochroic: shades of green and bluish green, pale blue to dark blue, pale pink to red, various shades of brown

PHYSICAL PROPERTIES AND THEIR IMPORTANCE

Its hardness and lack of cleavage make tourmaline an important resistate mineral in clastic sediments, where it can be used as a provenance indicator (Henry and Guidotti 1985; Henry and Dutrow 1992; Morton et al. 2005; Marschall et al. 2008). Such detrital tourmaline typically serves as a nucleus for authigenic crystallization of tourmaline, which, with continued increase in temperature, can grade into subsequent metamorphic growth (e.g. Henry and Dutrow 1996 and references therein) in a wide variety of metamorphic rocks (van Hinsberg et al. 2011). Its multitude of colors and its hardness combine to make tourmaline a spectacular gemstone (Pezzotta and Laurs 2011). Standard physical properties are listed in Table 1.

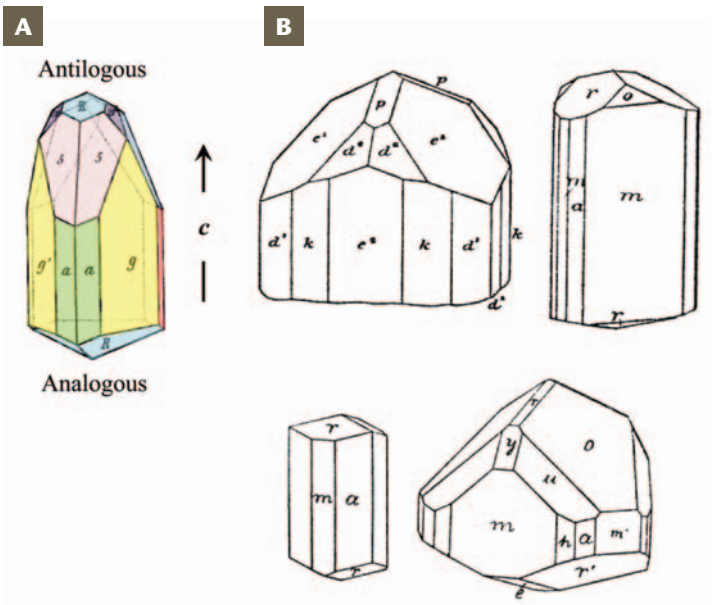

Figure 5 (**A**) Hemimorphic morphology (after Goldschmidt 1922) and the antilogous–analogous ends of a crystal. (**B**) Typical morphological forms of tourmaline (from Goldschmidt 1922)

Pyroelectricity

On heating, materials that are pyroelectric attract other materials. In 314 BCE, Theophrastus noted that tourmaline attracts ash and straw when it is heated (Dietrich 1985). This property of tourmaline gave rise to the name *Aschentrecker*, or ash puller, and Dutch traders of the 18th century used long prismatic crystals of tourmaline to clean ash from their meerschaum pipes. The term *pyroelectricity* is derived from the Greek *pyr*, meaning fire, and the word *electricity*, and describes the ability of certain materials to produce a temporary voltage when they are heated (or cooled). The change in temperature causes a corresponding change in the positions of the atoms such that the net polarization of the crystal changes, and this change results in a voltage across the crystal. Consequently, only polar crystals can be pyroelectric. Polar materials do not normally have a net dipole moment because the intrinsic dipole moment of the crystal is neutralized by electric charge that builds up on the surface of the crystal by conduction or electrostatic attraction. Polar crystals only show pyroelectricity when disturbed in some way (e.g. heating) that perturbs their interaction with the neutralizing surface charge (Nye 1957).

Piezoelectricity

When subjected to a mechanical stress, materials that are piezoelectric accumulate an electric charge. The piezoelectric effect was first shown by the brothers Pierre and Jacques Curie in 1880, using tourmaline, quartz, and topaz (Dietrich 1985). The term *piezoelectricity* is derived from the Greek *piezo*, meaning to squeeze, and the word *electricity*. In solid materials, an ion in an asymmetric environment has a dipole moment. In a centrosymmetric crystal, the symmetry results in zero net dipole moment. In a noncentrosymmetric crystal, the net dipole moment is nonzero. If a noncentrosymmetric crystal is mechanically stressed, the atoms in the crystal move in response to that stress, and the resulting strain induces a change in the net dipole moment. In turn, an electric charge is generated by this change in dipole moment, resulting in piezoelectricity. This gave rise to the use of Malagasy tourmaline as pressure gauges in submarines during WWI (Carl Francis, personal communication).

Tourmaline: the Viking Sunstone?

The Icelandic saga *Rauðúlfs þáttr* tells us that Viking sailors used crystals as a navigational aid—a *sólarsteinn* (sunstone) that allowed them to locate the sun in cloudy and foggy weather. The story describes the visit of Olav Haraldsson II, king of Norway from 995 to 1030 (also known as St. Olav), to Eystridalir, a remote part of Norway where a wise man named Rauðúlfr was accused of stealing cattle. Rauðúlfr and his family lived in a rather special house that rotated with the movement of the sun across the sky. King Olav asked Rauðúlfr how the house managed to follow the sun when the sky was obscured by cloud and fog. So Rauðúlfr showed the king his sunstone, which allowed him to locate the sun through cloud and fog. Subsequently, Rauðúlfr and his family were found innocent of the cattle theft, and Rauðúlfr's two sons, who were skilled astronomers, joined the king's retinue (Faulkes 1966).

The identity of Viking sunstone is strongly debated, the principal candidates being tourmaline (presumably elbaite), cordierite, and calcite (Karlsen 2000), all of which strongly polarize light. The atmospheric requirements for such navigation are as follows: (1) the degree of linear polarization, p, of the light from the sky should be high; and (2) at a given position of the sun, the pattern of the angle of polarization, α, of the foggy/cloudy sky should be similar to that of the clear sky (Hegedüs et al. 2007). Requirement (2) is always satisfied, but if the fog layer is illuminated by direct sunlight, requirement (1) is usually satisfied only if the sky is cloudy. Presumably, the effectiveness of this method is also strongly dependent on the optical quality of the specific crystal in the possession of the navigator.

HOW TO NAME A TOURMALINE

The numerous chemical constituents and their ability to occupy a variety of sites in the tourmaline structure has given rise to a modest number of recognized species in the past, but this number has been increasing significantly in the last few years. Tourmaline species are defined in terms of chemical composition, and the primary criterion is the dominance of a particular chemical constituent at a given crystallographic site. The result is that each distinct mineral species can be associated with an end-member composition

Table 2 IMA-ACCEPTED TOURMALINE SPECIES AND THEIR END-MEMBER COMPOSITIONS

General formula	(X)	(Y_3)	(Z_6)	T_6O_{18}	$(BO_3)_3$	V_3	W
Alkali Group							
Dravite	Na	Mg_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Schorl	Na	$Fe^{2+}{}_3$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Chromium-dravite	Na	Mg_3	Cr_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Vanadium-dravite	Na	Mg_3	V_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Fluor-dravite	Na	Mg_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
Fluor-schorl	Na	$Fe^{2+}{}_3$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
Elbaite	Na	$Li_{1.5}\ Al_{1.5}$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Povondraite	Na	$Fe^{3+}{}_3$	$Mg_2Fe^{3+}{}_4$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
Chromo-alumino-povondraite	Na	Cr_3	Mg_2Al_4	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
Fluor-buergerite	Na	$Fe^{3+}{}_3$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(O)_3$	F
Olenite	Na	Al_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(O)_3$	(OH)
Calcic Group							
Fluor-uvite	Ca	Mg_3	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
Feruvite	Ca	$Fe^{2+}{}_3$	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Uvite	Ca	Mg_3	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Fluor-liddicoatite	Ca	$Li_2\ Al$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
Vacancy Group							
Foitite	□	$Fe^{2+}{}_2Al$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Magnesio-foitite	□	Mg_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Rossmanite	□	$Li\ Al_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)

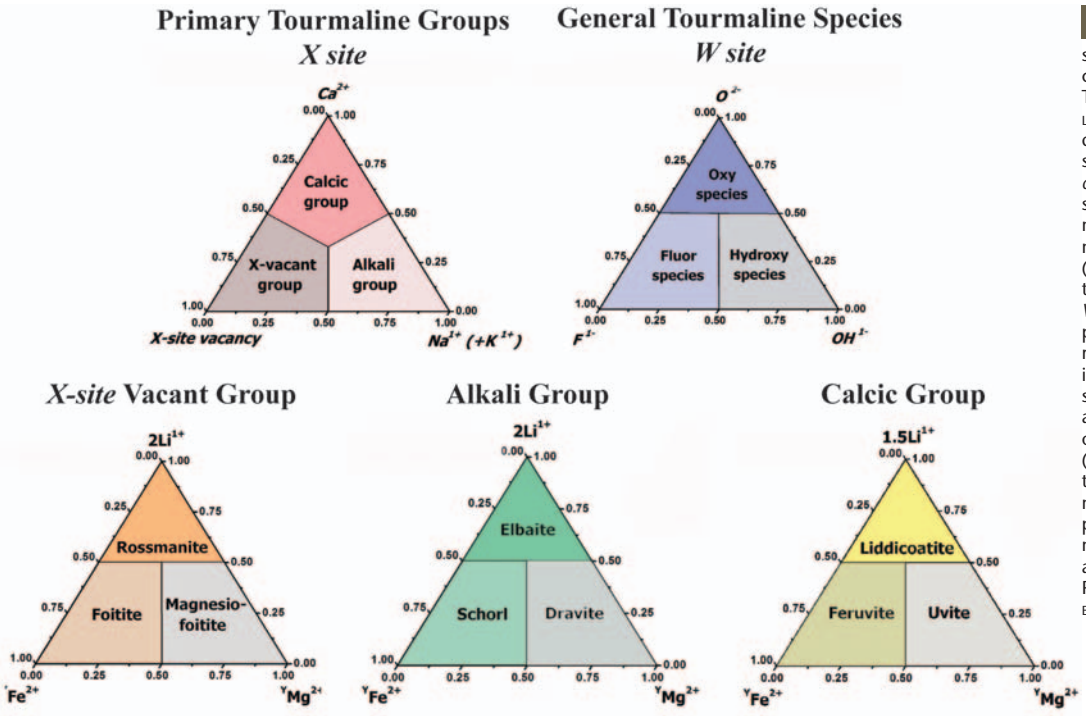

FIGURE 6 Classification of the tourmaline supergroup minerals by chemical composition. The primary division (TOP, LEFT) is made according to the dominant occupancy of the *X* site to give the *X-site vacant*, *alkali*, and *calcic* groups. The secondary division (BOTTOM) is made according to the dominant occupancy of the *Y* site (Mg, Fe^{2+}, 2Li or 1.5 Li) with the *Z* site = Al dominant and *V* = OH dominant for each primary group, giving the root names shown here and in TABLE 2. The tertiary divisions (TOP RIGHT) are made according to the dominant occupancy of the *Z* site (Al, Cr^{3+}, V^{3+}, not shown) and the *W* anions (OH, F, O^{2-}); the names involve the use of prefixes attached to root names and other trivial names and are listed in TABLE 2. FIGURES MODIFIED FROM HENRY ET AL. (2011)

that is irreducible, that is, it cannot be expressed in terms of two constituents of simpler composition and with the same atomic arrangement (Hawthorne 2002). For the majority of atomic arrangements and chemical compositions, this results in end-member formulae that have a single chemical species at each site, e.g. dravite: $^{X}Na\ ^{Y}Mg_3\ ^{Z}Al_6\ (^{T}Si_6O_{18})\ (^{B}BO_3)_3\ ^{V}(OH)_3\ ^{W}(OH)$. However, electroneutrality can require some end-members to have two constituents of different valence (and in a fixed ratio) at one site in their structure (the remaining sites having only one constituent each), e.g. elbaite: $Na\ ^{Y}(Li_{1.5}Al_{1.5})\ Al_6\ (Si_6O_{18})\ (BO_3)_3\ (OH)_3\ (OH)$, in which the *Y* site is occupied by both Li and Al in a 1:1 ratio. This point is of particular relevance to the tourmalines, as the end-member compositions of the Li-bearing tourmalines rossmanite, elbaite, and liddicoatite have the *Y* site occupied by $LiAl_2$, $Li_{1.5}Al_{1.5}$, and Li_2Al, respectively (TABLE 2). These chemical and structural complexities were recently evaluated to develop the currently IMA-accepted tourmaline minerals and their end-member compositions (TABLE 2; Henry et al. 2011). The tourmaline minerals are now referred to as a supergroup. Compositional variation in tourmaline may involve cations (or anions) of the same valence (homovalent variation) or cations (or anions) of different valence (heterovalent variation). Several common-mineral classifications are now based on the premise that distinct arrangements of formal charges at the sites in a structure are distinct root compositions, warrant distinct *root names*, and are distinct species (listed in TABLE 2). For a specific root name, different homovalent cations (e.g. Mg versus Fe^{2+}) or anions (e.g. OH versus F) are indicated by prefixes (e.g. magnesio-foitite: $\square(Mg_2Al)\ Al_6\ (Si_6O_{18})\ (BO_3)_3\ (OH)_3\ (OH)$; fluor-dravite: $Na\ Mg_3\ Al_6\ (Si_6O_{18})\ (BO_3)_3\ ^{V}(OH)_3\ ^{W}F$. Earlier established names are retained (e.g. schorl instead of "ferro-dravite"), but newly introduced tourmaline minerals, where appropriate, are named using prefixes, as indicated previously.

The tourmaline minerals show extensive compositional variation at the *X*, *Y*, *Z*, and *W* sites, and less variation at the *T* site. As a result, the tourmaline supergroup is divided into groups and subgroups according to compositional variation at these sites. The primary subdivision involves variation at the *X* site, resulting in the *X-site vacant*, *alkali*, and *calcic* groups (FIG. 6, TOP LEFT). For each group, the occupancy of the *Y* site is considered in terms of the constituents ^{Y}Fe, ^{Y}Mg, and ^{Y}Li (FIG. 6, BOTTOM). Next, the anion occupancy of the O(1) site (the *W* anions) is considered: *W* may be occupied by (OH), F, or O^{2-}, and this forms the basis of the next division (FIG. 6, TOP RIGHT) into the hydroxy-, fluor-, and oxy- species, defined as follows: hydroxyl- if OH + F ≥ O^{2-} and OH ≥ F; fluor- if OH + F ≥ O^{2-} and F > OH; and oxy- if O^{2-} > OH + F. Variation in *Z* site constituents is expressed in terms of prefixes (TABLE 2). It should be emphasized that this classification is designed specifically for tourmalines that have been chemically analyzed.

FIGURE 7 Tourmaline as eye candy. The Candelabra tourmaline is one of the stunning crystal clusters found in the legendary blue-cap tourmaline pocket at the Tourmaline Queen mine of Pala, California, in 1972. This rare blue-cap cluster (25 cm wide) of three elbaite crystals on quartz is now part of the Smithsonian Institution's collection. PHOTO © HAROLD & ERICA VAN PELT

Figure 8 A selection of faceted (1.28–3.02 ct; 6.75 mm round to 8.9 × 8.3 mm cushion), unheated, Cu-bearing tourmalines from Mozambique showing the vivid colors typical of the deposit. Gemstones courtesy of Pala International; photographer: Robert Weldon ©Gemological Institute of America, reprinted with permission

AESTHETICS

Despite the intellectual fascination of tourmaline, we should not lose sight of the fact that there are other (aesthetic) reasons to appreciate this mineral. It forms mineral specimens so beautiful that they acquire their own names and are well known worldwide (Fig. 7). In addition, tourmaline gemstones show a bewildering array of spectacular colors (Fig. 8) and large stones are common (although expensive). Color and zoning can combine to form beautiful *objets d'art* and jewelry, and wealthy socialites collect tourmaline jewelry. It is fitting that such an interesting mineral has such a beautiful appearance.

ACKNOWLEDGMENTS

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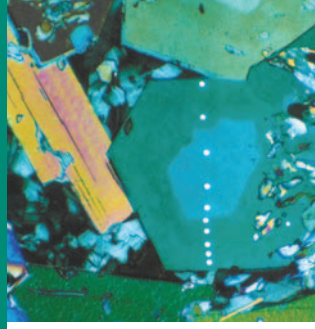
Tourmaline Isotopes: No Element Left Behind



Thin section photomicrograph (crossed-polarizers) of zoned hexagonal tourmaline (grain diameter ~0.4 mm) with chlorite (dark blue), phengite (orange and pink), and epidote (inclusions in tourmaline). The measurement spots produced by SIMS are visible as white dots.

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Tourmaline typically forms where crustal rocks interact with migrating hydrous fluids or silicate melts, and its isotopic composition provides a reliable record of the isotopic composition of the fluids and melts from which it crystallized. Minerals of the tourmaline supergroup are exceptional in their physical robustness and chemical variability, and they allow us to extract a uniquely broad range of isotopic information from a single mineral. The chemical variability of tourmaline confronts us with the difficulty of deciphering an extremely complex mineral system, but it also presents us with a geochemical recorder of half the periodic table, a breadth of representation that is unparalleled among minerals. Plate tectonic–scale geochemical cycles, local and regional fluid–rock interactions, magmatic–hydrothermal systems, ore-forming processes, and ages of tourmaline formation have all been reconstructed using this unique isotopic broadband recorder.

KEYWORDS: tourmaline, isotopes, boron, subduction zones, seawater, continental crust, ore deposits

INTRODUCTION

The chemical differentiation of our planet is largely achieved by fluids and melts that transport material from sources typically deep in the crust or upper mantle to the shallow crust or surface. These migration processes are keys to the long-term evolution of the Earth's outer layers and the enrichment of the upper continental crust in melt- and fluid-soluble elements. The mobile phases involved in these processes are rarely preserved in the geologic record, hampering reconstruction of their sources and chemical evolution. Consequently, research focuses on minerals, as these can potentially preserve the chemical and isotopic compositions of the fluids and melts from which they grew. Minerals of the tourmaline supergroup are ideally suited as recorders of fluid and melt compositions. Tourmaline is a borosilicate mineral with significant chemical variability (Hawthorne and Dirlam 2011 this issue). Once formed, tourmaline is highly stable in a variety of rock types over an exceptionally large *P*–*T* range, extending from surface conditions to the diamond stability field at pressures prevailing in the upper mantle (Marschall et al. 2009; Dutrow and Henry 2011 this issue). The chemical and isotopic information is commonly preserved because volume diffusion of major and trace elements in tourmaline is insignificant up to temperatures of at least 600°C (van Hinsberg et al. 2011a this issue). Tourmaline is also exceptionally robust in sediments during transport, diagenesis, and metamorphism, and together with zircon and rutile has been referred to as an "ultrastable mineral" in sedimentary geology (van Hinsberg et al. 2011a). Detrital grains can be readily identified in sediments and metasedimentary rocks by their distinct optical, chemical, and isotopic zoning patterns (FIG. 1; Henry and Dutrow 1996; Marschall et al. 2008). With the development of in situ analytical techniques, we can now investigate the chemical and isotopic composition of multiply zoned tourmaline at a spatial resolution of less than 50 µm and, in some cases, as small as 5 µm (FIG. 1).

The chemical complexity of tourmaline provides a geochemical recorder of unparalleled breadth, and a large number of major and trace elements in tourmaline are important tools in isotope geochemistry. The isotope systems of B, O, H, Si, Mg, Li, Sr, Nd, Pb, K(Ar), and Cu have already been applied to tourmaline, providing valuable information on the physicochemical conditions associated with fluid–rock interaction, fluid origin and evolution, the sources and genesis of ore deposits, and the timing of the magmatic, metamorphic, and hydrothermal events that produce tourmaline, including the highly valued gem tourmalines.

BORON ISOTOPES, SUBDUCTION ZONES, SEAWATER, AND THE CONTINENTAL CRUST

Subduction zones are areas of intense interest to geoscientists. In addition to being the sites of widespread volcanism, earthquakes, and ore deposit formation, subduction zones are also where crust and mantle interact extensively, such that material exchange takes place between the two reservoirs. Oceanic crust is subducted into the mantle and releases fluids rich in solutes into the overriding plate. Such fluids make their way back to the surface as metasomatizing agents altering rocks of the overriding mantle and crust, and they trigger subduction-related volcanism. However, our understanding of the detailed nature of the geochemical cycling in subduction zones and the sources and pathways of fluids and melts is incomplete.

The isotopic signatures of fluids and melts can be recorded in minerals such as tourmaline and provide important evidence for understanding subduction zone processes. The

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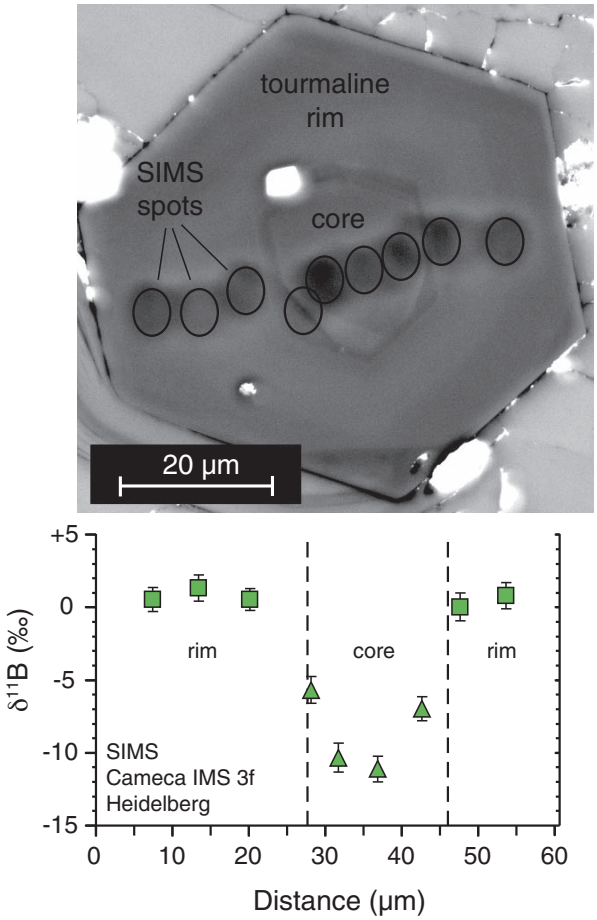

Figure 1 Backscattered electron image of a tourmaline grain in a siliceous marble from Syros (Greece) displaying a detrital core that is distinct from its metamorphic rim (Marschall et al. 2008). The B isotope composition of different parts of the grain was determined by SIMS (secondary-ion mass spectrometry) with a spatial resolution of 5–10 µm. The delta notation for isotope ratios describes the deviation of a sample from a standard in parts per thousand. The standard for B has been chosen arbitrarily, and 0 ‰ has no geologic meaning. Note the distinct texture and B isotope composition of the preserved detrital core compared to the metamorphic rim.

chemical feature that sets tourmaline apart from other common silicate minerals is the presence of ~3 wt% boron (B), an element essential to its crystal structure (Dutrow and Henry 2011; Hawthorne and Dirlam 2011). Boron is a quintessentially crustal element. Its abundance in the mantle is very low, whereas seawater and rocks of the continental crust show relatively high abundances, containing a large fraction of Earth's B budget (Dutrow and Henry 2011). At the surface, ambient temperatures and extensive interaction of the lithosphere and hydrosphere lead to a large fractionation of the two stable isotopes of B, ^{10}B and ^{11}B. Rocks of the oceanic crust incorporate isotopically heavy B (i.e. they have a higher proportion of ^{11}B) from seawater during seafloor alteration, whereas rocks of the continental crust become depleted in the heavy isotope during subaerial weathering. Consequently, B in continental crustal rocks is isotopically lighter than B in the mantle, and rocks with marine affinity are enriched in ^{11}B relative to the mantle and continental crust (Fig. 2; Leeman and Sisson 1996). During subduction, altered oceanic crust releases fluids that carry isotopically heavy B inherited from the oceanic crust's interaction with seawater, and some of these fluids contribute to subduction-related magmatism. Consequently, magmas produced in subduction zones are generally enriched in ^{11}B (Leeman and Sisson 1996). However, a large amount of B-rich fluid is released from the subducting slab in the shallow fore-arc region where magmatism is not developed, and methods for detecting and deciphering the geochemical cycle of subduction zones in this region are needed.

High-pressure metamorphic rocks are important sources of geochemical information from subduction zones. These rocks are fragments of oceanic crust or of a continental margin that were subducted to depths of at least 50 kilometers and returned to the surface. Importantly, much of the exhumation of such rocks typically occurs while the subduction zone is active. The exhuming rocks travel in a narrow channel on top of the subducting slab and are metasomatized by fluids released from the slab (e.g. Marschall et al. 2006). Hence, metasomatic minerals crystallized in high-pressure rocks during exhumation typically carry geochemical signatures of subduction zone fluids sampled at various depths. High-pressure metamorphic rocks provide information on multiple stages of subduction zone processes: the solid products of dehydration inform us about the dehydration stage of the rocks, while rocks overprinted during the rehydration stage bear witness to fluids released from the slab in shallower regions. Tourmaline has been discovered in both dehydrated and rehydrated rocks, and, in some cases, even retains relics of the presubduction protolith.

The resistant nature of tourmaline and its capacity to grow in a variety of environments make it a unique tracer of the B geochemical cycle within subduction zones. Subduction zone tourmaline has been subdivided into three genetic types (Marschall et al. 2009): (1) premetamorphic, relict grains derived from the protolith; (2) grains formed during subduction and dehydration under increasing pressure and temperature; and (3) grains formed during exhumation and influx of metasomatic fluids. Each tourmaline type contains information on the B isotope system in subduction zones: premetamorphic grains record information about the rock composition prior to subduction; prograde and peak-metamorphic grains record isotopic fractionation during dehydration; and retrograde metasomatic tourmaline reflects fluids released from the slab at shallower depths. Using experimentally determined tourmaline–fluid B isotope fractionation factors (Meyer et al. 2008), the B isotope composition of the fluid can be derived from the B isotope composition of tourmaline. However, experimental data are limited to simple Ca–Fe-free tourmaline compositions. In detail, B isotope fractionation may depend on the major element composition of tourmaline and on the amount of tetrahedrally coordinated B present in the crystal structure (cf. Hawthorne and Dirlam 2011). Boron isotope fractionation between crystallographic sectors with contrasting compositions has been detected, and may indicate a control related to major elements and tetrahedral B on tourmaline–fluid B isotope fractionation (van Hinsberg and Marschall 2007; Trumbull et al. 2009).

Several in situ B isotope studies have demonstrated that the ^{11}B/^{10}B ratio of prograde metamorphic tourmaline decreases from core to rim, consistent with preferential loss of ^{11}B during dehydration (e.g. Nakano and Nakamura 2001). In low-grade metamorphic rocks, B is primarily hosted in clay minerals and white mica. Upon heating and decomposition of these hydrous minerals, B-bearing fluids are released, and strong isotopic fractionation between sheet silicates (enriched in ^{10}B) and hydrous fluids (enriched in ^{11}B) drives the progressively dehydrating rock to successively lower ^{11}B/^{10}B ratios. Growing tourmaline captures part of the B released along the prograde metamorphic path and can be used to estimate the B isotope composition of released fluids (Nakano and Nakamura 2001). In contrast to B sourced directly from local rocks, during retrograde

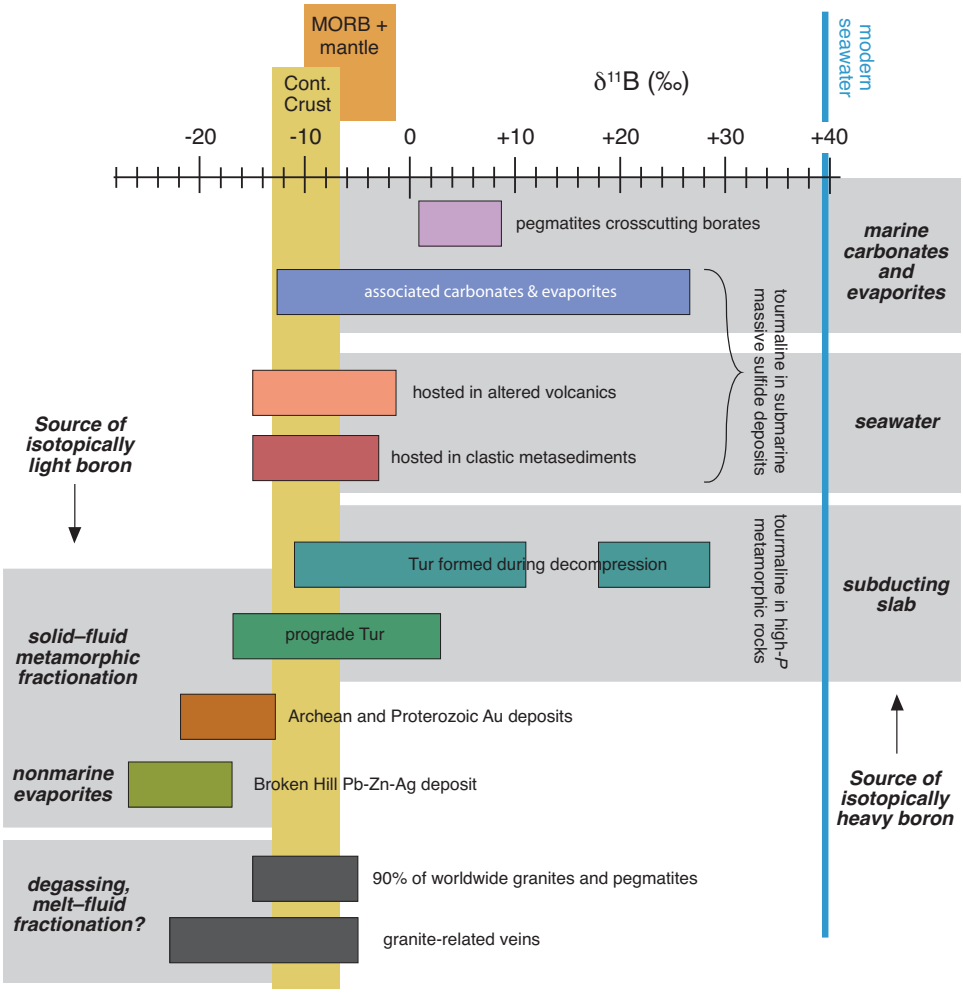

Figure 2 Measured B isotope composition as a function of host rock type (colored boxes) and inferred B sources (grey bands). Isotopically heavy B (= high δ^{11}B value) is ultimately sourced from seawater and may enter a rock via fluids or melts derived from a subducting slab or from carbonate or evaporite sequences in the crust, or directly from seawater circulating through the rocks. Isotopically light B (= low δ^{11}B value) is typically sourced from nonmarine evaporites or produced by isotopic fractionation between solids and fluids during metamorphic dehydration. Tourmaline in most granites and pegmatites shows δ^{11}B values close to average continental crust (–10 ± 3‰). Tur = tourmaline; MORB = mid-ocean ridge basalt. Modified from van Hinsberg et al. 2011b

metamorphism the B necessary to form tourmaline is typically introduced by external fluids, and these have distinctly higher $^{11}B/^{10}B$ ratios (Fig. 2).

The isotopically heavy B found in tourmaline formed from subduction-related fluids implies that ^{11}B enrichment could be used to identify subduction-related tourmaline. This hypothesis is important for studies of ancient crust, where most of the evidence of active continental margins has been lost to erosion and detrital grains in sediments may remain the sole geologic witnesses. Tourmaline is a stable detrital mineral and is relatively abundant in mature clastic sediments, forming an important source of information in provenance studies. Unfortunately, subduction-related fluids are not the sole carriers of isotopically heavy B. Tourmaline from two other geologic settings may also be enriched in ^{11}B (Fig. 2; Palmer and Slack 1989): (1) tourmaline in marine evaporites and carbonates or tourmaline formed from fluids or melts that interacted with such rocks (up to +26.5‰) and (2), less pronounced, tourmaline that formed in submarine massive sulfide deposits (up to –1.5‰). Ultimately, all these sources of isotopically heavy B are derived from seawater. In contrast, continental lithologies constitute the isotopically light part of the natural B cycle, and tourmaline formed in and around granite intrusions is typically enriched in ^{10}B, corresponding to the B isotope range of typical continental crust (Fig. 2).

The formation of tourmaline requires a local concentration of B. Tourmaline is commonly developed in sedimentary and metasedimentary rocks and in granites produced by melting of deeply buried sediments. In addition, tourmaline readily forms in crustal rocks as a result of the introduction of B-bearing hydrous metasomatic fluids derived from granitic intrusions, dehydrating metasediments, or subducting slabs. The physical and chemical robustness of tourmaline is indicative of its potential as a geochemical recorder of highly evolved continental crust. This feature may be particularly useful in the investigation of tectonic processes based strictly on the sedimentary and metamorphic record. In studies of Archean and Proterozoic crustal evolution, reliable and robust mineral recorders are of particular importance, as the rock record is very incomplete for the early eras of Earth history. While important insight has been gained from zircon and rutile, the unique advantage of tourmaline is that it contains a large number of isotope systems that can be related to highly differentiated crust, intracrustal recycling, and recycling at active plate margins.

Tourmaline tends to strongly influence our estimates of the B isotope composition of the continental crust because it is typically the dominant reservoir of B in a rock. It is a highly stable mineral, and no change in the bulk-rock B isotope composition can occur during metamorphism when no B enters or leaves the system. In tourmaline from

metamorphic rocks of increasing metamorphic grade, B isotope compositions do not vary, and partial melting in these rocks does not significantly fractionate B isotopes, as demonstrated by Kasemann et al. (2000). These authors also showed that tourmaline from metamorphic rocks and granites in the same crustal section have overlapping B isotope compositions, consistent with their estimate for the average continental crust of $\delta^{11}B = -10 \pm 3‰$ (Fig. 2).

Secular change of the B isotope composition of seawater is still largely enigmatic, but attempts to define such a change have used tourmaline. The oldest tourmaline-bearing rocks described in the literature are 3.6–3.8 Ga metasediments from Isua, West Greenland, and 3.44–3.23 Ga metasediments from the Barberton greenstone belt, South Africa (Hazen et al. 2011). Tourmaline from both localities formed on or near the seafloor during the alteration of submarine lava flows by seawater-derived hydrothermal fluids. The isotopic composition of this tourmaline was controlled by the two interacting reservoirs, i.e. the volcanic rocks and entrained seawater that fed the hydrothermal circulation. However, the B isotope composition of the tourmaline-forming fluids was likely not identical to that of seawater; rather, B was derived from and fractionated by the seafloor sedimentary and meta-igneous rocks that dominated the B budget and isotopic composition of the fluids (Byerly and Palmer 1991). Hence, fluid–rock isotopic fractionation prior to tourmaline formation hinders attempts to define the B isotope composition of Archean seawater. Still, the Isua tourmaline samples suggest that seawater has been enriched in the heavy isotope ^{11}B for at least the last 3.6 billion years.

MULTIPLE-ISOTOPE SYSTEMATICS AND FLUID SOURCES OF HYDROTHERMAL ORE DEPOSITS

Differentiation of the crust through fluid and melt migration leads to a strong enrichment of certain elements. Ore deposits are domains in the crust where enrichment of societally important elements reach a sufficient concentration to make mining operations economically viable. Because mining operations and exploration benefit from geologic guidance, knowledge of the genesis, internal structure, and spatial extent of these deposits is of direct economic importance. Tourmaline is widespread in a variety of hydrothermal ore deposits, especially massive sulfide, mesothermal gold, granite-related tin–tungsten, and uranium deposits (Slack and Trumbull 2011 this issue). Multiple-isotope systematics, extending from major (e.g. O, H, B, Si) to trace elements (e.g. Sr, Nd, Pb), have been successfully applied to the tourmaline supergroup minerals to identify likely fluid sources for, and to constrain, ore genesis.

The oxygen and hydrogen isotope compositions of tourmaline from several types of deposits, including lead–zinc massive sulfides, hydrothermal gold, and deposits in granites and pegmatites, have provided critical insights into the temperatures of tourmalinization and associated ore formation, sources of hydrothermal fluids, and genetic evolution of the deposits. Based on H–O isotope systematics of tourmaline, several different fluid sources have been identified:

1. Modified seawater for several massive sulfide deposits (e.g. Kidd Creek, Ontario; Taylor et al. 1999)
2. Metamorphic fluids for Archean and Proterozoic gold deposits (e.g. Star Lake, Rio, and Frontier, Saskatchewan; Tartan Lake, Manitoba; Big Bell, Western Australia; e.g. Ansdell and Kyser 1992; Jiang et al. 2002)
3. Granite-derived magmatic fluids for tin-rich hydrothermal veins (e.g. northwestern Tanzania; Taylor et al. 1992)

Boron isotopes also play a central role in the investigation of ore deposits. A global B isotope study conducted on tourmaline from over 40 massive sulfide deposits and associated tourmalinites (i.e. rocks with >30% tourmaline) revealed a wide range of B isotope compositions, largely indicative of the nature of the footwall lithologies (Palmer and Slack 1989). Tourmaline associated with rocks formed from marine evaporites and carbonates reflects the ^{11}B-enriched characteristic of seawater, whereas tourmaline from deposits hosted in clastic metasedimentary rocks shows relatively low $\delta^{11}B$ values, typical of continental crust (Fig. 2). Tourmaline from the Broken Hill, Australia, lead–zinc–silver ore deposit, interpreted to have been originally associated with nonmarine evaporites, has very low $\delta^{11}B$ values (Fig. 2).

Based on the silicon isotopes in tourmaline from tourmalinites of the Sullivan lead–zinc–silver deposit, British Columbia, Jiang et al. (2000) established the origin of two distinct ore-forming processes: (1) subseafloor replacement of clastic sediments by silicon from a local source (detrital clays), and (2) hydrothermal–exhalative processes with a significant hydrothermal silicon source. Tourmaline Si isotopes have also been used as an effective paleoenvironmental indicator and to define a stratigraphic horizon prospective for mineral exploration (Jiang et al. 2000). Silicon isotope ratios of rocks and minerals are not easily reset during regional metamorphism because the high Si abundance in most rocks would require massive silica exchange to significantly alter the initial isotopic composition.

Other isotopic systems and trace elements in tourmaline have been used to gather geological information. Initial Sr isotope compositions of hydrothermal fluids are recorded in tourmaline because of its strong preference for the daughter element Sr over the parent element Rb in the Rb–Sr decay system. Strontium isotope systematics have been used to trace sources of the fluids and to quantify fluid mixing in ore-forming systems (e.g. Ansdell and Kyser 1992). Tourmaline shows considerable variability in rare earth element (REE) concentrations and REE patterns, which can be used as an indicator of petrogenesis and ore genesis. The Sm–Nd isotope system and the initial Nd isotope composition of tourmaline reveal sources of REEs in the mineralizing fluids and track fluid–rock interaction (Anglin et al. 1996).

GEOCHRONOLOGY USING TOURMALINE

Knowledge of the absolute time of formation or cooling to a threshold temperature is essential to deciphering the temporal evolution of geological terranes. Dating tourmaline provides a way to link various recorded geochemical signatures to a distinct time frame. Tourmaline has a number of advantages in geochronology, such as relatively large grain size and growth zones recognizable at the microscopic or macroscopic scale. The color changes associated with differences in major and trace elements in tourmaline can be related to changing conditions, thus facilitating geochronological analytical procedures and geologic interpretations (van Hinsberg et al. 2011a). Of particular importance, tourmaline is characterized by very slow intracrystalline diffusion. This is evident from the preservation of sharp intragrain zoning in high-grade metamorphic grains (e.g. Henry and Dutrow 1996) and from experimental diffusion studies (e.g. Desbois and Ingrin 2007). Slow volume diffusion translates to a high retention of parent and daughter isotopes such that the isotopic clocks are not easily reset by subsequent thermal events. Tourmaline, therefore, can record its time of crystallization from a magmatic liquid, metasomatic fluid, and/or metamorphic event. High closure temperatures in

various isotope systems, the chemical and physical robustness of tourmaline, and its large *P–T* stability range make tourmaline a unique chronometer. Despite its apparent utility, there are a limited number of studies on tourmaline geochronology. These utilize a variety of radiogenic isotope systems, primarily K–Ar, $^{40}Ar/^{39}Ar$, Rb–Sr, Sm–Nd, and U–Th–Pb. Tourmaline samples as old as the Archean and Proterozoic and as young as the Miocene have been used in geochronology.

The most widely applied geochronologic method is $^{40}Ar/^{39}Ar$, which is based on the decay of ^{40}K to radiogenic ^{40}Ar. The challenges of this method include low K contents (typically <500 µg/g) in most common tourmalines and the possibility of incorporation of excess ^{40}Ar during tourmaline growth, which would yield erroneously old apparent ages. However, tourmaline samples with excess Ar can be recognized by disturbed Ar signals, and careful petrographic examination can eliminate tourmaline samples that have inclusions or show domains of recrystallization or dissolution–reprecipitation (see van Hinsberg et al. 2011a). Following this approach, several recent studies have obtained high-quality $^{40}Ar/^{39}Ar$ geochronologic results using tourmaline (e.g. Martínez-Martínez et al. 2010). Closure temperatures for Ar in tourmaline appear to be higher than in amphibole, based on investigations from Naxos Island (Greece), where K–Ar ages of tourmaline are indistinguishable from U–Pb crystallization ages of zircon, while K–Ar ages of amphibole and mica are ~5 and ~8 million years younger, respectively (Andriessen et al. 1991). This pattern has been interpreted in terms of cooling of the metamorphic complex, with zircon and tourmaline recording the time of peak-metamorphic temperatures of ~700°C, whereas amphibole and mica record subsequent cooling (Fig. 3). Closure temperatures for other radiogenic isotope systems in tourmaline are also considered to be high, with estimates of 580–630°C for the U–Th–Pb system and >600°C for Sr (e.g. Duncan et al. 2006).

Geochronological studies using tourmaline have been carried out on other isotopic systems. Tourmaline alone cannot be used for Rb–Sr isotope geochronology due to its generally low Rb and high Sr abundances. However, in combination with cogenetic minerals, it has been used successfully in multimineral Rb–Sr isochron geochronological studies of some ore deposits (e.g. Ansdell and Kyser 1992). The Sm–Nd isotopic system has been successfully applied to tourmaline and tourmalinites. For example, the inert nature of REEs in tourmaline preserves age information of a primary ore-related hydrothermal event and the Sm–Nd isotope system was unaffected by later metamorphic overprints (Anglin et al. 1996). Single-mineral dating of tourmaline using the Pb–Pb stepwise leaching method yielded precise ages (±0.5–3%) for Archean and Proterozoic tourmaline samples from mono- and even polygenetic hydrothermal veins (e.g. Duncan et al. 2006). The high-precision analytical facilities currently available (e.g. laser ablation multicollector ICP–MS, ion microprobe) provide the tools needed to date individual growth zones in tourmaline grains and to use contemporaneous sector zones in tourmaline for isochron dating of single grains.

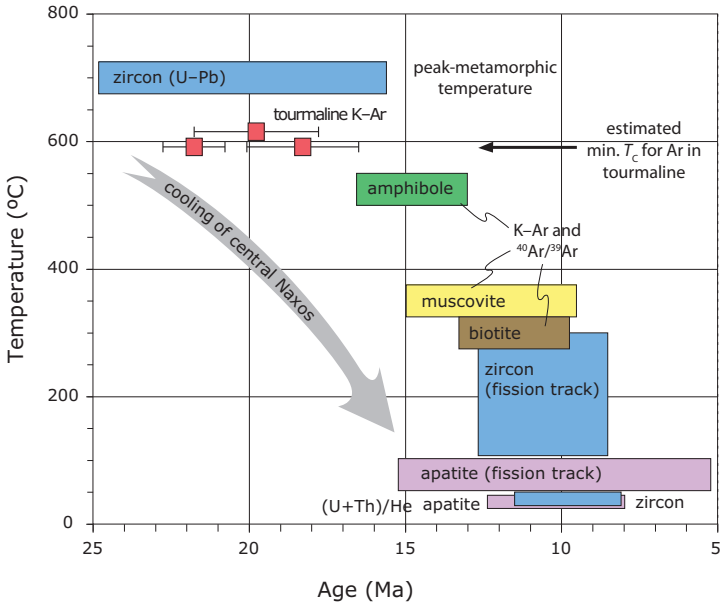

Figure 3 Temperature–time diagram for the high-grade metamorphic dome of central Naxos (Greece), displaying crystallization and cooling ages determined using different chronometers with accepted closure temperatures (data from Martin et al. 2006 and references therein). The tourmaline K–Ar ages (Andriessen et al. 1991) are in the same range as the zircon U–Pb ages and are significantly older than K–Ar and $^{40}Ar/^{39}Ar$ ages of amphibole and mica, arguing for a very high closure temperature (T_C) for Ar in tourmaline.

LITHIUM ISOTOPES, GRANITES, AND PEGMATITES

The interpretation of Li isotopes has undergone significant paradigm shifts in the last decade. Li isotope fractionation in rock–fluid–melt systems was previously assumed to be governed by equilibrium fractionation among coexisting minerals, melts, and fluids. Equilibrium stable isotope fractionation decreases with increasing temperature, and it was assumed that Li isotope fractionation would be negligible at high-grade metamorphic and magmatic temperatures. Lithium isotope compositions of minerals and rocks were, therefore, interpreted to represent the source regions of melts and fluids. However, in the course of experimental fractionation studies and analysis of natural samples, it became evident that in many natural, high-temperature geologic processes, ^{6}Li and ^{7}Li are strongly fractionated kinetically due to their different diffusivities. The lighter isotope, ^{6}Li, diffuses faster than the heavy isotope, ^{7}Li, creating transient isotopic excursions in minerals and rocks with magnitudes that far exceed those produced by equilibrium fractionation (e.g. Teng et al. 2006; Richter et al. 2009).

The amount of Li isotope data on bulk rocks and minerals from granites and pegmatites is relatively small, and the quantity of Li isotope data on tourmaline is even smaller (e.g. Ludwig et al. 2011). However, Li–B-rich granite–pegmatite systems show the following general trends: (1) the main granite bodies, which have relatively low Li concentrations, have low $\delta^{7}Li$ values, in a range typical of continental crust (0 ± 2‰); (2) pegmatites show a general increase in Li concentrations with increasing magmatic differentiation, accompanied by a rise in $\delta^{7}Li$ values; and (3) pegmatites show strong Li isotope disequilibria among coexisting minerals, such as spodumene, tourmaline, feldspar, mica, and quartz. (e.g. Teng et al. 2006; Maloney et al. 2008; Ludwig et al. 2011). This Li isotope evolution has been explained by fluid–melt separation processes in the granite–pegmatite systems and by preferential diffusive loss of isotopically light Li from the pegmatite dikes into the country rocks (e.g. Teng et al. 2006; Maloney et al. 2008). Tourmaline Li isotopes (in contrast to B isotopes) are, therefore, not suitable for tracing sources of pegmatites. However, large tourmaline crystals in pegmatites are typically chemically zoned (e.g. from schorl to elbaite) and record the chemical and isotopic evolution of the dikes. These crystals are most suitable for monitoring the Li isotope evolution of pegmatite dikes, from emplacement,

through magmatic–hydrothermal transition, to solidification and cooling (Maloney et al. 2008).

ISOTOPES IN GEM TOURMALINE

Gem tourmaline is commonly close to elbaite in composition and occurs in pegmatite dikes as comb-like layers and as crystals in miarolitic cavities and veins (Pezzotta and Laurs 2011 this issue). Prices for gem tourmaline vary by several orders of magnitude, depending not only on quality, color, and clarity, but also on provenance. The highest-quality blue Paraíba tourmaline from the Batalha mine, Brazil (the original discovery site) may demand prices of more than twenty thousand dollars per carat (1 ct = 0.2 g), whereas similarly colored stones from Mozambique or Nigeria may sell for a fraction of that price, despite similar qualities. Hence, there is a potential for fraud, and gemologists are challenged to develop effective provenance tools.

Elbaite major element compositions are variable, and all three localities show compositional overlaps such that chemistry provides no provenance criteria. Trace element abundances (e.g. Ga, Bi, Pb) have been successfully employed to distinguish Paraíba tourmaline from Paraíba-type tourmaline from Mozambique and Nigeria, but the grains show significant zoning and some compositional overlap exists between localities (Rossman 2009). Thus additional provenance tools are required. The three localities can be distinguished using B and Li isotopes (Ludwig et al. 2011). Boron isotopes of Brazilian and Mozambican samples, in particular, differ by ≥10‰ in $\delta^{11}B$ (Fig. 4), a difference that is well outside analytical uncertainties of secondary-ion mass spectrometry (SIMS), used to analyze the Li and B isotopes. Because SIMS uses a minimum of sample material, with analysis spots significantly less than 1 µm deep and ~10 µm in diameter (Fig. 1), the critical criterion in gemology of an essentially nondestructive analytical method is fulfilled by this technique.

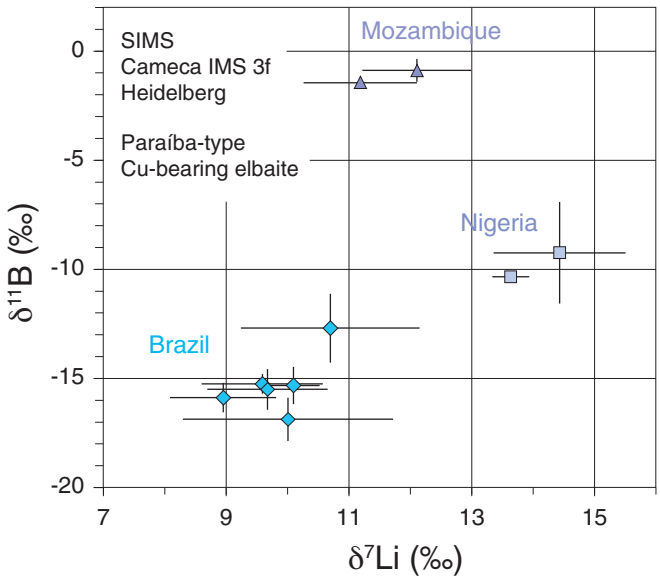

Figure 4 Lithium versus boron isotope compositions of Paraíba tourmaline (Cu-bearing elbaite) from the Batalha mine (Paraíba, Brazil) and Paraíba-type tourmaline from the Mavuco mine (Alto Ligonha pegmatite district, Mozambique) and Nigeria (after Ludwig et al. 2011). Each data point represents an individual grain; between 3 and 21 SIMS spots were analyzed on each grain (error bars are 2σ). The combination of Li and B isotope compositions enables a clear distinction among Cu-bearing elbaites from the three localities and can be employed as a provenance tool for these gems. Reproduced from Ludwig et al. (2011) with the permission of the Mineralogical Society of Great Britain & Ireland

Apart from provenance certification, a second important challenge for gemologists is the identification of gems that have been modified. Most widely applied treatments to improve color involve the heating of stones to several hundred °C and/or irradiation with gamma rays. Many of these methods are legal, but gems must be clearly labeled as "treated" and the method must be disclosed to the customer. Treatment methods, however, have become sophisticated, and gems that have been colored by diffusion techniques have recently entered the market. For example, specimens exhibiting colors that bring lower prices are packed with mixtures of oxides containing the necessary chromophores (e.g. Cu) to improve color and then pressurized and heated for several hours or days, during which time the chromophores diffuse into the gems. Tourmaline is less susceptible to this method because of its slow volume diffusion and its more limited temperature stability compared to other gems (e.g. varieties of corundum). However, small grains of tourmaline may still be treated in this way. Also, both irradiation prior to diffusion and the use of high oxygen fugacity in the diffusion setup increase the density of lattice defects, which significantly enhances diffusivities. Chemical zoning and compositional heterogeneity are common in tourmaline, and both hamper clear identification of diffusion-treated specimens. However, diffusion is a kinetic process that fractionates elements according to their relative diffusivities. Different elements diffuse at different velocities within a crystal structure, and the same is true for different isotopes of the same element, generating isotopic patterns that are distinct from those produced by equilibrium fractionation (Richter et al. 2009). For example, in situ analyses of Cu isotope ratios ($^{65}Cu/^{63}Cu$) in Cu-bearing gem tourmaline by laser ablation ICP–MS with a spatial resolution of ~200 µm revealed very large intragrain variations in $^{65}Cu/^{63}Cu$ ratios, thus allowing the stones to be identified as diffusion treated (Fontaine et al. 2010). In fact, an entire range of isotope systems could be employed to identify diffusion treatment in tourmaline and other gems, and different elements could be used to detect diffusion treatment at different temperatures and timescales.

CONCLUSIONS AND OUTLOOK

Tourmaline is typically formed from boron carried by hydrous fluids or silicate melts migrating through the continental crust in the course of tectonomagmatic processes. As tourmaline records the isotopic signature of these fluids and melts, it can be used to reconstruct sources, pathways, and interaction processes of the mobile agents. Significant progress has been made in applying tourmaline as a geochemical monitor of crustal systems, combined with precise geochronology and thermobarometry. Studies on the generation of ore deposits, on tectonic processes in orogens, on fluid and melt migration in fossil subduction zones, and on the provenance of clastic sediments have all been made possible by the unique isotopic characteristics of tourmaline supergroup minerals. However, the potential of this broadband geochemical recorder has yet to be fully exploited. Combining various isotope systems and trace element data derived from individual growth zones in tourmaline grains will provide a path forward for studies of processes in magmatic, metamorphic, and hydrothermal rocks and on detrital tourmaline in (meta)sediments.

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From GRS GemResearch Swisslab AG

Chemical Variations in Multicolored "Paraiba"-Type Tourmalines from Brazil and Mozambique: Implications for Origin and Authenticity Determination, by Adolf Peretti, Willy Peter Bieri, Eric Reusser, Kathrin Hametner, and Detlef Guenther. GRS GemResearch Swisslab AG Contributions to Gemology no. 9, May 2009, 77 pp, hardbound, ISBN 978-3-9523359-9-4, US$40

Copper-bearing tourmalines found in the state of Paraíba in Brazil in 1989 with "neon" blue color are known as "Paraíba" tourmalines. They have become one of the most valuable and sought-after gems, comparable to rubies and sapphires. New localities were subsequently found in Rio Grande do Norte in Brazil, as well as in Nigeria and in Mozambique. In 2006 GRS announced it was able to distinguish "cuprian elbaites" from different origins on the basis of chemical compositions. GRS and the Laboratory of Inorganic Chemistry and Applied Biochemistry of ETH Zurich published the results of that research in this specialized research report. This study combines the capabilities of several different analytical techniques, concentrating on the analysis of element variations within single crystals of copper-bearing tourmalines, which show pronounced color zoning and extensive chemical variability.

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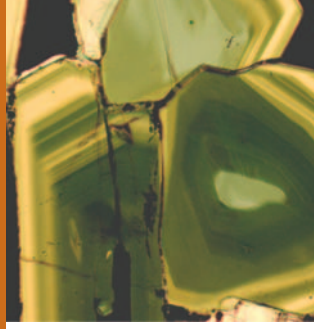
Tourmaline as a Recorder of Ore-Forming Processes



Zoned tourmaline from the Ore Knob VMS deposit, North Carolina, USA. The matrix (black) is chalcopyrite.

John F. Slack[1] and Robert B. Trumbull[2]

1811-5209/11/0007-0321$2.50 DOI: 10.2113/gselements.7.5.321

Tourmaline occurs in diverse types of hydrothermal mineral deposits and can be used to constrain the nature and evolution of ore-forming fluids. Because of its broad range in composition and retention of chemical and isotopic signatures, tourmaline may be the only robust recorder of original mineralizing processes in some deposits. Microtextures and in situ analysis of compositional and isotopic variations in ore-related tourmaline provide valuable insights into hydrothermal systems in seafloor, sedimentary, magmatic, and metamorphic environments. Deciphering the hydrothermal record in tourmaline also holds promise for aiding exploration programs in the search for new ore deposits.

KEYWORDS: tourmaline, ore deposits, hydrothermal, compositions, isotopes

TOURMALINE IN HYDROTHERMAL ORE DEPOSITS

Tourmaline is a common mineral in many types of hydrothermal ore deposits from diverse tectonic settings (FIG. 1). Two broad categories of hydrothermal deposits are recognized: (1) those that formed by "epigenetic" processes in which mineralization was superimposed on preexisting rocks in veins, breccias, or replacements (FIGS. 2, 3, 4); and (2) "syngenetic" deposits in which ore minerals formed during the deposition of sedimentary or volcanic host rocks. Within the epigenetic category are porphyry Cu ± Mo deposits, Cu–Au breccia pipes, and Sn–W veins in or near granitoid intrusions; orogenic Au–quartz veins in greenschist and amphibolite facies metamorphic rocks and Au–quartz–sulfide veins in these rocks near granitoid intrusions; and iron oxide–copper–gold (IOCG) deposits in a variety of continental settings. The syngenetic category mainly comprises sedimentary-exhalative (SEDEX) Zn–Pb–Ag deposits and volcanogenic massive sulfide (VMS) Cu–Zn–Pb–Ag–Au deposits, both of which form in seafloor settings (FIG. 1). These diverse deposit types cover a broad spectrum of chemical environments and pressure–temperature conditions, from oceanic to deep crustal (Hedenquist et al. 2005), and the fact that tourmaline occurs in each is testament to its wide stability range (Dutrow and Henry 2011 this issue). As we explore in this article, tourmaline has the ability to preserve textural, chemical, and isotopic features that reveal considerable detail about the hydrothermal system in which it formed. Not discussed here are tourmalines in magmatic rare-metal deposits (Li, Cs, Ta) and gem varieties in pegmatites (see van Hinsberg et al. 2011 this issue; Pezzotta and Laurs 2011 this issue).

The formation of hydrothermal tourmaline requires the fortuitous convergence of complex processes: derivation of boron and other essential elements from one or more sources; transport in fluids of diverse provenance (magmatic-derived, metamorphic, basinal or evaporitic brines, heated meteoric water, evolved seawater); and finally precipitation in settings and conditions that may coincide with the deposition of economically valuable metals. In favorable cases, constraints on *P*–*T*–*X* conditions (where *P*, *T*, and *X* are pressure, temperature, and fluid composition, respectively) of hydrothermal fluids can be obtained by measurements of primary fluid inclusions in mineral hosts, such as quartz, or estimated from isotope fractionation data or chemical equilibria among the associated minerals. However, many deposits have a polyphase history, and for these, primary fluid inclusions, mineral parageneses, and isotope compositions commonly are masked or destroyed by post-ore hydrothermal, tectonic, or metamorphic events. If not recrystallized, tourmaline may be the only robust recorder of original hydrothermal processes in such ore deposits. Documenting the hydrothermal record in tourmaline is important for furthering our understanding of mineralizing processes and can potentially aid in the exploration for new ore deposits.

The past decade has witnessed major progress in the use of tourmaline in ore research on two fronts. The first is the assembly of a growing geochemical database on tourmaline from diverse hydrothermal settings (Slack 2002). This database includes major elements determined by electron microprobe (EMP) analysis and, for some deposits, trace elements and stable isotopes (B, O, H, Si) measured on tourmaline separates. The second is the increased use of secondary ion mass spectrometry (SIMS) for in situ boron isotope analysis of hydrothermal tourmaline (following the early work of Smith and Yardley 1996), and a much-improved understanding of boron isotope systematics in geologic systems (Marschall and Jiang 2011 this issue). These advances have opened a new window on provenance and fluid evolution in ore deposits (e.g. Jiang et al. 2008; Trumbull et al. 2011).

The potential of in situ techniques for determining element and isotope compositions in tourmaline has by no means been fully exploited. For example, there are surprisingly few studies of ore-metal concentrations in tourmaline, although trace element analysis for Cu, Zn, Pb, Sn, etc. can be made with high precision at very low detection limits (<10 ppm) by laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS). Moreover, because

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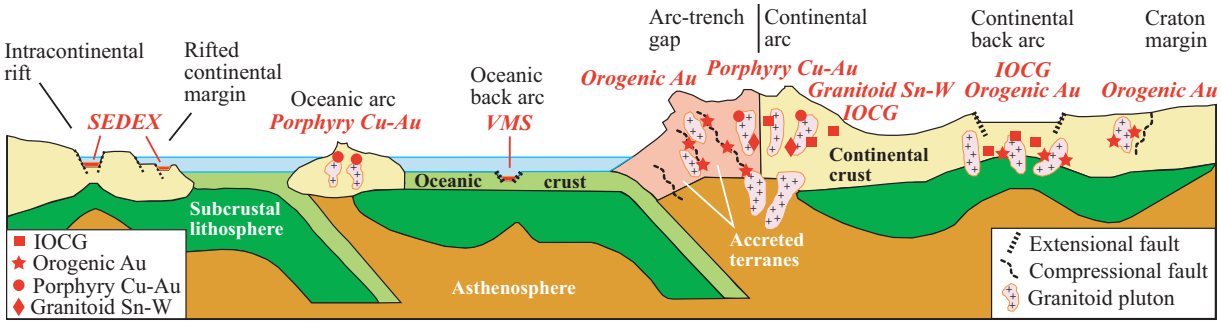

FIGURE 1 Schematic diagram showing tectonic settings of tourmaline-bearing hydrothermal ore deposits. Abbreviations: SEDEX, sedimentary-exhalative; VMS, volcanogenic massive sulfide; IOCG, iron oxide–copper–gold. MODIFIED FROM GROVES ET AL. (2005)

tourmaline is a hydrous mineral, it would be valuable to expand SIMS studies to include oxygen and hydrogen as well as boron isotope ratios (Trumbull et al. 2010).

GENETIC LINKS TO ORE DEPOSITION

An important precondition for the use of tourmaline as an aid in understanding ore formation is a clear temporal link between the deposition of tourmaline and ore minerals. Close spatial associations, even on the scale of a thin section, can be misleading because many ore deposits form by multistage processes involving different paragenetic stages and different fluids. Tourmaline may form in one or more stages that predate or postdate ore deposition. For example, tourmaline in diverse types of granitoid-related hydrothermal deposits commonly formed prior to the ore minerals, as shown by textural analysis (e.g. Frikken et al. 2005). However, detailed paragenetic studies have demonstrated contemporaneous tourmaline deposition and ore mineralization in many orebodies, such as the Batu Hijau porphyry Cu–Au deposit in Indonesia (Garwin 2002), the San Rafael Sn–Cu vein deposit in Peru (Mlynarczyk and Williams-Jones 2006), the Sigma, Big Bell, and Mount Gibson orogenic Au–quartz vein deposits in Québec and Western Australia (Garofalo et al. 2002; Jiang et al. 2002), the Kidd Creek Cu–Zn–Pb–Ag VMS deposit in Ontario (Slack and Coad 1989), the Broken Hill Pb–Zn–Ag SEDEX deposit in Australia (Slack et al. 1993), and the Igarapé Bahia Au–Cu–REE–U IOCG deposit in Brazil (Dreher et al. 2008). Some VMS and SEDEX deposits also have associated stratabound tourmaline-rich rocks (tourmalinites; >30 vol% tourmaline) that occur in the hangingwall and/or footwall of the orebodies, or along strike at the same stratigraphic level (FIG. 5).

COMPOSITIONAL AND ISOTOPIC ZONING

An overview of within-grain compositional variations in tourmaline from hydrothermal ore deposits and their implications deserves its own richly illustrated monograph. For lack of space, we focus here on a few examples where compositional zoning combined with in situ chemical and/or stable isotope data provide information with which to decipher ore-forming processes.

Concentric growth zoning is only one of several distinct patterns of internal variations reported in tourmaline. Meaningful interpretation of compositional differences can depend critically on recognizing what the "zoning" represents. The principal types of tourmaline zoning that may be found in hydrothermal ore deposits are:

1. Concentric growth zoning resulting from compositional changes in the growth medium, not uncommonly rhythmic (FIG. 6A)
2. Hourglass (sector) zoning, a variety of growth zoning, where the polar properties of the tourmaline lattice cause selective partitioning of elements—and isotopes—into opposite poles
3. Irregular, patchy variations in composite grains or clusters of anhedral tourmaline subgrains; common in recrystallized ("healed") brecciated tourmaline
4. Overgrowth or replacement zoning that can occur in stratabound deposits, in which hydrothermal tourmaline encloses older detrital grains. In cases of discontinuous or multistage tourmaline growth, late material may be deposited on (or cut) preexisting crystal faces or fill cracks within fractured grains (FIG. 6A, 6B).

One example of chemical and isotopic zoning of tourmaline is in the shear zone–hosted Jaduguda U–Cu deposit in India (Pal et al. 2010). In this deposit, two-stage tourmaline

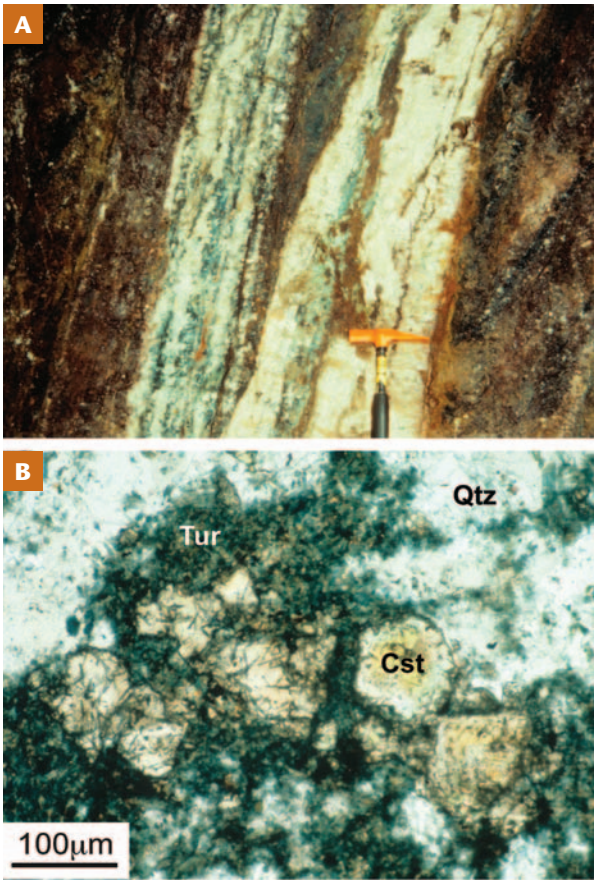

FIGURE 2 (**A**) Cassiterite-bearing quartz–tourmaline vein (left-center), Geevor tin mine, Cornwall, England. (**B**) Fine-grained tourmaline intergrown with zoned cassiterite and quartz, South Crofty tin mine, Cornwall. Abbreviations: Cst, cassiterite; Qtz, quartz; Tur, tourmaline. PHOTOS BY D. A. C. MANNING

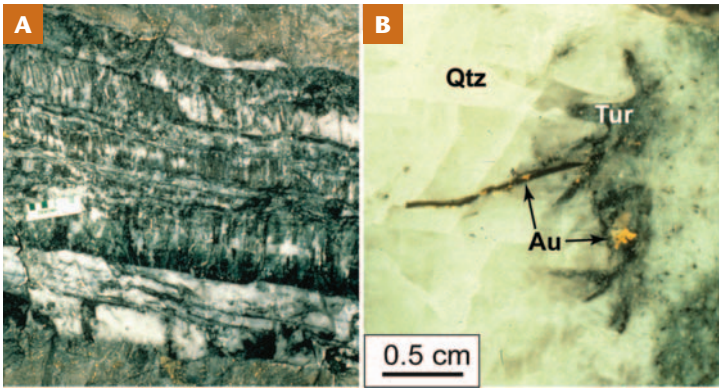

Figure 3 (**A**) Multistage gold-bearing quartz–tourmaline extension vein, Sigma gold mine, Québec (scale is in centimeters). (**B**) Gold grains (yellow) intergrown with tourmaline (black) in quartz gangue, Sigma mine. Abbreviations: Au, gold; Qtz, quartz; Tur, tourmaline. Photos by F. Robert

growth records a shift from host-rock to fluid control (Fig. 7). Paragenetically early tourmaline from different sample types shows distinctive chemical differences that reflect the local host-rock composition. In contrast, second-stage tourmaline, which is related to the main ore-forming event in shear zones, displays a narrow compositional range due to a high fluid flux within the shear zones. The early and late tourmalines in this case also have contrasting boron isotope compositions (Fig. 7c), which is consistent with the shift from a dominance of locally derived (host-rock sourced), isotopically heavy boron to a distally sourced, isotopically lighter boron as mineralizing fluids were channeled along the shear zone.

INSIGHTS INTO HYDROTHERMAL PROCESSES

Compositional and stable isotope data from ore-related tourmaline can reveal valuable details of hydrothermal ore-forming processes, including fluid mixing and boiling, redox states, temperature and pressure conditions, and fluid provenance. The use of such data is limited if assumptions of equilibrium between the hydrothermal fluid and tourmaline, or between tourmaline and coexisting phases, cannot be justified. Other limitations involve recrystallization of tourmaline by hydrothermal or metamorphic events, which may erase any preexisting growth zoning, resulting in compositions that are appropriate for the new *P*–*T*–*X* conditions but differ from those during mineralization. Deformation can also produce compositional modification by causing chemical diffusion between and among growth zones (Büttner and Kasemann 2007). Stable isotope systematics of B, O, and H in tourmaline are commonly preserved through deformation and recrystallization, but not during high-fluid-flux events (Marschall and Jiang 2011). Despite these caveats, geochemical and isotopic studies of tourmaline using well-characterized samples that contain primary tourmaline crystals have proven valuable in constraining several key parameters, as outlined below.

Fluid Properties

The precipitation of ore metals and the paragenesis and composition of ore and gangue mineral assemblages in many ore deposits are controlled by diverse features of the hydrothermal system, including fluid flux, fluid composition, fluid mixing, and boiling. Tourmaline is an excellent monitor of such features as its composition is governed largely by those of the fluid and/or wall rocks and by chemical equilibria with coexisting phases. In low fluid/rock systems, represented by stratabound tourmaline-rich rocks (tourmalinites) like those in the Broken Hill district of Australia (Fig. 5), tourmaline chemistry is mainly controlled by the bulk composition of argillaceous sedimentary protoliths (Slack 2002). Protolith controls are strong in cases where ferromagnesian minerals are selectively replaced by tourmaline. In high-fluid-flux systems, such as those in breccia pipes, shear zones, veins, and feeder zones of seafloor-hydrothermal deposits, tourmaline chemistry is generally buffered by the fluid phase. A good example of the latter is shown by the Kidd Creek VMS deposit, where tourmaline displays a range of compositions, from schorl (Na–Fe^{2+}-rich) to near dravite (Na–Mg-rich) (Fig. 8); this range of composition is interpreted to mainly record subseafloor mixing of Fe-rich hydrothermal fluid and Mg-rich seawater (Slack and Coad 1989). This fluid-mixing model is further supported by oxygen, hydrogen, and boron isotope systematics in Kidd Creek tourmaline (Taylor et al. 1999). Modeling of isotope variations in that study also suggests that boiling occurred in the hydrothermal system prior to ore deposition. Boiling is an important mechanism for metal precipitation in many ore deposits, and in some cases it can also lead to tourmaline formation by increasing the concentration of $B(OH)_3$—the major B species in hydrothermal fluids—within the residual liquid (Lynch and Ortega 1997).

Redox State

Ferric/ferrous ratios in ore-related tourmaline serve as a monitor for changes in the redox state of hydrothermal fluids, which in turn can be a trigger for ore deposition. Fluid oxidation related to ore deposition is recorded by variations in Fe^{3+}/Fe^{2+}, such as in tourmaline from Sn–Cu veins at San Rafael, Peru (Mlynarczyk and Williams-Jones 2006). Textural and analytical work in that study underpinned a model in which influx of meteoric waters into the vein system produced late oxidation of hydrothermal fluids, precipitation of Fe^{3+}-rich tourmaline, and initiation of cassiterite deposition (see also Williamson et al. 2000). Tourmaline in some porphyry Cu ± Mo deposits also likely formed from oxidized fluids, based on EMP data documenting Al-poor compositions and inverse Al–Fe correlations that imply significant Fe^{3+} in the tourmaline (Slack 2002). More detailed studies, including Mössbauer determinations of Fe^{3+}/Fe^{2+}, are needed for evaluating redox changes

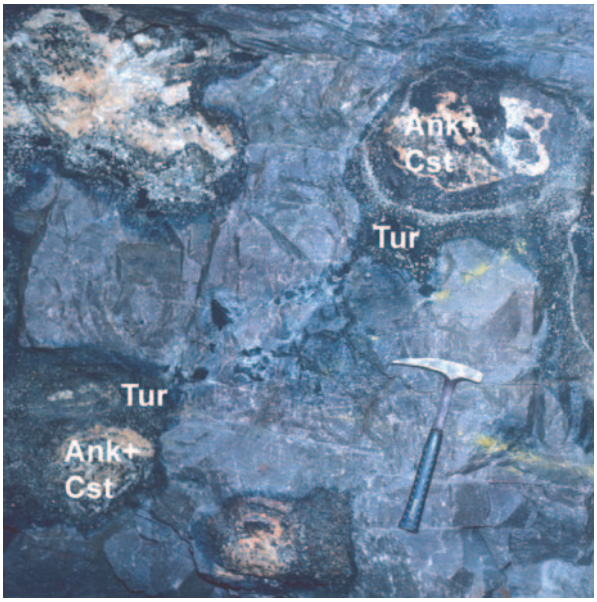

Figure 4 Zoned tourmaline–ankerite–cassiterite orbicules (replacements) in dark arkose, Rooiberg tin mine, South Africa. Abbreviations: Ank, ankerite; Cst, cassiterite; Tur, tourmaline. Photo by F. Pirajno

Figure 5 Layered quartz–tourmaline tourmalinite in the Broken Hill district, Australia, from the same stratigraphic level as the main Pb–Zn–Ag lodes

during the formation of tourmaline-bearing ore deposits and the influence of such changes on metal concentration.

Temperature Conditions

Tourmaline has been used in several ways to constrain mineralizing temperatures. Fluid inclusion microthermometry, the most obvious method, has seen limited application because primary inclusions in hydrothermal tourmaline appear to be uncommon and, where present, are generally small (<5 µm; Skewes et al. 2003; Frikken et al. 2005) and difficult to study. Some deposits, however, contain abundant large primary fluid inclusions in tourmaline that provide useful microthermometric data (Ootes et al. 2010). Other workers have used oxygen isotope fractionations in coexisting tourmaline–quartz pairs for geothermometry, an approach that has proven fruitful even for moderately deformed and metamorphosed deposits such as Kidd Creek (Taylor et al. 1999). Data from fluid inclusions, stable isotopes, and mineral assemblages indicate a temperature range for tourmaline precipitation in hydrothermal ore deposits, from ~150–300 °C in seafloor base metal deposits (VMS and SEDEX) to at least 450 °C in granitoid-related Cu ± Mo deposits. Tourmaline also forms from higher-*T* (350–550 °C) and high-*P* metamorphic fluids in orogenic Au–quartz vein deposits, under greenschist to amphibolite facies conditions (see Jiang et al. 2002).

In theory, geothermometry using boron isotope fractionation between tourmaline and coexisting B-bearing hydrothermal minerals, such as white mica, biotite, or amphibole, should be feasible but remains untested. Mineral-exchange geothermometry of tourmaline and coexisting phases is complicated by intersite partitioning within the tourmaline, but there is promise for a new method that utilizes partitioning of Ca and Ti between opposing sectors of hourglass-zoned crystals to yield temperatures of tourmaline formation (van Hinsberg and Schumacher 2011). This method has two possible limitations for studies of ore deposits: (1) the required hourglass zoning may be uncommon in hydrothermal tourmaline, and (2) the method has not been calibrated for temperatures less than ~350 °C, meaning that it may be relevant only for higher-*T* ores such as those in porphyry Cu ± Mo deposits, orogenic Au–quartz veins, and IOCG deposits.

Fluid Provenance

Isotopic data from tourmaline yield an important record of fluid sources in hydrothermal ore deposits. Less useful in this regard is major element chemistry, which commonly reflects compositions of the local hydrothermal fluid, precursor minerals, or wall rocks. Thus, fluid provenance generally is poorly indicated by data for major cations, although trace element contents can be useful (Griffin et al. 1996). Insights are best provided by stable isotope data, especially from boron isotopes, which in many cases can discriminate among diverse B reservoirs, including crustal, granitic, sedimentary, volcanic, seawater, basinal brine, marine evaporitic, and nonmarine evaporitic reservoirs (Marschall and Jiang 2011). Boron isotope studies of ore-related tourmaline have been crucial in identifying major fluid components that were derived from evaporite-bearing sequences, including nonmarine evaporites at the giant Broken Hill Pb–Zn–Ag deposit (Slack et al. 1993) and marine evaporites at the giant Carajás IOCG deposits (Xavier et al. 2008). Tourmaline B isotope compositions can also readily distinguish between B sources from continental versus marine protoliths. Granites, felsic gneisses, and schists have isotopically light compositions ($\delta^{11}B < -5‰$), whereas metabasites, MORB, altered oceanic crust, and marine sediments have higher $\delta^{11}B$ values (Marschall and Jiang 2011). This distinction is generally sufficient to demonstrate, or rule out, a granitic origin for associated ore deposits (e.g. Garda et al. 2009; Trumbull et al. 2011). However, it is rarely possible to identify more specific source lithotypes within these two broad categories, partly because a number of processes related to fluid evolution and tourmaline precipitation fractionate B isotopes

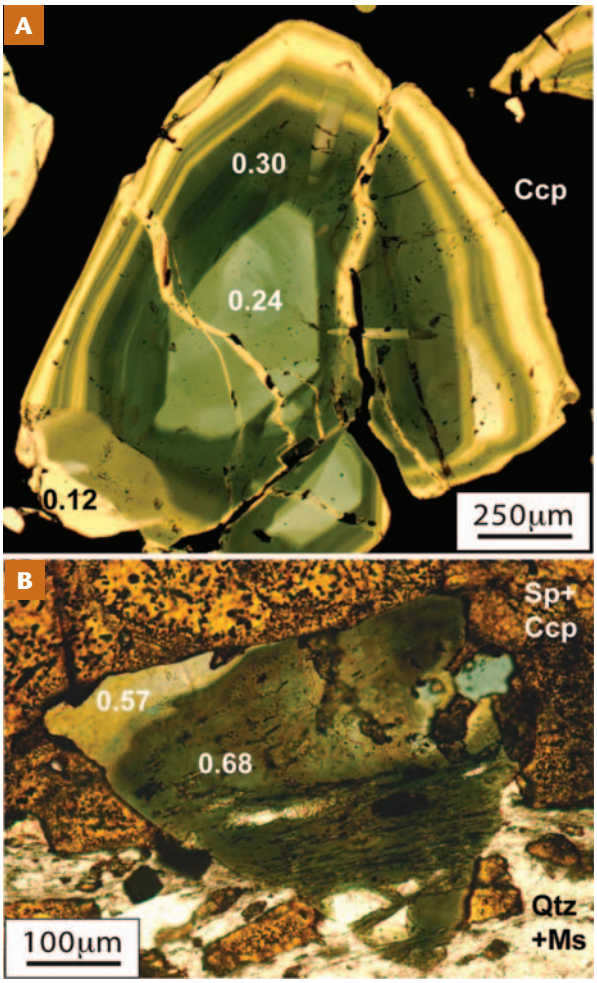

Figure 6 (**A**) Oscillatory growth zoning and discordant reaction rims in dravite, Ore Knob VMS deposit, North Carolina; note crosscutting dravite veinlets (yellow). (**B**) Pale discordant metamorphic reaction rims on schorl, Kidd Creek VMS deposit, Ontario. Values are Fe/(Fe+Mg) ratios determined by EMP (Taylor and Slack 1984; Slack and Coad 1989). Abbreviations: Ccp, chalcopyrite; Qtz, quartz; Ms, muscovite; Sp, sphalerite (in B, the black inclusions in yellow sphalerite grains are chalcopyrite).

and thus modify the source signal. In principle, these processes can be recognized and their effects accounted for, but doing this requires independent constraints on temperature and fluid composition. Valuable as they are, boron isotope data work best when combined with data from other stable isotope systems. Additional insights into hydrothermal processes have come from Sr and Nd isotopes in ore-related tourmaline (Slack 2002) and from Si isotopes (Marschall and Jiang 2011).

Tourmaline Geochronology

Tourmaline can be dated directly by a variety of radiometric methods, including Rb–Sr, Sm–Nd, Pb–Pb, K–Ar, and $^{40}Ar/^{39}Ar$. Analyses of mineral separates by these methods yield meaningful results when the effects of mineral inclusions are carefully considered or eliminated. For example, robust Pb–Pb ages of metamorphic tourmaline in the Mount Isa Inlier of Australia were obtained by Duncan et al. (2006) using sequential step-leaching and LA–ICP–MS analyses. Especially promising is the application of high-precision $^{40}Ar/^{39}Ar$ dating (e.g. Martínez-Martínez et al. 2010), if potential problems of low K contents and excess ^{40}Ar in tourmaline can be addressed. The use of tourmaline geochronology in ore deposit studies is not yet fully explored but has the potential to provide critically needed ages of mineralization for orebodies that, otherwise, lack suitable minerals for dating.

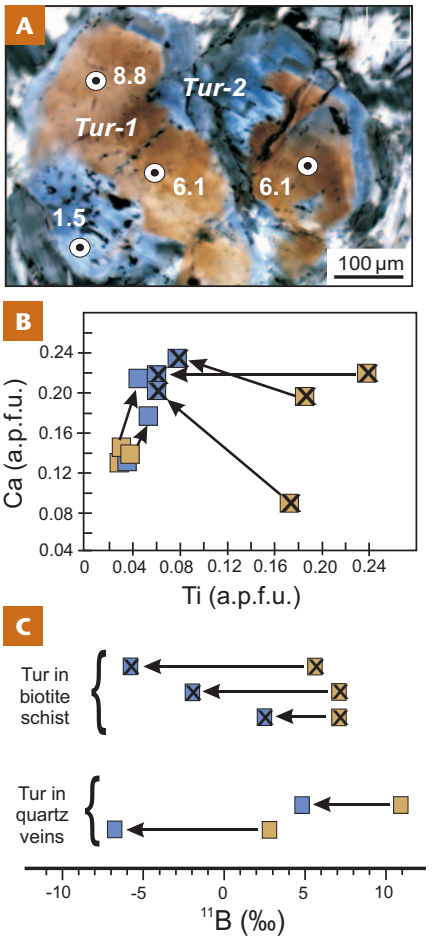

Figure 7 Two-stage tourmaline growth in the shear zone–hosted Jaduguda U-Cu deposit, India (Pal et al. 2010). (**A**) Cores of brown tourmaline (Tur-1) rimmed and partly replaced by blue tourmaline (Tur-2); dots locate SIMS analyses and numbers give $\delta^{11}B$ values. (**B**) Chemical zoning is interpreted to reflect a shift from host-rock control for Tur-1 (wide range of Ti, Ca) to fluid control for Tur-2 (narrow range). (**C**) Fluid-controlled Tur-2 is isotopically lighter than Tur-1; the isotopic shift is observed in both vein-hosted and schist-hosted tourmaline.

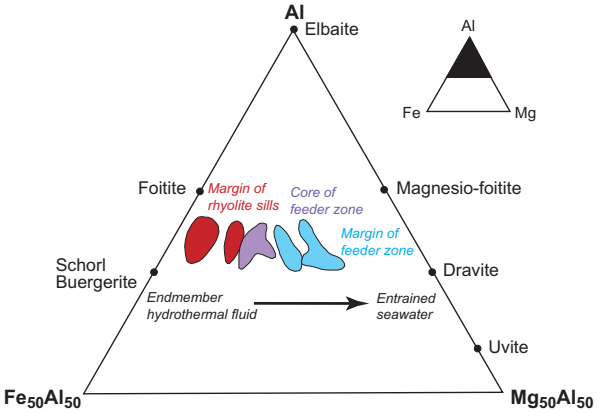

Figure 8 Large compositional range in ore-related tourmaline from the Kidd Creek VMS deposit, Ontario, due to mixing of Mg-rich seawater with Fe-rich hydrothermal fluid (modified from Slack and Coad 1989). Each field represents data for a single sample, based on ca 25 EMP analyses. The restricted compositional variation for each sample, together with the large overall range (for VMS deposits), indicate control on tourmaline composition by the hydrothermal fluids and not the host rocks. The trends in two samples toward dravitic compositions reflect post-ore overprints by sulfide–silicate reactions during metamorphism.

EXPLORATION APPLICATIONS

Early workers considered the empirical association of tourmaline with diverse types of ore deposits as a simple, first-order prospecting guide. Studies in the 1990s, and later, demonstrated that hydrothermal tourmaline has a large range of major element compositions and that a strong control was exerted in many deposits by the compositions of precursor minerals and wall rocks that were selectively tourmalinized during B metasomatism (Slack 2002). Thus, special care must be taken in using major element data on tourmaline in mineral exploration programs because such data do not necessarily record a hydrothermal signature. Nevertheless, some generalizations are warranted. In granitoid-related ore deposits, tourmaline compositions typically evolve from schorl in magmatic assemblages toward dravite (with or without a povondraite [$Na–Fe^{3+}$-rich] component) in hydrothermal assemblages. Dravite predominates in VMS and most SEDEX systems, owing to the influence on tourmaline composition of Mg-rich seawater during subsurface fluid mixing and to later sulfide–silicate reactions between tourmaline and iron sulfide minerals (pyrite, pyrrhotite) during post-ore metamorphism (Slack 2002). Identifying an appreciable povondraite component may have exploration applications because this appears to form preferentially from highly saline fluids (van Hinsberg et al. 2011). Such fluids are critical in forming rich porphyry, SEDEX, and IOCG deposits because the high salinities permit greater concentrations of aqueous metal-chloride complexes to be carried in the hydrothermal fluids. Identification of such high-salinity fluids can also be done by modeling B and H isotope data from tourmaline, as shown by Taylor et al. (1999) for the Kidd Creek VMS deposit.

A promising approach for mineral exploration is the use of trace elements in tourmaline. Griffin et al. (1996) acquired in situ trace element data on tourmaline from VMS and SEDEX deposits and from stratabound tourmalinites using a proton microprobe (PIXE). They found broad Zn–Fe correlations that suggest chemical control on Zn contents by temperature or fluid–mineral equilibria, and Cu–Zn–Pb signatures in the tourmalines that broadly match those of the associated ore deposits. Furthermore, these signatures were not destroyed by post-ore metamorphism, enhancing utility of the trace element data for exploration. Development in the early 1990s of the LA–ICP–MS method for in situ analysis of a wider suite of trace

elements in minerals offers exciting potential for improved understanding of tourmaline formation in hydrothermal systems and its use as an exploration guide. This technique can provide rapid multielement analyses at low detection limits, yielding a wealth of trace element data that will likely further enhance tourmaline applications in the exploration for new ore deposits.

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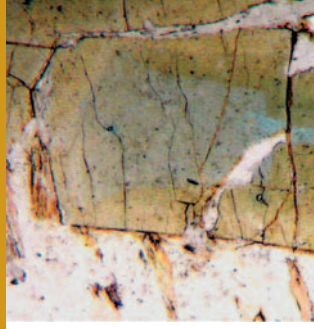
Tourmaline as a Petrologic Forensic Mineral: A Unique Recorder of Its Geologic Past



Photomicrograph of an hourglass sector zoned tourmaline in a metapelite (blue +**c** sector, brown –**c** sector and yellow *a* sector)

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Tourmaline is nature's perfect forensic mineral. From a single grain, the full geological past of its host rock can be reconstructed, including the pressure–temperature path it has taken through the Earth and the changing fluid compositions it has encountered. Tourmaline is able to provide this record owing to its compositional and textural sensitivity to the environment in which it grows, and is able to preserve this record because element diffusion in its structure is negligible. Furthermore, tourmaline has an exceptionally broad stability range, allowing it to record conditions in igneous, sedimentary, metamorphic, and hydrothermal settings. As our mineralogical and geochemical tools advance, we are able to interrogate tourmaline's memory with increasing precision, making tourmaline a truly powerful indicator of conditions in the Earth.

KEYWORDS: tourmaline, petrogenetic indicator, compositional zoning, growth history

INTRODUCTION

Tourmaline has precisely the characteristics of a forensic mineral: it is widespread, occurring in most rock types; it is stable over a significant portion of the pressure (P)–temperature (T)–composition (X) space of the crust (Dutrow and Henry 2011 this issue); its crystal structure accommodates an exceptional range of geochemically different elements (Hawthorne and Dirlam 2011 this issue); its (trace) element and isotopic compositions are responsive and reflective of physical and chemical conditions encountered and of element source-reservoirs (e.g. Marschall and Jiang 2011 this issue; Slack and Trumbull 2011 this issue); and it shows negligible intracrystalline element diffusion over geologic time, even at temperatures in excess of 600°C (van Hinsberg et al. 2011). Because of these characteristics, tourmaline records a signature of the conditions and chemistry of its environment, in an extraordinary range of settings within the Earth, and, most crucially, preserves this signature for later interrogation. Moreover, tourmaline grains are commonly growth-zoned, and this "memory" is recorded and stored for the full growth history of the grain, just as tree rings store information about the tree's environment during its growth. Unconformities can develop in this record, when growth stalls for lack of boron (B) or growth zones are eroded away, but these can be informative as well (e.g. van Hinsberg and Schumacher 2011).

The primary microstructures and compositions of tourmaline are commonly well preserved, even when grains are weathered from their parent rocks and transferred to sediment. When these are properly interpreted, they provide robust evidence that tracks the mineral's formation and modification by igneous, sedimentary, and metamorphic processes. In this article, we explore a hypothetical record of a single, multigenerational tourmaline grain and illustrate how tourmaline can record geologic information in igneous, sedimentary, and metamorphic settings (FIGS. 1, 2). This "tourmaline construct" provides a framework for discussion of tourmaline formation and modification in these varied geologic settings.

TOURMALINE IN IGNEOUS ROCKS

Many tourmalines begin "life" in the geologic record as crystallization products of an igneous melt. The most common tourmaline-bearing igneous rocks are those that have undergone significant chemical fractionation, because boron, an essential constituent of tourmaline, behaves incompatibly in igneous systems and is therefore highly enriched in fractionated melts (e.g. London et al. 1996). Tourmaline is most important in silicic and peraluminous volcanic and plutonic rocks, such as rhyolites, granites, granitic pegmatites, and nodular granites. If these rocks are derived from the melting of metasedimentary material, which is commonly enriched in B compared to average crust, tourmaline may occur in substantial modal amounts.

Tourmaline displays a myriad of morphologies in igneous deposits, from beautiful faceted prisms (e.g. Pezzotta and Laurs 2011 this issue), to skeletal grains, to interstitial masses, and to mineral fibers. These shapes reveal the timing and style of tourmaline growth in the melt. Commonly, tourmaline forms late in the crystallization history of the magma, and its growth may be rapid owing to the enhanced concentration of boron and water in the residual melt.

Chemically, igneous tourmaline tracks the composition and mineral assemblage of its host magma. Therefore, it provides a first-order approximation of the composition of the magma from which it nucleated, including changes in major components such as Fe, Mg, and Mn (e.g. Jolliff et al. 1986). Tourmaline in intermediate igneous rocks generally has compositions that are Na-rich and intermediate in Fe and Mg contents, e.g. schorl and dravite, whereas tourmaline crystallized in moderately fractionated granitic rocks tends to be Fe-rich (i.e. schorl and foitite; see nomenclature in Hawthorne and Dirlam 2011). With increased fractionation, tourmaline gets enriched in Li, so that in

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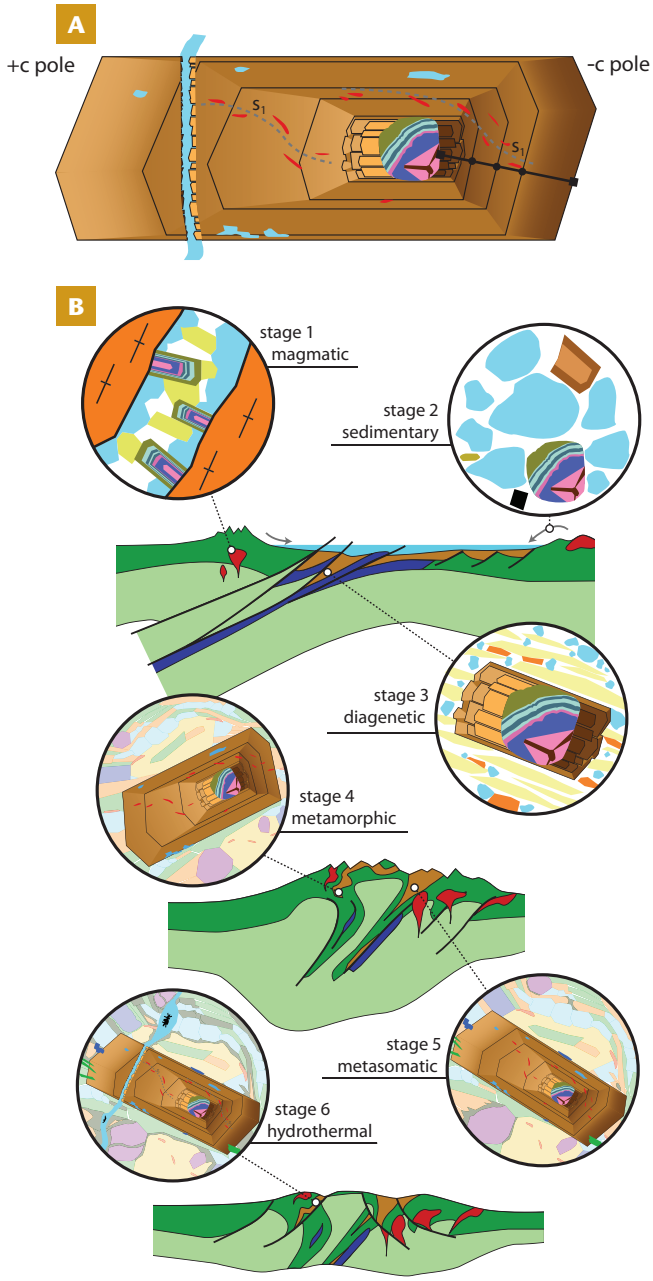

Figure 1 (**A**) Schematic drawing of an "idealized" multigenerational tourmaline that encountered various geologic processes and environments (see Figure 1B). From the inside outward, the grain contains: a rounded detrital core that formed by crystallization from a melt; asymmetric diagenetic overgrowths with preferred growth towards the +**c** pole; metamorphic and metasomatic zones overgrowing an internal foliation (S_1) marked by inclusions; and a fracture sealed by hydrothermal growth on the fracture surfaces. Polar growth and hourglass sector zoning are marked by color shading. The heavy black line marks the transect described in Figure 2. (**B**) Geologic settings for growth of the tourmaline grain shown in A. These are: magmatic setting (stage 1) with subsequent weathering (stage 2); diagenetic growth on relict grains in a sedimentary basin (stage 3); prograde metamorphic growth (stage 4); retrograde metasomatic growth owing to input of boron in fluids from a cooling pluton (stage 5); and growth in extensional brittle fractures associated with ore formation (stage 6).

highly differentiated pegmatites, the Li species elbaite, fluor-liddicoatite, and rossmanite are characteristic. Tourmaline is most common in the B-enriched Li–Cs–Ta family of pegmatites and occurs more rarely in Nb–Y–F pegmatites (e.g. London 2008). Volatile-rich, commonly late-stage cavities in pegmatites can contain gem varieties (see Pezzotta and Laurs 2011).

Because the environment continuously changes in a differentiating magmatic system, tourmaline commonly exhibits well-developed color and compositional growth zoning, in addition to sector zoning (Fig. 1B stage 1; Figs. 2, 3; Hawthorne and Dirlam 2011). Chemical transects across such zoned grains provide a record not only of the evolving melt composition but also of dissolution/precipitation events and changes in alkalinity, fluorine content, and redox state of the melt and associated fluid (e.g. Dutrow and Henry 2000; London 2008).

The late-stage hydrothermal fluids associated with many igneous plutonic rocks are enriched in B and can infiltrate the surrounding host rocks. This influx of boron may cause tourmaline to form, creating tourmaline-rich rocks at the margins of igneous bodies and in their country rocks. Such fluids proximal to igneous bodies can be highly oxidized, yielding tourmaline with a significant proportion of Fe^{3+} (e.g. povondraite), and they are associated with many types of ore deposits (Slack and Trumbull 2011). Metasomatic tourmaline generally exhibits fine-scaled oscillatory zoning and typically displays a hybrid composition that reflects reaction between the host rock and a B-bearing fluid phase. One can commonly determine the relative contributions of the host rock and fluid to these metasomatic tourmalines from their isotopic and trace element compositions, as well as reconstruct changes in these contributions over time. Tourmaline thus tracks the evolution of magmatic–hydrothermal systems, and it will retain this information despite separation from its site of crystallization by weathering.

TOURMALINE IN SEDIMENTS AND SEDIMENTARY ROCKS

Tourmaline as a Detrital Mineral and Provenance Indicator

The exceptional mechanical and chemical stability of tourmaline makes it highly resistant during weathering. Once exposed to surface conditions, tourmaline can be disaggregated from its igneous, metamorphic, or sedimentary parent rock to become a clastic component in sediment. Together with zircon and rutile, tourmaline is one of the most durable heavy minerals in sedimentary environments.

Tourmaline in sediment retains the signature of its original host rock (Fig. 1A, 1B stage 2) and has, therefore, long been a provenance indicator in clastic sedimentary rocks. Early attempts focused on features such as absorption color, grain size, and degree of roundness either to infer provenance or to correlate clastic sedimentary units (e.g. Krynine 1946). However, absorption colors can yield equivocal results in source-rock correlations. The compositions of detrital tourmaline grains are much better indicators of likely source rocks. "Environmental diagrams" that compare Al–Fe–Mg and Ca–Fe–Mg abundances show how detrital tourmaline compositions relate to probable source rock types (Fig. 4; Henry and Guidotti 1985). These diagrams, along with other compositional and textural variables, successfully yield provenance determinations in a number of different lithologic settings (e.g. Henry and Dutrow 1992; Morton et al. 2005). In addition, the relative degrees of rounding of tourmaline clasts provide general information on the energetics and potential cycles of sedimentation that each clast has undergone (Krynine 1946).

A challenge in using tourmaline composition to derive sediment provenance is that composition is not solely reflective of host rock. Variations in pressure, temperature, and oxygen fugacity, among others, can modify the parent-rock signature. The presence of compositional zoning in

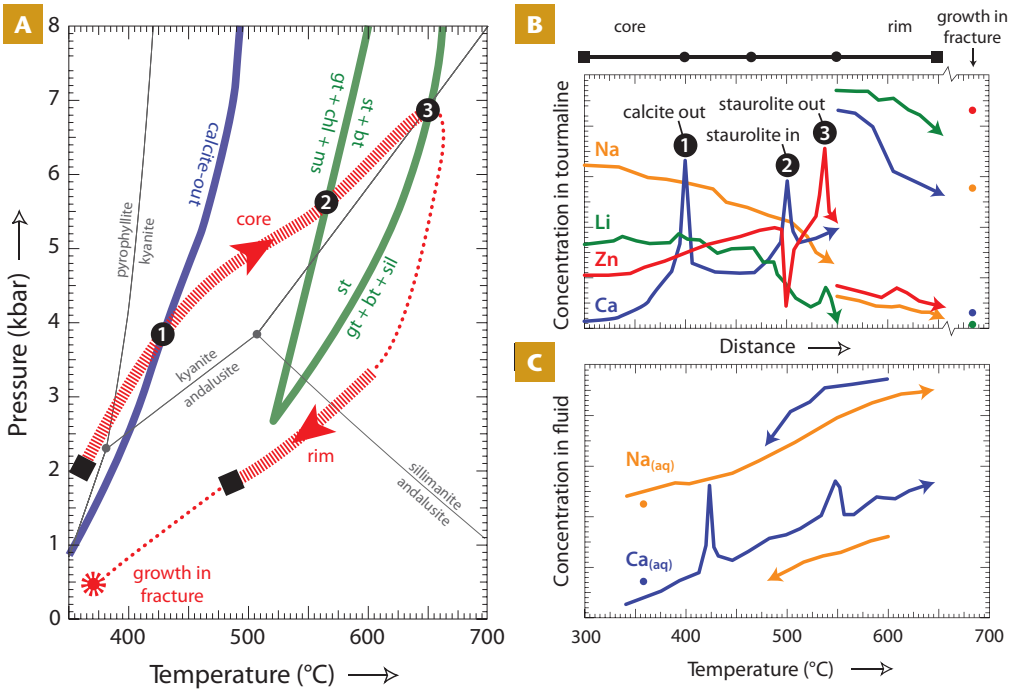

FIGURE 2 *P–T* conditions (**A**) and element contents (**B**, **C**) for selected major and trace elements along a core–rim transect of the tourmaline grain shown in FIGURE 1A, as well as the fracture growth (shown as a star in A). Arrows show the time direction. The spikes in composition (points 1–3, FIG. 2B) allow for mineral reactions to be recognized and for a temperature to be assigned to each reaction using inter-sector tourmaline thermometry. Combined with reaction positions from the literature (the green and blue lines in the *P–T* diagram), this allows the *P–T* path to be constrained (in red; stippled parts of the *P–T* path were not recorded for lack of tourmaline growth). Tourmaline compositions, combined with partition coefficients from the literature, allow Ca and Na contents in the fluid to be reconstructed, shown schematically against temperature along the *P–T* path in FIGURE 2C.

detrital grains provides a further challenge. However, such zoning also provides an opportunity, because it allows trends in composition to be matched to a source region. Trends are more distinctive than a single composition, thereby improving source identification, and may even be used to pinpoint a specific location within a source terrane. For example, if the model tourmaline in FIGURE 1 were to end up as a detrital grain, the *P–T* and compositional history retrieved from it would provide a highly characteristic signature for use in provenance studies.

Diagenetic Tourmaline

The burial and lithification of sedimentary detritus to form sedimentary rock commonly lead to new tourmaline growth on detrital grains or nucleation of a new tourmaline generation. A diagenetic origin is inferred for these occurrences because overgrowths typically develop as fragile, slender, syntactic needles (FIG. 5) that would not have survived transport in a clastic sedimentary environment (Krynine 1946). Most commonly, such tourmaline occurs as monopolar (restricted to one side of the grain) or highly asymmetric overgrowths on detrital tourmaline (e.g. Krynine 1946; Sperlich et al. 1996; Henry and Dutrow 1996), with distinctly different colors for overgrowths on either side of their detrital core (commonly blue and brown). A pale-hued overgrowth is found on the +**c** end of the detrital grain, whereas a darker-colored overgrowth develops on the –**c** end (see Hawthorne and Dirlam 2011). Growth also predominates on, and may even be restricted to, the +**c** side, which, together with color, provides a good marker of the crystallographic orientation of rounded detrital grains (FIGS. 1B STAGE 3; FIG. 5). The distinctive overgrowths on the two sides of a detrital grain testify to tourmaline's polar nature (see Hawthorne and Dirlam 2011), which results in tourmaline growing in the +**c** direction taking up different elements than tourmaline growing in the –**c** direction. This feature is useful, because these polar differences are temperature dependent and can be used to constrain the temperature of diagenetic tourmaline formation (e.g. Henry and Dutrow 1996).

In contrast, diagenetic tourmaline with no evidence of a detrital tourmaline nucleus is common in carbonate rocks, stromatolites, and, rarely, in mudstones (Srivastava and Schnitzer 1976). Compositions of pale-colored, diagenetic tourmaline are generally *X*-site-vacant foitite or magnesiofoitite species (e.g. Henry et al. 1994; Rosenberg and Foit 2006). These diagenetic tourmaline grains continue to grow as temperature and pressure increase and B is released from associated minerals.

TOURMALINE IN METAMORPHISM

Metamorphic rocks, especially those of metapelitic composition, are the second most important host of tourmaline. In contrast to their igneous counterparts, many metamorphic tourmaline grains develop on preexisting detrital grains or diagenetic cores, as is shown in the model tourmaline (FIG. 1A). Tourmaline textures and compositions reflect both local metamorphic reactions and changing *P–T–X* conditions, and this chemical and textural evidence of events can be preserved from the lowest to the highest grades of metamorphism (FIG. 1A, 1B STAGES 4 AND 5; FIG. 2).

During progressive metamorphism, tourmaline grows when B is available and the composition of the fluid is amenable to tourmaline formation (e.g. Dutrow et al. 1999). In sediments and metasedimentary rocks prior to the formation of tourmaline, B predominantly resides in layer silicates, with concentrations up to several hundred parts per million (Grew 1996; Steppan 2003). Even after tourmaline begins to grow, coexisting phases retain appreciable amounts of B. In a typical pelitic metasediment (Steppan 2003), the B distribution among coexisting phases is in the order tourmaline >> muscovite > andalusite > chlorite > biotite > plagioclase > garnet > kyanite > staurolite, although it varies as a function of metamorphic grade. In general, the sheet silicates contain more B than their breakdown products, leading to release of B during prograde metamorphism.

The release of B along a typical prograde metamorphic path (e.g. FIG. 2) can be predicted by combining thermodynamic calculations of changes in mineral proportions for a metapelitic bulk composition (using the PerpleX suite of programs; Connolly 2005) with typical B contents for metamorphic minerals (e.g. Steppan 2003). These calculations suggest a steady, but punctuated, supply of B on the prograde metamorphic path, with the largest B release at low grade by breakdown of muscovite and chlorite (FIG. 6). Consequently, tourmaline develops episodically as B is

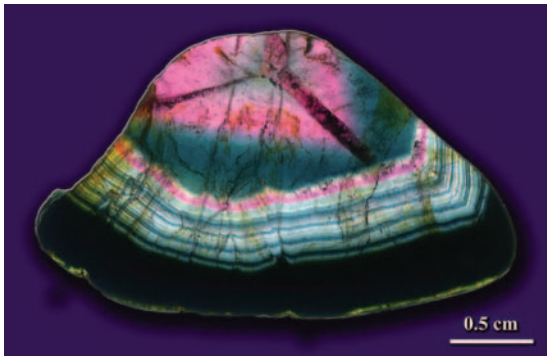

Figure 3 Polished slab of color-zoned tourmaline cut perpendicular to the **c** axis from a pegmatite in Madagascar. The tourmaline exhibits color zoning related to both sector zoning (cross in core) and oscillatory zoning (rim).

released in mineral reactions, and the timing and amount of tourmaline growth are linked to changes in the assemblage of associated minerals. A rock dominated by muscovite will release its B load at different times along the metamorphic path compared to one dominated by chlorite, because of differences in their respective stability. Boron released in a mica-rich unit, which releases aqueous fluid upon mica decomposition, is likely to infiltrate enclosing rocks, where it may form distinct tourmaline overgrowths or lead to mineral replacement and/or development of tourmaline-rich pseudomorphs (Dutrow et al. 1999). The liberation of B is nearly complete at peak metamorphic conditions such that, for a closed system, tourmaline is unlikely to grow on the retrograde path (Fig. 6). Comparison of the thermodynamically calculated B release with the timing of growth of tourmaline from three different metapelites from the Massif Central, France (colored lines in Figure 6) shows good overall agreement and matches the prediction that the most substantial growth takes place at lowest grade.

The composition of metamorphic tourmaline changes notably throughout its growth history as it directly reflects the changing environment (Fig. 2). Nonetheless, typical compositions are primarily schorl to dravite (i.e. the Fe^{2+} to Mg series), albeit with appreciable foitite, olenite, and uvite components, which introduce *X*-site vacancies, Al on the *Y* site and Ca on the *X* site, respectively. With increasing grade, the Mg/Fe^{2+} ratio and the content of Al on the *Y* site increase, along with vacancies and Ca content on the *X* site (van Hinsberg et al. 2011). However, these general trends are easily disturbed. For example, where sulfides sequester most of the Fe, anomalously Mg-rich tourmaline ensues (Henry and Dutrow 1992). Whereas the Mg/Fe^{2+} ratio of tourmaline commonly shows a smooth change from core to rim with changing conditions, other elements, including Ca, show spikes and troughs that reflect sudden changes in element abundance as the mineral assemblage or fluid composition changes (e.g. calcite breakdown; Fig. 2B, C).

Constraining Conditions of Tourmaline Formation

Recently, it has become possible to directly constrain the temperature of tourmaline formation on the metamorphic path by using tourmaline geothermometry. The most promising approach is the temperature-dependent partitioning of elements among sectors in a single tourmaline grain that displays hourglass-shaped sector zoning, i.e. different compositions in a single growth horizon for domains that originated on different growth surfaces (van Hinsberg and Schumacher 2007). This inter-sector thermometry can be applied to isolated grains, including detrital clasts and tourmaline inclusions, and to single growth zones. Its greatest value lies in application to tourmaline grains that show both sector and growth zoning, because in these cases complete temperature histories can be extracted from single grains (e.g. van Hinsberg and Schumacher 2007, 2011). Moreover, tourmaline thermometry accesses the low-temperature prograde conditions of metamorphic growth, for which few other robust mineral thermometers are available.

In sections cut parallel to tourmaline's long axis, hourglass zoning occurs as a pale-colored, commonly blue sector in the **+c** direction, a dark-colored, typically dark brown sector in the **–c** direction, and an intermediate-colored sector on either side (Fig. 1A). In sections perpendicular to the long axis, tourmaline exhibits a homogeneous, light- or dark-colored core surrounded by a zoned rim. This core–rim color difference can be mistaken for two-stage growth. Sector zoning reflects tourmaline's polar nature and is a different manifestation of polar diagenetic growth. Although tourmaline sector zoning is commonly regarded as a disequilibrium feature, this is a misconception. The sector differences form as a result of different local equilibria between the various growth surfaces and their identical host environment (van Hinsberg and Schumacher 2007). There is no direct exchange of elements between the sectors; instead, they communicate through the fluid, an exchange that equals direct exchange in thermodynamic terms.

Sector zoning and polar growth are controlled by differences in the surface properties of the growth surfaces; differences in charge are of most importance in tourmaline. Because the Si-tetrahedra all point in the same direction along the **c** axis in the tourmaline structure (Hawthorne and Dirlam 2011), a partial positive charge develops on surfaces at high angles to **c**. A corresponding negative charge develops on the opposite side, leading to the preferential incorporation of higher-charged cations for growth in this direction, such as Ti^{4+} on the *Y* site and Ca^{2+} on the *X* site. With increasing temperature, the ability of time-equivalent, but crystallographically distinct, growth surfaces to segregate elements decreases because the increased vibration of the atoms diminishes the charge asymmetry along the **c** axis; the inter-sector partition coefficients converge to unity. This change in partition coefficients provides the basis for thermometry. Because the compositional contrasts are in equilibrium only at the growth surface, sector zoning should disappear by element

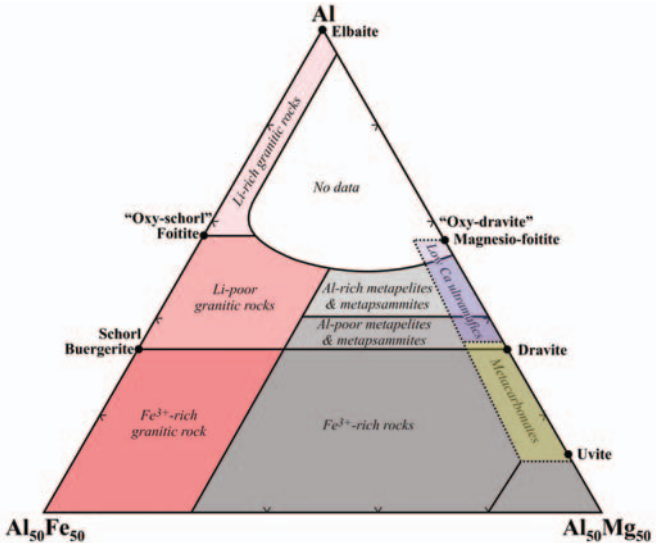

Figure 4 Environmental diagram correlating tourmaline composition to host-rock type. The locations of selected tourmaline species are indicated. The diagram is modified after Henry and Guidotti (1985).

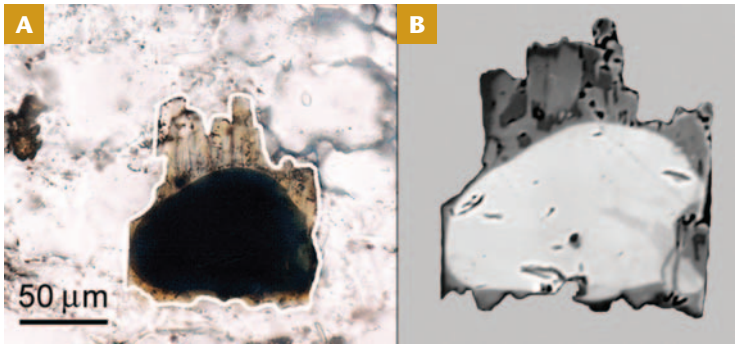

Figure 5 Detrital tourmaline grain with asymmetric diagenetic tourmaline overgrowth. (**A**) Optical photomicrograph highlighting the color distinction between the detrital core (blue) and overgrowth (yellow; top is +**c**). (**B**) Backscattered-electron image illustrating the textural and chemical complexity of the diagenetic overgrowth shown in A.

diffusion in the crystal bulk. The preservation of sector zoning is therefore not only evidence of slow diffusion in tourmaline, but also a confirmation that a grain has retained its chemical signature.

At present, other tourmaline thermometers only provide broad indications of conditions. The scatter observed in calibration attempts seems to reflect disorder of cations over the different tourmaline sites, in particular Fe, Mg, and Al over the *Y* and *Z* sites (Hawthorne and Dirlam 2011), and changes therein with changing conditions (van Hinsberg and Schumacher 2009). Element exchange and occupancy on the *X* site is more promising, especially Na–Ca exchange between tourmaline and plagioclase (van Hinsberg and Schumacher 2009) and *X*-site occupancy (Henry and Dutrow 1996; Ertl et al. 2010).

Constraining the pressure of formation is more difficult. Tourmaline barometers have not as yet been established, although tourmaline's K/Na ratio increases with pressure in exchange with biotite or phengite (van Hinsberg, unpublished data). Nonetheless, pressures can be constrained indirectly, for example, by barometry on mineral or fluid inclusions. In addition, specific mineral reactions are seen as sharp changes in tourmaline composition. If the position of such a reaction is known in *P–T* space and the temperature can be constrained from tourmaline thermometry, pressure can be established from the intersection of this reaction line in *P–T* space (e.g. van Hinsberg and Schumacher 2011). This approach is highlighted for our model tourmaline, in which the terminal breakdown of carbonate appears as a spike in Ca (Fig. 2B), whereas the reaction garnet + chlorite + muscovite to staurolite + biotite + quartz + fluid is seen by the combination of a trough in Zn + Li and a spike in Mn + Ca owing to the different element preferences of products and reactants. By combining this information, the *P–T* path of a tourmaline-bearing rock can be established (Fig. 2A).

Our model tourmaline shows both growth and sector zoning (Fig. 1A), allowing reconstruction of its thermal history. Compositions within the same growth zone, but on either side of the sector boundary, provide an inter-sector partition coefficient that constrains the formation temperature of this growth zone. These calculations can be performed along the entire length of the crystal. From core to rim, the compositional differences between the sectors decrease, which shows that this sequence corresponds to prograde growth (growth with increasing temperature). Qualitatively, this decrease in compositional contrasts among sectors is seen as a decrease in color contrast, and the peak growth zone is identical in color for all sectors. In natural metamorphic tourmalines, this convergence is observed for temperatures in excess of 650 °C (van Hinsberg and Schumacher 2007).

Growth of tourmaline during cooling and exhumation (retrograde growth) is unlikely in a closed system, because B has already been sequestered in tourmaline or lost to the fluid upon reaching peak metamorphic conditions (Fig. 6). Metasomatic introduction of B is the most common cause of tourmaline growth on the retrograde path, although such metasomatism can also take place during other stages of the rock's formation. The typical retrograde rehydration observed in metamorphic rocks and the high solubility of B in hydrothermal fluids suggest that this process is common. Intrusion of late "suturing" granites in orogenic belts and the likelihood of release of fluids from such plutons is a common source for retrograde boron addition, as is shown for our model tourmaline (Fig 1B stage 5). In many cases, this retrograde overprint takes place over a range of temperature, and tourmaline may record this history (van Hinsberg and Schumacher 2007). The growth of metamorphic tourmaline can thus span a remarkable range of conditions and provide a treasure trove of information on the *P–T* history of its host rock.

Tourmaline as an Indicator of Fluid Composition

Tourmaline not only preserves *P–T* information but also captures a fingerprint of the *composition* of its growth environment(s). This fingerprint allows changes in mineral paragenesis to be recognized, but its real power is the record provided on trace element mobility and the isotopic signature of the host environment. For example, in hydrothermal settings this fingerprint of element mobility has allowed tourmaline to be used as an exploration tool in the search for ore deposits (e.g. Slack and Trumbull 2011).

Recent experimental work on element partitioning between tourmaline and fluid permits a quantitative reconstruction of element contents in the coexisting aqueous fluid (von Goerne et al. 2011 and references therein). In a way that

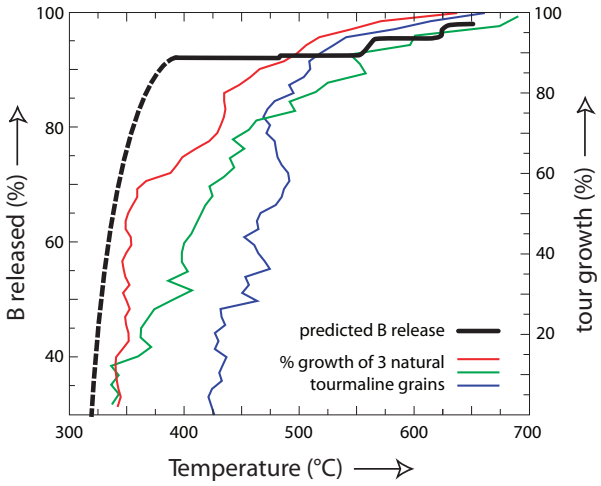

Figure 6 For a typical prograde path (Fig. 2A), B is liberated as grade increases (black line), as a result of decreasing modal abundance of the sheet silicates. This progressive, but episodic, B release agrees well with the growth history of three natural metamorphic tourmaline grains (colored lines; data from van Hinsberg and Schumacher 2011).

is analogous to reconstructing a thermal history using sequential growth zones, one can reconstruct the evolution of fluid composition. Because inter-sector partition coefficients for trace elements are poorly known, the **a** sector composition should be used in such reconstructions because its growth is perpendicular to the polar axis and therefore unaffected by polar element preferences. This technique used for our model tourmaline (Fig. 2c) highlights characteristic differences in composition between the metamorphic and metasomatic fluids. Partition coefficients are sensitive to *P–T* conditions, and this requires that coefficients be matched to those of tourmaline formation. For example, a static coefficient predicts a decrease in Na in the fluid with increasing grade, whereas the use of temperature-dependent partitioning produces an increase in predicted Na (Fig. 2c).

In the model tourmaline, final growth takes place on fracture surfaces, a feature commonly observed in nature (e.g. Henry et al. 2002). Typically, this growth reflects late-stage fluid infiltration in a brittle extensional regime (e.g. during orogenic collapse, Fig. 1b stage 6). New tourmaline growth is typically fibrous, with **+c** and **–c** polar differences, and compositionally distinct from its tourmaline substrate, marked here by elevated Zn and accompanied by a high Na/Ca ratio. This signature is suggestive of the infiltration of basinal-brine fluids, and such episodes have been linked to the formation of several types of ore deposits (Slack and Trumbull 2011). A combination of polar tourmaline thermometry and fluid-inclusion barometry constrains the *P–T* conditions of this final stage of tourmaline growth.

CLOSING REMARKS

Tourmaline has the unique ability to record and retain chemical and textural information that testifies to the geologic evolution of the rocks in which it develops. It can survive through weathering, diagenesis, metamorphism, and exhumation to track a complete geologic "life-cycle." With our current understanding of the crystallography and element partitioning of tourmaline, the results of recent tourmaline–fluid experiments, and the availability of a new generation of analytical equipment, tourmaline has the potential to become the prime forensic tool in the mineral sciences.

ACKNOWLEDGMENTS

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Tourmaline: The Kaleidoscopic Gemstone

7.7 carat fancy blue-green Namibian tourmaline (set in 18k gold). Gordon Aatlo design

Federico Pezzotta[1] and Brendan M. Laurs[2]

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With their multitude of colors, gem tourmalines are among the most popular colored gemstones. Spectacular color-zoned tourmalines are valued as gems and crystal specimens, and some complexly zoned crystals contain nearly the entire spectrum of color variation found in the mineral world. The top-quality "neon" blue-to-green, copper-bearing tourmaline, the *Paraíba-type*, is one of the highest-priced colored gemstones, with values comparable to those of some diamonds. The wide variety and intensity of colors are related primarily to color-producing ions in the structure and to exposure to natural radiation. Gem tourmalines that form in magmatic, pegmatitic environments are most commonly elbaite and fluor-liddicoatite species, and the rarer gem tourmalines that develop in metamorphic rocks are generally dravite–uvite species.

Keywords: tourmaline, gemstone, Paraíba-type, chromophores, gem deposits

TOURMALINE AS A GEMSTONE

Perhaps more than any other gemstone, tourmaline is renowned for its spectrum of colors, even within individual crystals (Fig. 1). In addition, tourmaline has the appropriate combination of beauty, durability, and rarity to make fine gemstones. Its moderate refractive index (~1.61–1.67; see also Hawthorne and Dirlam 2011 this issue) gives significant return of light, and its chemical complexity produces a wide range of appealing colors. Its relatively high hardness (7½ on the Mohs scale) makes it less likely to be scratched, and its lack of cleavage makes it unlikely to fracture during wear. Its growth as highly transparent material, mostly free of internal flaws, provides the gem-quality crystals required for cutting faceted stones (Fig. 1). These attributes make tourmaline well suited for fashioning, and it is available in sufficient quantities to support a commercial market. Gemmy crystals of tourmaline with sharp, undamaged morphology and rich colors are collected by mineral connoisseurs (Fig. 2), and cut stones are mounted into jewelry (Fig. 3). Clearly, tourmaline is one of the most important gem materials on the market today.

HISTORIC HIGHLIGHTS

Tourmaline gemstones have a distinguished and colorful history. At the beginning of the 18th century, Amsterdam lapidaries noticed that in mixed parcels of gem rough from Ceylon (now Sri Lanka), there were some gems characterized by relatively low density (~3.07 g/cm^3), and they were given the name *turamalin*. These were thought to be a new type of gem, having gone unrecognized for some time, and by 1717 they were referred to as *pierre de Ceylon* (King 2002). Nevertheless, the name *turamalin* was retained, and in the second half of the 18th century the spelling changed to *tourmalin*. In 1771 the term *tourmaline garnet* was coined, probably referring to *rubellite* (the pink to red gem variety of tourmaline). Until the early 18th century there were only small amounts of Ceylonese gem tourmaline on the market. In the late 18th century the discovery of rubellite deposits near Nerchinsk, Siberia, and the finds of Brazilian tourmalines, referred to as *smaragdus brasilicus*, produced significant quantities of gem tourmaline (King 2002).

Long before it was recognized as a new gem, some magnificent red tourmaline gemstones had been mounted as jewels for Europe's royalty. The great Czech crown of Saint Wenceslas, fashioned between 1346 and 1387, features a large, bright red "ruby" (39.5 × 36.5 × 14 mm) that is actually tourmaline (Hyršl and Neumanova 1999). The tourmaline in the Wenceslas crown is the oldest-known tourmaline gemstone, predating the coining of the word *tourmaline* by several hundred years. In 1925, Russian mineralogist Alexander Fersman identified a vivid pink, chicken's egg–sized gem from the Kremlin's Treasure Room as a Burmese tourmaline. It was traced to the reign of Emperor Rudolph II (1575–1612), and until Fersman's work it was considered an oriental ruby (Glas 2002). At the turn of the last century, demand for tourmaline soared as it was popularized by one of its greatest enthusiasts, the Dowager

Figure 1 Broad spectral color range displayed by tourmaline. These cut stones weigh 3.71 to 16.21 ct. The round green stone at the top center is about 15 mm in diameter. From the GIA collection; photo by Robert Weldon, reprinted with permission

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Figure 2 Specimen of polychrome elbaite crystals (28 cm tall), characteristic of gem tourmaline found in Pederneira, Minas Gerais, Brazil. Specimen from Daniel Trinchillo; photo by James Elliott

Figure 3 Pendant consisting of two Mozambique copper-bearing tourmalines (10.95 ct pink and 6.95 ct yellow) set in 18 k gold with diamonds. From the Buzz Gray and Bernadine Johnson collection; photo by Robert Weldon

Empress Tz'u Hsi, who ruled China from 1860 to 1908. Her passion for carved pink tourmaline consequently led to its desirability among the Chinese royalty (e.g. Fisher 2008).

COLOR AND OPTICAL PHENOMENA IN GEM TOURMALINE

The extensive range of colors in gem tourmaline, from colorless, through red, pink, yellow, orange, green, blue, and violet, to brown and black, generally reflects interactions at a structural level. Several mechanisms can cause color in tourmaline, the most common ones being crystal-field transitions (CFT), intervalence charge transfer interactions (IVCT), and color centers. The transition elements Fe^{2+}, Fe^{3+}, Mn^{2+}, Mn^{3+}, Ti^{4+}, Cu^{2+}, and V^{3+} act as important color-causing agents, or chromophores, in tourmaline. Most transition element chromophores occupy the *Y* and *Z* edge-sharing octahedral sites (Hawthorne and Dirlam 2011), and they influence color and color intensity through both CFT and IVCT (Table 1). Trivalent chromium is also a strong chromophore in many tourmalines, but gem chromian tourmalines are relatively rare.

Naturally occurring colors can be produced or enhanced by natural irradiation (i.e. through the ionizing radiation of decaying isotopes such as ^{40}K, ^{238}U, and ^{232}Th) from minerals proximal to the tourmaline. For example, when tourmaline is associated with potassium feldspar or a U/Th-bearing accessory mineral (such as monazite or zircon), its color can be modified and intensified by radiation. In addition, irradiation can alter the color by creating color centers (e.g. Reinitz and Rossman 1988).

To achieve the best color when cutting a tourmaline gemstone, the pronounced dichroism of tourmaline must be taken into account. In general, the ε-ray of light traveling parallel to the **c** axis of the crystal, corresponding to the direction parallel to prism faces, is significantly absorbed compared to the ω-ray. The color of the gem rough typically appears darker and more saturated when observed parallel to the **c** axis. In dark brown crystals the effect can be so strong that the ε-ray is completely absorbed, and in the 19th century mineralogists used thin slabs of such crystals, cut parallel to the **c** axis, as a light polarizer (Anderson 1980). Dichroism in gem tourmaline is quite variable and may even make it challenging to identify.

Table 1 PARTIAL LIST OF TOURMALINE COLORS, VARIETIES, CAUSES OF COLOR, AND PROBABLE SPECIES[a]

Color	Varietal name	Cause of color	Probable tourmaline species[b]
Colorless	Achroite	No or minor chromophores	Elbaite, "fluor-elbaite," fluor-liddicoatite, rossmanite
Pink and red	Rubellite	Mn^{3+} [c], Mn^{3+} + Fe [d] or Mn^{2+}-Mn^{3+} IVCT Natural radiation	Elbaite, "fluor-elbaite," fluor-liddicoatite, rossmanite
Yellow, yellow-green	Canary	Mn^{2+} [d], Mn^{2+}-Ti^{4+} IVCT [d]	Elbaite, "fluor-elbaite," fluor-liddicoatite
Green	Verdelite	Fe^{2+}, Fe^{3+}[d], Fe^{2+}-Ti^{4+} IVCT	Elbaite, "fluor-elbaite," fluor-liddicoatite
Green (deep)	"Chrome"	V^{3+}, Cr^{3+}	Dravite–uvite
Blue	Indicolite	Fe^{2+}, Fe^{2+}-Fe^{3+} IVCT	Elbaite, "fluor-elbaite," fluor-liddicoatite
Blue (neon)	"Paraíba-type"	Cu^{2+}	Elbaite, liddicoatitic tourmaline[e]
Brown	--	Fe^{2+}-Ti^{4+} IVCT	Dravite, elbaite, liddicoatitic tourmaline
Black	--	High concentrations of Fe^{2+}, Mn^{2+}, and/or Ti^{4+}	Schorl, elbaite, liddicoatitic tourmaline

[a] Compiled after Zang and da Fonseca-Zang (2002), and from G. R. Rossman's spectroscopy website (http://minerals.caltech.edu/FILES/Visible/tourmaline/Index.html)

[b] Species names are from the tourmaline classification of Henry et al. (2011). Those species that have not been currently accepted by IMA-CMNMC, but are likely to exist, are indicated by quotes.

[c] Commonly associated with ionizing radiation

[d] G.R. Rossman, personal communication to B. Dutrow

[e] Fluorine content not available

Figure 4 Faceted elbaite stones from Paraíba, Brazil (2.59–3.68 ct; the stone on the left is about 6 mm tall). These stones owe their intense, "neon" blue colors to the influence of Cu^{2+} in the tourmaline structure. In some cases, Cu^{2+} in combination with other cations modifies the resulting colors. © Gemological Institute of American. Photo by Robert Weldon. Reprinted by permission

Occasionally tourmaline crystals display chatoyancy. This light-scattering effect is caused by the interaction of light with bundles of parallel, microscopic, needle-like inclusions aligned along the **c** axis. Cabochons (rounded, convex, polished stones) are fashioned from these crystals to showcase their "cat's-eye" appearance. The intensity of this phenomenon depends on the size and density of the tubes that cause this effect (Graziani et al. 1982).

In the absence of compositional data for tourmaline, gem miners and dealers use a series of color-based trade names that are common in the marketplace (Table 1). The classic varietal names are *rubellite* (rose, dark pink, to red), *verdelite* (yellow-green to green), *indicolite* (blue-green to blue), and *achroite* (colorless) (Zang and da Fonseca-Zang 2002). However, these trade names do not universally correlate with tourmaline species names. Tourmaline crystals with a given color can develop in several species, and some individual species can develop many colors. For example, elbaite and fluor-liddicoatite, which represent most of the tourmaline gemstones, can display a nearly complete color spectrum (see Table 1). Recently, additional color-based varietal names have come into popular use, such as *canary tourmaline* (yellow, Mn-rich elbaite from Zambia; Simmons et al. 2011) and *chrome tourmaline* (a vivid green tourmaline from Tanzania)—a perplexing name for a dravite-to-uvite tourmaline with significant vanadium content (Bank and Henn 1988). The intense blue-green tourmalines, termed *Paraíba-type*, are of special interest as gemstones (Fig. 4).

Paraíba-Type – The Most Precious Tourmaline

Copper-bearing tourmaline, in vivid blue-to-green and purple hues, is one of the most desirable colored gemstones in the world (Fig. 4). Following its discovery in the late 1980s in the Paraíba State of Brazil (e.g. Fritsch et al. 1990; Beurlen et al. 2011 and references therein), it became popular for its highly saturated "neon" colors, and prices escalated rapidly. Recent prices have reached ~US$25,000/carat for exceptionally clean, intensely colored Brazilian stones. In the 1990s additional deposits were found in Paraíba State and in the neighboring Rio Grande do Norte State (Shigley et al. 2001), and more were discovered later in Nigeria (Milisenda and Henn 2001) and in the Alto Ligonha pegmatite district of Mozambique (Laurs et al. 2008 and references therein). Although the blue-to-green-to-purple colors of the Mozambique material are typically less saturated than those of the Brazilian stones, the lower price and greater availability have further enhanced this tourmaline's popularity. Demand for gem laboratories to differentiate stones by locality has stimulated research into their provenance using the analysis of trace elements and isotopes (e.g. Abduriyim et al. 2006; Shabaga et al. 2010; Marschall and Jiang 2011 this issue).

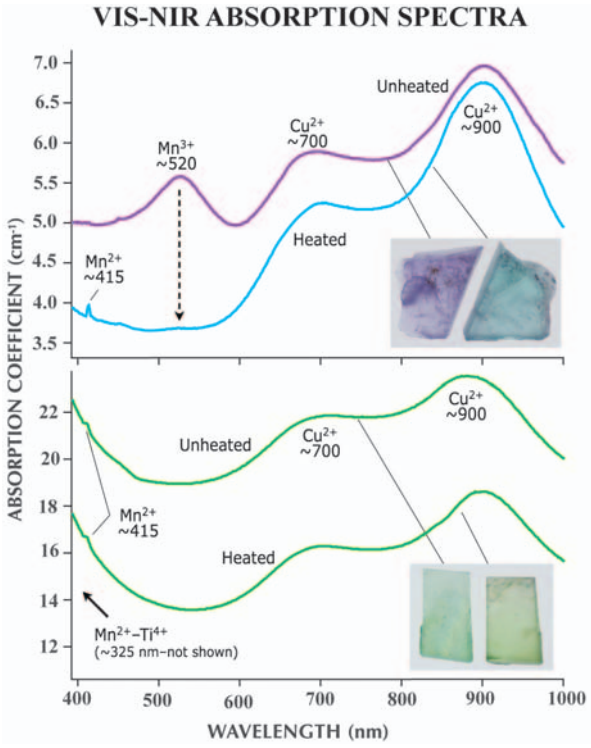

Figure 5 Visible light–near-infrared absorption spectra for two pairs of polished tourmaline slabs from Mozambique, before and after heating. (TOP) The dramatic change in color from violet to blue-green with heating results from the reduction of Mn^{3+}. (BOTTOM) Little change in color is observed when heating the yellowish green tourmaline due to strong Mn^{2+}-Ti^{4+} absorption. Figure from Laurs et al. (2008), modified by B. Dutrow; inset photos by C. D. Mengason

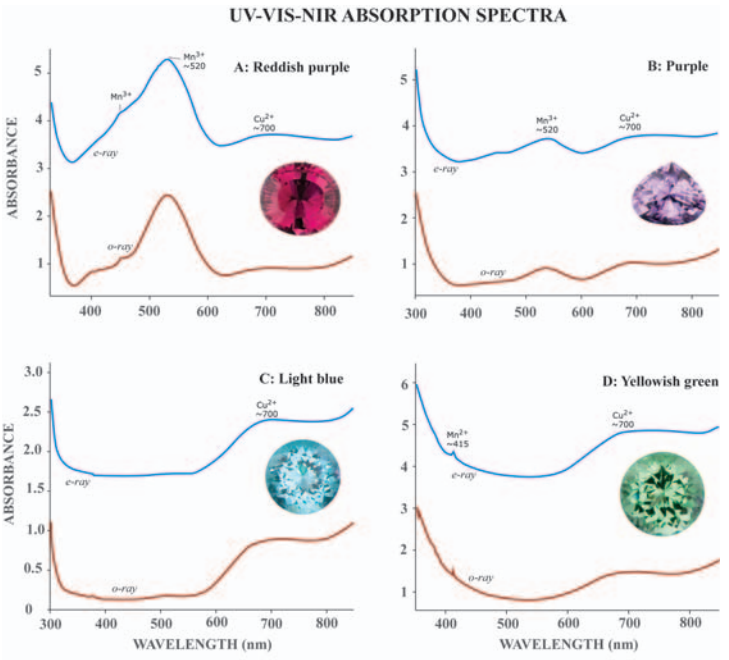

Figure 6 Ultraviolet–visible light–near-infrared absorption spectra for various colors of unheated Cu-bearing tourmaline from Mozambique. Two distinctive broad bands centered at ~700 and ~900 nm (the latter not shown in the spectra) are caused by Cu^{2+}; some exhibit absorption between ~500 and ~550 nm due to Mn^{3+}. Weights of the inset stones are: (a) 12.90 ct, (b) 3.70 ct, (c) 1.46 ct, (d) 2.24 ct. Figure from Laurs et al. (2008), modified by B. Dutrow, inset photos by Robert Weldon

The coloration of Paraíba-type tourmaline is controlled mainly by a combination of the cationic concentrations and oxidation states of Cu, Mn, Fe, and Ti (Fritsch et al. 1990; Rossman et al. 1991; Laurs et al. 2008). In the absence of significant amounts of Fe and Ti, and when manganese occurs as Mn^{2+}, the tourmalines show an intense "neon" blue color due to strong Cu^{2+} absorptions centered at ~700 and 900 nm (Figs. 5, 6). Heat treatment of Cu- and Mn-bearing tourmaline reduces Mn^{3+}, which causes violet-pink coloration, to Mn^{2+}, which is a less intense chromophore in tourmaline (Fig. 5). Removal of the Mn^{3+} absorption at ~520 nm creates a transmission window from ~400 to 580 nm that yields the "neon" blue color (Fig. 4); heat treatment of a similar stone containing significant Ti and Fe produces a green coloration (e.g. Laurs et al. 2008). Paraíba-type tourmalines are typically elbaitic species, but may also be fluor-liddicoatite (Karampelas and Klemm 2010).

TREATMENTS AND SYNTHETICS

Gamma irradiation and heat treatment are techniques used to modify the color of many gem materials to make them more marketable (e.g. Nassau 1996). Pale-colored tourmaline is generally irradiated to add color; most commonly, near-colorless stones are transformed into vivid pink and red ones. Heat treatment is generally applied to dark tourmaline, with the heating conditions (peak temperature, time of heating and cooling, etc.) optimized on a case-by-case basis to achieve the desired color saturation and tone. Most commonly, dark blue or green material is heated to obtain lighter blue green or yellow green colors. Heat treatment of Paraíba-type tourmaline reduces the influence of the Mn^{3+} chromophore to create or enhance the intensity of the "neon" blue color (see above). The treatment temperature can range from 120 °C to over 700 °C, and a complete heating run can be less than 2 hours to over 48 hours. Details of the mechanisms involved in the color modifications in tourmaline during heat treatment are reported in Castañeda et al. (2006).

The synthesis of gemstones has an economic incentive. Most of the important gem minerals and their varietals [including sapphire (corundum), ruby (corundum), emerald (beryl), aquamarine (beryl), and diamond] have been successfully grown in laboratories as relatively large gem crystals using various techniques. However, gem tourmaline, common and widespread in pegmatites as large crystals, has not yet been synthesized (London 2011).

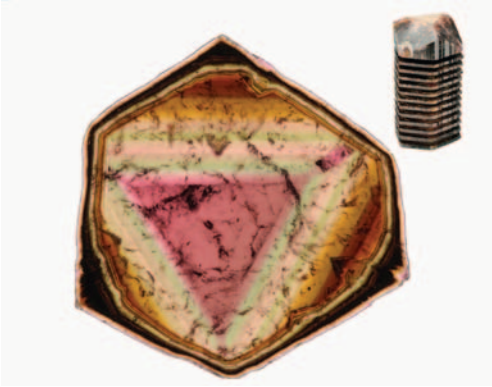

Figure 7 A slice of a large fluor-liddicoatite crystal (7 cm in diameter, viewed in plane-polarized light) from Anjanabonoina, Madagascar; the inset image shows the crystal cut into a series of slices perpendicular to the **c** axis. The zoning patterns, which likely are nonequilibrium features, reveal a complex growth history characterized by dramatically changing chemical environments. These chemical changes, combined with crystallographic effects, produced the color pattern observed. Natural History Museum of Milan specimen; photo by Roberto Appiani

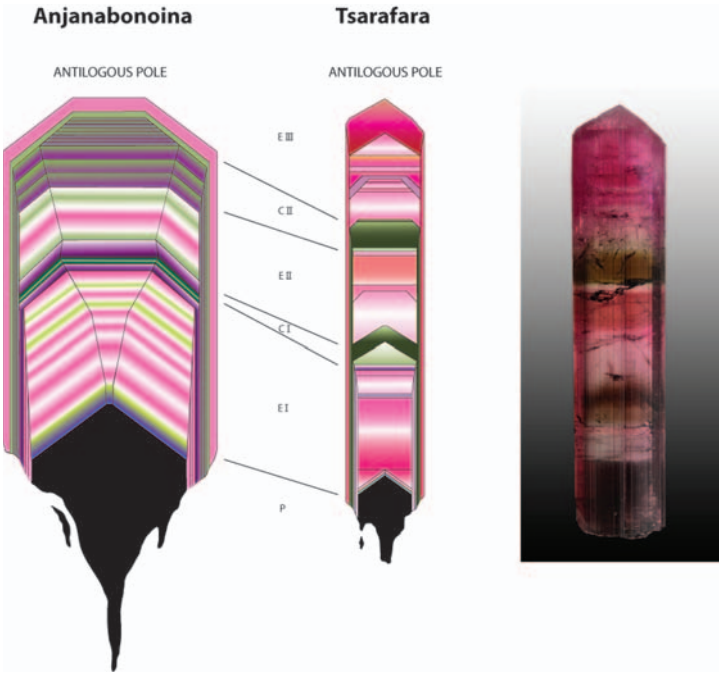

Figure 8 Comparison of the complex zoning patterns in fluor-liddicoatite crystals from Anjanabonoina and Tsarafara, Madagascar. Backlighting reveals the color zoning in the 8 cm long, gem-quality Tsarafara tourmaline (right). The lines join corresponding stages of crystal growth. From the bottom of the crystals to their termination, the following growth zones can be distinguished and interpreted in terms of chemical composition: P – primitive root, EI – first evolved growth, CI – first contaminated growth, EII – second evolved growth, CII – second contaminated growth, EIII – third evolved growth. Gem crystal from the Gerhard Wagner collection; photo by Roberto Appiani

ZONED GEM CRYSTALS

Tourmaline crystals are sensitive to physicochemical changes in their growth environment and are effective recorders of this information (van Hinsberg et al. 2011 this issue). Such crystals are typically zoned—some with extraordinary color zoning with dramatically variable colors (Figs. 7, 8). In gem-bearing pegmatites, the "roots" (the most primitive portions) of the tourmaline crystals are typically black and are generally schorl or foitite (Fig. 8). The black root is commonly overgrown by gem tourmaline that may show compositional variations involving several changes in chromophore elements (Figs. 2, 7, 8). Such chemical variations can result in *simple zoning*, typically from nearly black Fe–Mg-rich elbaite to green-to-blue Fe-bearing elbaite to pink Mn-rich or Mn-poor elbaite to pale pink rossmanite. In many cases, a "reverse" geochemical trend is shown at the latest stages by a green overgrowth, producing "watermelon" color zonation (pink core, colorless-to-white midsection, and green rim) in sections cut perpendicular to the **c** axis.

Complexly zoned crystals can be spectacular. They are typically characterized by oscillatory and sector color zones that reflect interactions between the surface energies of distinct faces and the dynamic local chemical environment, such that different chromophoric cations are incorporated into chemical zones within the tourmaline (Fig. 7; e.g. Lussier and Hawthorne 2011). The large, beautifully color-zoned crystals of fluor-liddicoatite from Madagascar are particularly illustrative of this style of zoning (Figs. 7, 8; Dirlam et al. 2002). Although they show a relatively drab, dark color on the outside (Fig. 7, inset), when they are cut perpendicular to the **c** axis a myriad of geometric patterns appear, including triangular zones and three-rayed

FIGURE 9 Major world gem tourmaline–producing localities. ☐ Historic gem production; ▾ limited gem production; ▼ significant gem production; ♦ exceptional gem production. FROM SHIGLEY ET AL. (2010) AND REFERENCES THEREIN

Continent	Country	Locality	Significance
North America	(1) California, USA	Mesa Grande district	☐
		Pala district	▾
		Ramona district	☐
		Warner Springs	▾
	(2) Maine, USA	Oxford County	▼
	(3) Northwest Territories, Canada	O'Grady Lake	☐
South America	(1) Minas Gerais, Brazil	Araçuaí district	♦
		Conselheiro Pena district	♦
		Malacacheta district	▼
		São José de Safira district	♦
	(2) Paraíba, Brazil	São José da Batalha area	▾
	(3) Rio Grande do Norte, Brazil	Parelhas area	▾
Africa	(1) Kenya	Mangare and elsewhere	▾
	(2) Madagascar	Antsirabe-Betafo area	▾
		Fianarantsoa area	▼
		Tsitondroina area	▼
	(3) Mozambique	Nampula Province	♦
		Zambézia Province	▼
	(4) Namibia	Karibib area	▾
	(5) Nigeria	Nassarawa Province	♦
		Oyo Province	♦
	(6) Tanzania	Arusha area	▾
		Morogoro area	▾
		Tanga area	▾
	(7) Zambia	Kabwe district	☐
		Lundazi district	▼
Europe	(1) Italy	Elba Island	☐
	(1) Russia	Mursinka	☐
Asia	(1) Afghanistan	Nuristan Province	♦
		Kunar Province	♦
	(2) Myanmar	Shan State	▼
		Mandalay State	▼
	(3) Pakistan	Gilgit-Baltistan	▼
		Azad Kashmir	▾
	(4) Russia	Transbaikalia	▼
	(5) Sri Lanka	Various	☐
	(6) Vietnam	Yen Bai Province	▼

"stars" surrounded by oscillating color zones (FIG. 7; e.g. Dirlam et al. 2002; Rustemeyer 2003). Chemical sector zoning is shown by the central triangle (representing the pedion face) and the surrounding triangular zones and the star (representing pyramidal faces). In some rare cases, relatively thin and elongated gem crystals are sufficiently transparent to display this dramatic color variation (when backlit) without being sliced (FIG. 8).

GEM TOURMALINE LOCALITIES, GEOLOGIC ENVIRONMENTS, AND INCLUSIONS

Gem tourmalines have been found in a variety of locations throughout the world (FIG. 9). One of the most notable tourmaline discoveries took place in April 1978 at the Jonas mine, Conselheiro Pena, Minas Gerais, Brazil (SOUTH AMERICAN LOCALITY 1 IN FIG. 9; Cornejo and Bartorelli 2010). These intense deep red crystals include the Rocket (a prism 107 cm tall; see FIG. 4 in Hawthorne and Dirlam 2011) and the Tarugo (a cluster 82 cm long and weighing 74 kg, corresponding to 375,000 ct). Giant prismatic crystals, up to ~1 m in length and 35 cm in diameter, have been found in Madagascar, primarily as polychrome crystals that provide colorful sliced material.

Gem tourmalines are found in a number of geologic settings. Most gem tourmalines form in granitic pegmatites where they are concentrated in miarolitic cavities. Such miarolitic pegmatites are typically emplaced in the continental crust at moderate to shallow depth, in a pressure range of 1–3 kilobars (0.1–0.3 MPa). The ages of these gem tourmaline–bearing pegmatites are variable. Many of the largest such pegmatitic fields, including those in Brazil, Namibia, Mozambique, and Madagascar, are about 500–550 million years old and formed during the latest stages of the tectonometamorphic Pan-African event involving the Gondwana supercontinent. However, some gem tourmaline–bearing pegmatites formed more recently. The famous tourmaline-bearing pegmatites of southern California, USA, formed about 100 million years ago (Snee and Foord 1991), and those on Elba Island, Italy, formed about 6.2 million years ago (Dini et al. 2002). Metamorphic rocks can host unusual deposits of gem-quality tourmaline, such as the well-known "chrome" tourmaline from Tanzania (Simonet 2006). Because they are highly resistant to mechanical and chemical weathering (van Hinsberg et al. 2011), gem tourmalines can accumulate in eluvial and alluvial deposits, such as those found in Madagascar (Dirlam et al. 2002).

Inclusions in tourmaline reflect the environment of its formation and, in rare cases, provide a fingerprint for specific deposits (Koivula 1994 and references therein). For example, native copper inclusions are indicative of gemstones from Paraíba, Brazil (Fritsch et al. 1990). Other mineral inclusions in tourmaline include albite, muscovite, lepidolite, fluorapatite, monazite, pyrite, pyrochlore-group minerals, quartz, zircon, and, more rarely, minerals such as hydroxylherderite, manganotantalite, and topaz (Koivula 1994). Most of these mineral inclusions are consistent with a pegmatitic paragenesis. However, the inclusions found in tourmaline are more commonly in the form of trapped fluids. These fluid inclusions manifest themselves as negative crystals (fluid-filled voids shaped like the host crystal), fine randomly arranged capillary-like tubes, partially healed fractures, and sometimes growth tubes. Fluid inclusions in tourmaline, generally single-phase gas or two-phase aqueous liquid-plus-gas inclusions, represent fluid

trapped during some stage(s) of tourmaline development, and they can be used to establish the pressure–temperature–fluid evolution of the system (e.g. van Hinsberg et al. 2011).

CONCLUSIONS

In addition to its scientific value as a recorder of the geologic environments during its formation, tourmaline is a fascinating and beautiful gemstone known for its full spectrum of colors. Its attractive and complex color zoning and its occurrence as sharp prismatic crystals make it highly sought-after by mineral connoisseurs and gem aficionados. Particularly notable are large (up to 1 m long) crystals of elbaite, intricately zoned crystals of liddicoatitic tourmaline, and vivid blue-to-green Paraíba-type elbaite. Tourmaline's remarkable variety of colors and its availability as large, gem-quality crystals are directly related to its most common mode of formation, within miarolitic cavities in moderately to highly differentiated granitic pegmatites. The most important commercial deposits—all pegmatitic—are located in Brazil, Mozambique, Nigeria, and Afghanistan. Demand for this attractive gemstone will continue to drive mining and will likely result in additional discoveries that will yield magnificent crystals and deepen our knowledge of the dynamic Earth processes leading to its formation.

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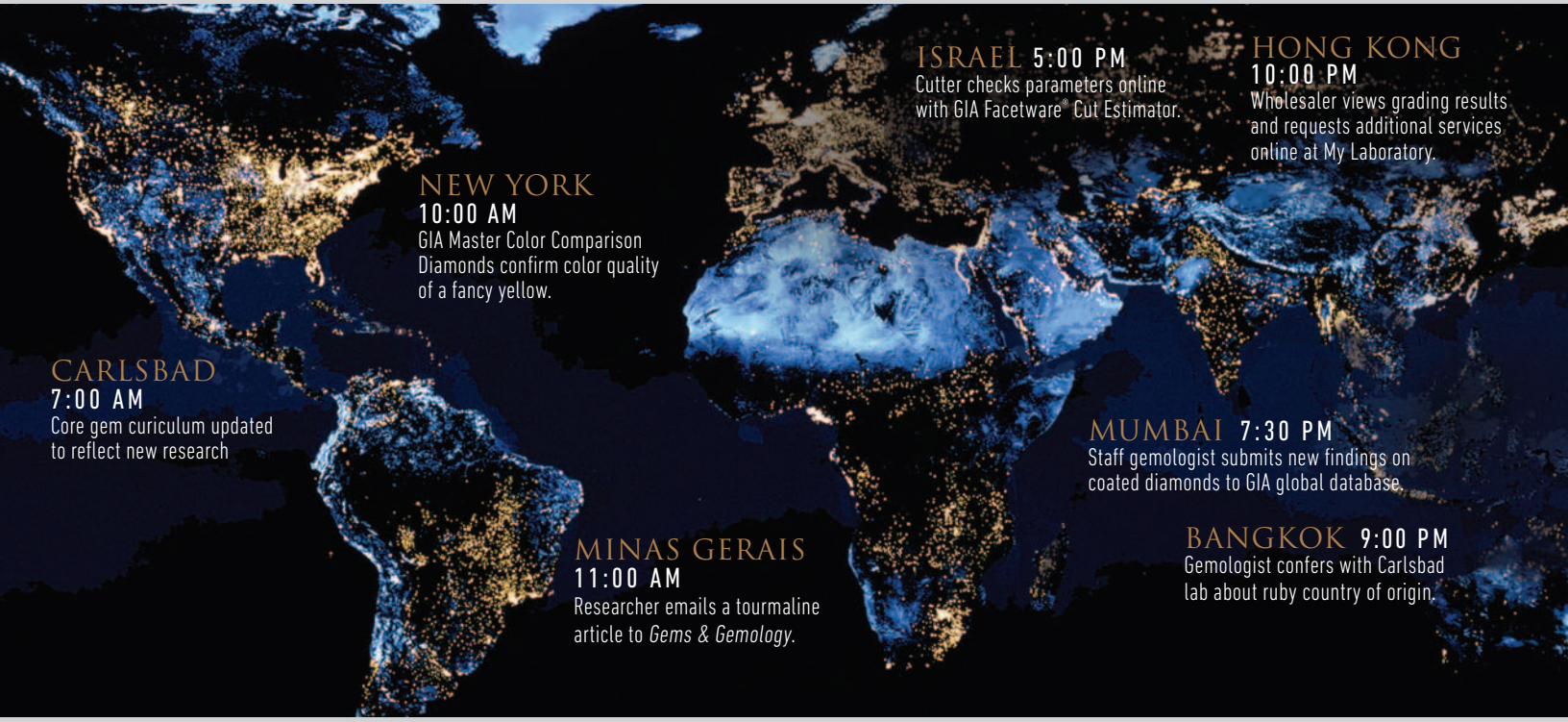
ADVANCING EXPERTISE IN A CHANGING WORLD.



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PRESIDENT'S LETTER

Dave Bish

This has been a busy year, and a number of exciting initiatives are ongoing within MSA, several of them direct outgrowths of MSA-Talk discussions (by the way, MSA-Talk now has over 1750 subscribers!). As regular readers of MSA-Talk know, there has been interest in forming some sort of clearing house for rock and mineral specimens for teaching and research purposes. I have long been interested in this and have often wondered if our members might use our web presence to benefit institutions in need of mineral samples and perhaps even books and periodicals. For example, when a member retires or changes fields, very often their mineral/rock collections and personal libraries are no longer needed and are often discarded. With this in mind, I have had numerous discussions with the management of the National Association of Geoscience Teachers (NAGT) in an effort to create a mechanism for transferring such collections to secondary schools, community colleges, or small four-year institutions in need of teaching materials. NAGT has been very supportive of this idea, particularly because they share the belief that many small institutions have difficulty assembling teaching materials. NAGT has generously offered to create a web page to facilitate this, and we hope to have something up for testing this fall. We also envision eventually using such a site, which will be linked to the MSA home page, to allow mineral scientists to exchange mineral and rock research materials, as suggested by the recent thread on MSA-Talk.

There has also been considerable dialogue on MSA-Talk about the nature of asbestos, and we received a number of comments on the proposed MSA policy statement. The discussion period is now closed, and the committee that originally proposed the statement is considering the comments and, where possible, incorporating them. We anticipate that the revised policy statement will be presented to MSA Council at this fall's GSA meeting in Minneapolis.

Yet a third initiative has come out of discussions on MSA-Talk, and we recently formed an ad hoc committee to formulate what I hope will become an MSA policy statement on the teaching of the mineral sciences. It seems that many MSA members have experienced efforts to minimize or even eliminate teaching of some fundamental aspects of the mineral sciences. It is our desire to draft a statement focusing on the reasons for and importance of teaching the basics of our science. I believe that such a statement will not only help us in discussions with departmental colleagues and university administrators, it can also help crystallize our own thoughts on the subject (e.g. what is the optimum balance between theoretical and applied subjects?).

In other news, after discussion at our May Council meeting, we decided to change the name of the American Mineralogist Undergraduate Award to the MSA Undergraduate Prize to reflect more accurately its purpose. This has been a very successful program to recognize outstanding achievement in the mineral sciences, and we had 24 awardees in 2010 and have had 11 so far in 2011. Indeed, we have had 503 awardees since the inception of the award in 1985, representing encouragement to a large population of mineral science students. The Prize provides an award certificate, student membership in MSA with access to the electronic version of *American Mineralogist*, and a choice of one of our Monographs or Reviews in Mineralogy and Geochemistry volumes. I encourage all of you in educational institutions to take advantage of this very nice mechanism to recognize our top students. You can find more information on the Prize on our web page under the old name, which we will retain for a while. We will also shortly begin revamping the highly successful K–12 section of our website, one of the most popular parts of our web presence.

I am happy to report that we will again sell mineral calendars this fall, and you will have the option to purchase one when you renew your membership. The calendars are beautiful and very reasonably priced, so be sure to purchase one for your office wall and a few for gifts. When you do renew your membership, I hope you keep in mind the many benefits that come with it, including reduced registration fees at our meetings and free color in *American Mineralogist*, among many others. You will shortly also have the opportunity to purchase all of our RIM and RIMG volumes electronically, on a subscription, individual volume, course pack, or chapter-by-chapter basis, as our business office recently completed scanning volumes 1 through 73. I have personally looked forward to the opportunity to obtain electronic copies of our older RIM and RIMG volumes.

This is my last *Elements* newsletter as president of MSA, and I'd like to reflect for a moment on the operations of the society. MSA is healthy, and the society runs smoothly through the operations of our business and editorial offices, our staff of editors, and countless volunteer members. Throughout the year I have been tremendously impressed by the dedication and support of the numerous individuals who keep our society vibrant and drive its evolution. Our members and their contributions to our publications and operations are responsible for the strength and vitality of our society over so many years. Scientific societies such as ours are increasingly intertwined with other societies, and we have had a long and productive interaction with the Geological Society of America (GSA). We also have a constructive relationship with the Geochemical Society through our participation in the Goldschmidt Conferences. This year we began discussions aimed at creating stronger ties with the American Geophysical Union, and I anticipate that we will hear more news from President Hochella about this exciting new opportunity for both societies. Speaking of the longevity of MSA, our 100th anniversary is coming up in 2019. Past anniversaries have been occasions for creating exciting new programs, such as our very popular lecture program, and I hope our members will put their heads together to suitably celebrate our first 100 years and the beginning of our second. In closing, I'd like to thank the business office staff, the editorial office staff, and the myriad of engaged MSA members for their constant support and guidance.

I look forward to seeing you at the upcoming GSA meeting in Minneapolis and participating in our MSA functions with you.

Dave Bish (bish@indiana.edu)
President, Mineralogical Society of America

IN MEMORIAM

James F. Olmsted – Senior Member–1965

NOTES FROM CHANTILLY

- Results of the 2011 election: The 2012 president of the society is Michael F. Hochella Jr.; the vice president is John M. Hughes. Andrea Koziol was elected secretary, and Darrell J. Henry remains in office as treasurer. The new councilors are Christine M. Clark and Kimberly T. Tait. They will join continuing councilors Wendy A. Bohrson, Sumit Chakraborty, Pamela C. Burnley, and Guy L. Hovis.

- The following short courses are planned for 2012:

  Applied Mineralogy of Cement and Concrete (Maarten Broekmans, organizer), to be held in conjunction with the First International Congress on Durability of Concrete (17–21 June 2012; www.icdc2012.com) in Trondheim, Norway

  Environmental Arsenic Mineralogy, Geochemistry & Microbiology (Rob Bowell, organizer), which will coincide with the International Geological Congress (5–10 August 2012) in Brisbane, Australia

  Spectroscopic Methods in Mineralogy and Material Sciences (Grant Henderson, Daniel Neuville, and Robert Downs, organizers), which will be held immediately before the Goldschmidt Conference in Montreal, Canada, in June 2012

- MSA members were contacted electronically in September to renew their membership for 2012. Members who renew and pay online before 31 October 2011 will receive a $5 dues discount; the discount reflects cost savings to MSA from members who renew early online. There will be several electronic reminders before a paper copy is sent during November to those who do not renew online by the end of October.

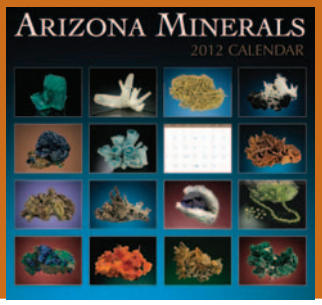
- Members and fellows who are in the senior, honorary, and life categories are sent renewal notices. They need not pay dues, but are sent notices as the best way to prompt an update of membership information, particularly mail and e-mail addresses.

  Members qualify for senior member or senior fellow status if they have reached the age of 65, have retired from full-time professional employment, and have been a member of the society for at least 30 years. Senior members and fellows retain all benefits of MSA membership (receiving *Elements*, voting, reduced rates on MSA products, etc.), but need not pay dues. They can subscribe to the paper or electronic versions of *American Mineralogist* or other journals, purchase society publications, and attend short courses all at member rates. If you are interested in senior status, select senior member or fellow dues on your next renewal and write us in the text box that you would like to become a senior member.

- If you subscribe to other journals through MSA—*Journal of Petrology*, *Physics and Chemistry of Minerals*, *Rocks & Minerals*, *Mineral News*, or *Gems & Gemology*—please renew early. MSA needs to forward your renewal to the respective publishers before your subscription runs out.

J. Alex Speer, MSA Executive Director
jaspeer@minsocam.org

2012 CALENDAR: *ARIZONA MINERALS*

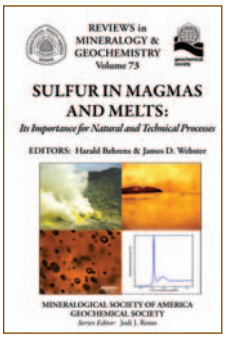


Arizona was granted statehood on February 14, 1912. This calendar is part of a community-wide Centennial tribute to Arizona's minerals and mines and to their champions.

Published by Lithographie, LLC, in cooperation with MSA and Martin Zinn Expositions, it is available from MSA, **www.minsocam.org**.

REVIEWS IN MINERALOGY & GEOCHEMISTRY

MINERALOGICAL SOCIETY OF AMERICA
AND THE GEOCHEMICAL SOCIETY



Volume 73 • Sulfur in Magmas and Melts: Its Importance for Natural and Technical Processes, Harald Behrens and James D. Webster, Editors. i–xiv + 578 pages, 2011 ISBN 978-0-939950-87-4, $40 ($30 for members of MSA, GS, CMS)

Following an overview in chapter 1, this volume is divided into 4 parts: (1) Analytical and Spectroscopic Methods – chapters 2 and 3; (2) Physical and Chemical Properties of S-Bearing Silicate Melts – chapters 4–7; (3) Constraints from Natural and Experimental Systems – chapters 8–11; and (4) Natural and Technical Applications – chapters 12–16.

For more description, a table of contents of this book, and online ordering, visit www.minsocam.org or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110, USA; phone: +1 (703) 9950; fax: +1 (703) 652-9951; e-mail: business@minsocam.org.

AMERICAN MINERALOGIST

EDITORS: Martin Kunz, Jennifer Thomson, and Ian Swainson

Call for Special Associate Editors

Of course, all *American Mineralogist* associate editors are special. They are hardworking and very generous of their time. A special associate editor would organize papers on a specific topic to create a collection—see the Amorphous Materials collection, for example, via GeoScienceWorld or the MSA website (http://ammin.geoscienceworld.org/misc/specialissuelist.dtl).

We would like volunteers for the topics of:
REE Mineralogy
Mineralogy and the Nuclear Industry
Deep Earth and Planetary Mineralogy—High-P and High-T Minerals
Additional topic suggestions welcome!

All special collection papers go through the same peer review and editorial process as any other paper. They are published when ready and not held up waiting for slower papers to finish. But the collection also grows virtually over time via the web!

Would you like to be a special associate editor for one of these topics? In this capacity, you would:

- Organize a call for papers on your topic
- Find reviewers for submissions
- Create detailed revision instructions for authors
- Recommend acceptance (or rejection) to the editors
- Provide additional editing help as needed
- Write a preface or introduction to go with the first batch of papers

Inquiries are welcome about volunteering as an associate editor. Contact and other information: ww.minsocam.org/MSA/AmMin/Special_Section.html.

Quick Facts

Average of recent 316 papers: submission-to-acceptance time: 137 days (~4.6 months) (s.d. 88 days) • Submission-to-publication: 293 days (~10 months) (s.d. 99 days) • See our list of most read and most cited papers via GSW: http://ammin.geoscience- world.org.

American Mineralogist
Founded in 1916

The Clay Minerals Society

www.clays.org

THE PRESIDENT'S CORNER

Paul Schroeder

Taking Risks

Taking a risk is part of everyone's day. Some risks are big and some small. For those who don't know me, I've broken so many bones related to motorcycle, skiing, and other racing sports, my wife stopped counting when the number reached double digits. So speaking from experience, taking a big risk can result in a big failure. The flip side is big reward. Finding the balance between reward and failure is really the way clay science advances. I begin by thanking all CMS members in industry, government, and academia who are willing to risk their time and resources to mentor new clay scientists (in my case it was Taylor Loop, Larry Doyle, Harry Dahl, Bob Reynolds, and Bob Berner). This is my last President's Corner, so I'd like to share some ideas that might be considered, with the realization that there are associated risks.

Our initiative to create a Distinguished Lecturer program is moving forward. Tentatively, each year the Distinguished Lecturer will deliver a talk designed to broaden and advance ideas in clay science. The target audiences will include large groups assembled at a public forum, such as colloquia held at colleges/universities, special events, or societal meetings not normally focused on clay science. The subject will be at the discretion of the Distinguished Lecturer; however its content will be crafted in a way to reach a broad range of scientific interests beyond clay science. Topics will be appreciated by a variety of audiences, ranging from first-year undergraduates to seasoned researchers. Here's the risk. CMS agrees to pay travel transfer expenses for the Lecturer, with a limit of $3000 per year. The host organization agrees to pay local transfers, accommodations, and meals for the Distinguished Lecturer (i.e. the risk is shared). If this fails, we have lost the money. The reward however is the ambassadorship of ideas, resources, and knowledge that clay scientists have developed and the hope they may be used to benefit medical science, environmental cleanup, agricultural productivity, materials development, or natural resource sustainability.

Clever CMS members are already taking risks as I write, and here are a few ideas I suspect are already in the works to be delivered with great reward. Industry: In addition to selling bulk and filler clays at hundreds of dollars per ton, clays will be modified on-site and sell at tens of thousands of dollars per ton. At that rate, students could be hired, plants modernized, and energy efficiency increased. Government: Regulate with reason, monitor our environment in real time, and educate the public (and our elected officials) about sustaining clay resources. This includes developing soils, fossil fuels, and clay deposits in a way that considers people living 10 generations from now. Yes, I know that's a long time from now. Academics: Success rates for submissions to competitive grant programs are seemingly below 10% (at least for me!). This prospect hinders enthusiasm to advance novel ideas. The risk of failure is not in having your funding proposal declined but in failing to learn something new when formulating your proposal; so keep submitting. Also, continue to put time into student mentoring; don't ever attempt to predict the outcome of a student on the first day you meet them. I've often been wrong (in a good way).

Finally, I wish the best to my presidential successor, David Laird. If we were on Broadway, I'd say, "Break a leg," but I've already done that several times and it's not fun. Take a risk with your clay science today. Now that's fun!

Paul Schroeder (schroe@uga.edu)
President, The Clay Minerals Society

2011 CMS AWARDEES

The following awards were presented at the CMS annual meeting in South Lake Tahoe, USA. Details of the awardees' presentations will appear in the December issue of *Elements*.

Sridhar Komarneni

The Marilyn and Sturges W. Bailey Distinguished Member Award was presented to **Dr. Sridhar Komarneni**, Distinguished Professor of Clay Mineralogy, Department of Crop and Soil Sciences and Materials Research Institute, The Pennsylvania State University. Dr. Komarneni has made fundamental contributions to the field of clay mineralogy through his investigations of the atomic architecture and nanostructure of clay minerals using a variety of techniques, including solid-state nuclear magnetic resonance spectroscopy and transmission electron microscopy. He has shown creative excellence in the design and synthesis of novel clays, which are expected to have a tremendous impact on providing clean drinking water worldwide through filtration and soil remediation. Dr. Komarneni has also designed and synthesized new nanocomposites of clays with oxides and metals, which are useful as desiccants and catalysts, respectively.

Douglas McCarty

The Marion L. and Chrystie M. Jackson Mid-Career Clay Scientist Award was presented to **Dr. Douglas McCarty**, Senior Staff Geologist, Chevron Energy Technology Company. Dr. McCarty has developed new methodologies for studying clay-bearing sedimentary rocks, clays, and other rock-forming minerals. His research combines a knowledge of geology, petrology, and mineralogy with contemporary experimental methods. Dr. McCarty's research involves studies of the structural and crystal-chemical features of clay minerals, including periodic and defective structures, which have led to the discovery of mechanisms for structural and phase transformations of these minerals in various natural processes. In addition, he has greatly improved the practice of quantitative mineral analysis, having been one of the founders of the Reynolds Cup competition.

Glenn Waychunas

The Pioneer in Clay Science Lecture was delivered by **Dr. Glenn Waychunas**, Senior Scientist, Geochemistry Department, Lawrence Berkeley National Laboratory. Dr. Waychunas was one of the first to use synchrotron X-ray absorption spectroscopy to study mineral interfaces, including arsenate uptake on ferrihydrite. This work has sparked investigations of mineral–water interfaces at several synchrotron facilities. In 2005 he helped to form the Berkeley Nanogeoscience Center for studying nanoparticle structure, formation, aggregation, and transformations.

International Association of GeoChemistry

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PRESIDENT'S MESSAGE

Clemens Reimann

Last week I spent my time submitting two papers and a conference abstract. I guess you can all imagine what I was busy with: editing the papers, and especially the conference abstract, to meet the publisher's demands. It was certainly not science! And I wondered, as I have often done before: Is this really effective? I was typesetting, and I was entering the authors' names and affiliations and the names of the suggested reviewers not only once but up to three times on the different websites. In short, lots of fun and very time consuming.

I am old enough to remember the time when we still had secretaries to do a lot of this work, when the journal offices offered help in typesetting and even went to the length of redrawing figures if the submitted version was "not good enough." All this is gone. When we want to publish in open access journals, we even have to pay for the publication of papers that we submit more or less print ready. These days everything is "do it yourself." The argument I often hear is, "But it is all so easy these days with the computer and much more effective." Is it really?

I have noticed the last couple of years that it is increasingly difficult to find reviewers for manuscripts coming in for publication. It is also becoming more difficult to find volunteers for the work in our learned societies. I hardly find time to read through the issues of the few journals that I still get. Where has all that time gone? I think you all know the answer: it goes to typesetting, filling in time sheets, writing travel bills of ever increasing complexity, preparing project proposals exactly according to prescribed standards, and reading through pages and pages of "author instructions" on the Internet. Is that really the way we want it? Do we really want less and less time for science and ever increasing bureaucracy? Is there really nothing that can be done about this?

If you want to see how science could function, I strongly recommend that you read the Goldschmidt biography by Brian Mason (*Victor Moritz Goldschmidt: Father of Modern Geochemistry*, 1992, Geochemical Society). Of course Goldschmidt was an exceptional geochemist. But do we really need to wonder why science made such great advances during these years? Might it have something to do with the fact that scientists were allowed to do what they are really good at: science instead of administration?

I have a very personal message to our young scientists: Do not lose sight of the fact that it is the science that is paramount, not all this bureaucracy that is forced upon us these days. Keep in mind that it is the science that counts and not the number of letters in the title of a paper or in the research highlights that many journals now require. It is the science that is the interesting and important part of our work. Solving the many societal needs that require the expertise of a geochemist is our real task!

Clemens Reimann
(Clemens.Reimann@NGU.NO)
IAGC President

GEOCHEMISTRY OF THE EARTH'S SURFACE (GES-9)

Superbly organized by Suzanne Anderson, the IAGC-sponsored GES-9 meeting was held on 3–7 June 2011 in Boulder, Colorado, USA, on the campus of the University of Colorado. Drawing more than 120 participants from 12 countries, the meeting addressed the following themes through keynote lectures and poster presentations: critical zone processes, organic contaminants, microbial geochemistry, environmental geochemistry, and landscape integration. A full report on the conference will appear in the next issue of *Elements*.

GES working group leadership. From left to right: Steven Banwart, Suzanne Anderson (GES-9 Chair), Jérôme Gaillardet (GES-10 Chair), Siggi Gislason (GES Working Group Leader), Mark Hodson (GES-8 Chair)

CALL FOR IAGC 2012 AWARD NOMINATIONS

Now is the time for 2012 IAGC award nominations! The window of opportunity for nomination submission will extend through 30 November. The awards to be bestowed in 2012 are the Vernadsky Medal, the Ebelman Award, the Distinguished Service Award, the IAGC Fellow award, and the IAGC Certificate of Recognition. For a summary of the awards and instructions on how to submit your nomination, visit www.iagc-society.org/awards.html.

2012 PHD STUDENT RESEARCH GRANTS

Generously supported by Elsevier, the IAGC PhD student research grants help support the cost of analytical needs of geochemistry PhD students. Up to three PhD student research grants (US$3,000 maximum) may be awarded annually, based upon receipt of deserving proposals, as determined by the Committee. Applications for 2012 will be accepted through 1 December 2011. Funds will be dispersed to winning applicants before 1 May 2012. Recipients will be profiled in *Elements*, on the IAGC website and in the spring edition of the *IAGC Newsletter*. Recipients will also receive a one-year complimentary IAGC membership. For application instructions and to download the necessary forms, please visit www.iagc-society.org/phd_grants.html.

Mineralogical Society of Great Britain and Ireland

www.minersoc.org

FROM THE PRESIDENT

100 Most Important Questions in Mineralogy

Richard Pattrick

You will probably have seen the initiative to determine the 100 most important questions in mineralogy. I encourage you all to embrace this enterprise. Very heartening support has been received from many national societies, and I thank you for that. It is no gimmick – it is a serious attempt to demonstrate the importance and pervasive role mineralogical research will play in many of the academic and applied challenges facing the world. The perception of 'mineralogy' to much of the public may be limited to the pretty specimens that decorate rock shops. Even colleagues in academia can be sadly ignorant of the range and complexity of the science and engineering on which our research impacts and of the variety of investigative techniques we use. Other disciplines are fast defining their future roles – here is a chance for *our* global community to reveal its importance, define its future role and produce a document for the co-ordinated lobbying of decision makers. The fact you are reading *Elements* means you have a serious interest in activities related to mineralogy. So please visit www.100-questions.org and place your question.

Mark Welch Stands Down as Principal Editor of Mineralogical Magazine

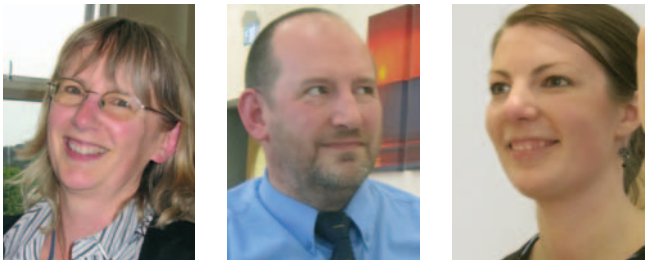
I must add my thanks to Mark Welch for his six-year tenure as Principal Editor of *Mineralogical Magazine*. During this period, the time from submission to publication fell dramatically (to as little as 17 days in one case) and quality improved measurably. I think it is a testament to Mark's work that we have been able to recruit editors of the calibre of Peter Williams and Roger Mitchell to succeed him. Many thanks to Mark and good luck to Pete and Roger.

Richard Pattrick
President, Mineralogical Society

FRONTIERS IN ENVIRONMENTAL GEOSCIENCE

Report of Annual Conference

This year's Annual Conference of the Mineralogical Society was held in the pleasant surroundings of the University of Aberystwyth on the Welsh coast. Many delegates joked about the challenge of making it to Aberystwyth. It is a three-hour train ride from Birmingham International Airport! Erika Greisshaber drove from Zurich to Aberystwyth to attend the meeting and chair her session. She returned afterwards to complete a beamtime session at the Swiss light source. Dedication to the cause! Surely the science and the friendly welcome made it all worthwhile for everyone though.



The convenors of Frontiers 2011, Karen Hudson-Edwards of Birkbeck University of London, Nick Pearce of Aberystwyth University and Ruth Warrender of SRK, Cardiff

The conference began with a musical icebreaker reception. Heavy rain outside threatened to dampen enthusiasm, but the Côr cymysg o Aberystwyth a Bro Ceredigion (local choir) and a glass or two of wine soon lifted delegates' spirits. The reception was held in the rarified surroundings of the National Library of Wales, and the singing was most uplifting.

The science began in earnest on Tuesday, June 21, with a session entitled 'Applied Mineralogy of the Critical Zone: Metal Reactions at Mineral Surfaces,' convened by John Bowles, Caroline Peacock, Hazel Prichard and Pascal Reiller. After a brief introduction by the session chair, John Bowles, the session began with a keynote talk by Dave Sherman titled 'Metal Complexation by Minerals Surfaces: From Molecular Insights to Thermodynamic Models'. The session also contained an invited talk by Dmitri Vlassopoulos: 'Approaches to In Situ Remediation of Mercury and Arsenic Contaminated Soils and Sediments Using Mineral Amendments'.

Session 2,'Reactivity and Toxicity of Nano- and Micro-Particles in Natural and Contaminated Environments', was convened by Karen Hudson-Edwards and Kevin Taylor. The keynote talk was delivered by Eva Valsami-Jones and had the title 'Reactivity and Toxicity of Engineered Nanoparticles: Linking Physicochemical Properties to Behaviour'.

The first afternoon session (3) was entitled 'Shining Synchrotron Light on the Natural Environment: Metals, Microbes and Minerals' and was convened by Sam Shaw and Caroline Peacock. The keynote talk was by the Society president, Richard Pattrick, and had the title 'Investigating Mineral Systems Using Synchrotron Soft X-rays'. The session also had an invited talk by Gareth Law entitled 'The Environmental Biogeochemistry of Neptunium – An XAS Study'.

Jill Banfield receiving her Hallimond Lecturer certificate from Richard Pattrick

The final session of the day (4) was 'Biological Mineralization: Palaeoarchives, Natural Functional Materials and Bacterial Mineralization Processes', convened by Erika Griesshaber and Wolfgang Schmahl. The keynote talk, 'From Confinement to Composites: A Biological Perspective', was delivered by F. Meldrum. The first day concluded with a poster session accompanied by locally brewed beer.

Day two consisted of a half-day plenary session (session 5) comprising three invited lectures. The first was the Hallimond Lecture, the Society's foremost invited lecture. It was delivered by Jill Banfield and had the title 'Subsurface Microbial Diversity and Microbe–Mineral Interactions'. This talk, as befits a multidisciplinary meeting like this one, had a strong bio-focus. Dr Banfield spoke passionately about the need to remove barriers between areas of science. She will produce a short paper highlighting this and other themes from her talk for publication in *Mineralogical Magazine*.

Georges Calas, Schlumberger Award winner for 2011

The second talk was by Georges Calas, this year's winner of the Mineralogical Society's Schlumberger Award. His talk had the title 'Impurities and Defects in Minerals: Witnesses of Environmental Processes'. Georges has used synchrotron radiation in his research since the technique was invented and has been one of those responsible for opening the door to this analytical tool to mineralogists.

Andy Rankin (left) receiving the Mineralogical Society's Collins Medal from Richard Pattrick

The third talk, 'The Application of Fluid Inclusion Studies to Some Major Issues in the Environmental Geosciences', was by the Mineralogical Society's 2011 Collins Medal winner, Andy Rankin. He began his talk by speaking about his background in the science and how he moved to fluid inclusion research.

Session 6, 'Mine Drainage – Mineralogy, Geochemistry, Remediation', was convened by Nick Pearce and Bill Perkins. The keynote was delivered by Phil Verplanck and had the title 'Determining the Origin of Portal Discharge by Underground Sampling, the Standard Mine, Crested Butte, Colorado, USA'.

In Session 7, 'Geochemical and Biogeochemical Behaviour of Radionuclides and Toxic Elements in the Environment', convened by Ian Burke, Sam Shaw and Gareth Law, the keynote was delivered by Dave Polya and had the title 'Biogeochemical and Hydrogeological Controls on Arsenic Mobilization in Aquifers – Implications for Secular Changes in Groundwater Arsenic Hazard and Concomitant Health Risks in Southern Asia'.

Afternoon Session 8, 'Ash and Aerosol Emissions from Active Volcanoes: Characterizations, Processes and Impacts', was convened by Tamsin Mather and Rob Martin. The keynote by Pierre Delmelle was entitled 'Understanding the Reactivity of Volcanic Ash in the Environment'.

Session 9 was 'Geologic Carbon Capture and Storage: Observations and Models of Mineral–Fluid–Microbe Interactions and CO_2 Transport'. The keynote talk, 'Natural Analogues for Geological CO_2 Storage: A Reality Check for Computer Simulation?,' was given by Mark Wilkinson. An invited talk delivered by Dominique Tobler had the title 'Plugging of Porous Media Using Ureolysis-Driven Calcite Precipitation and Its Potential for Sealing Leaks at CO_2 Storage Sites'.

In total, there were three plenary lectures, 42 other oral presentations and 22 posters, which were attended by 90 delegates from 16 countries. A longer version of this report, with more photographs, is available in the archive section of the Mineralogical Society website. A full copy of the programme and the abstracts volume is also available at www.minersoc.org/pages/meetings/frontiers-2011-archive/frontiers-2011-report.html. A special issue arising from the meeting is planned for early 2012. More news of this will be provided as it becomes available. Many thanks to Karen, Nick and Ruth, to the Mineralogical Society staff, to departmental colleagues in Aberystwyth, and to the staff at the university for helping to make this meeting a success.

New Focus for Environmental Mineralogy Group

The bio-focus of this meeting was a fitting lead-in to a new departure for the Environmental Mineralogy Group. In 2012 a joint meeting with the Society for General Microbiology will hopefully be the first in a series of joint events between the two groups, catering for the growing number of people interested in the interface between minerals and microbes.

Kevin Murphy, Executive Director

THEMATIC SET OF PAPERS FOR *MINERALOGICAL MAGAZINE*

A set of papers arising from the September 2010 Annual Conference was published in the August 2011 issue of *Mineralogical Magazine*. This set includes the following papers:

- Actinides and radiation effects: impact on the back-end of the nuclear fuel cycle, R.C. Ewing
- Interfacial reactivity of radionuclides: Emerging paradigms from molecular-level observations, A.R. Felmy, E.S. Ilton, K.M. Rosso and J.M. Zachara
- A review of analogues of alkaline alteration with regard to long-term barrier performance, D. Savage
- Recrystallization of metamict allanite, T. Beirau, C. Paulmann and U. Bismayer
- Microbiological influences on fracture surfaces of intact mudstone and the implications for geological disposal of radioactive waste, H. Harrison, D. Wagner, H. Yoshikawa, J.M. West, A.E. Milodowski, Y. Sasaki, G. Turner, A. Lacinska, S. Holyoake, J. Harrington, D. Noy, P. Coombs, K. Bateman and K. Aoki
- Sorption of Tc(IV) to some geologic materials with reference to radioactive waste disposal, R.J. Hallam, N.D.M. Evans and S.L. Jain
- Research and development for geological disposal of higher activity wastes: the role and expectations of the Environment Agency, C.R. Cailes, I. Barraclough, R.E. Smith and G. Thomson
- Redox interactions of technetium with iron-bearing minerals, J.M. McBeth, J.R. Lloyd, G.T.W. Law, F.R. Livens, I.T. Burke and K. Morris

EMU NOTES IN MINERALOGY VOLUME 11 PUBLISHED

The eleventh book in the EMU Notes in Mineralogy series, *Layered Mineral Structures and Their Application in Advanced Technologies* (M.F. Brigatti and A. Mottana, editors), from the European Mineralogical Union and the Mineralogical Society, has been published.

This volume aims to provide an in-depth knowledge of the complex field of layered materials and addresses diverse and fundamental aspects, including crystal chemistry and structure, layer packing disorder, surface properties and the description of the most advanced experimental techniques for the characterization of layered materials.

The book is now available from the Mineralogical Society bookshop (£25.50 for individuals, £40 for libraries and other institutions). Follow the link to the online bookshop from www.minersoc.org.

Association of Applied Geochemists

www.appliedgeochemists.org

FROM THE PRESIDENT

Paul Morris

In AAG's March 2011 edition of its quarterly magazine *EXPLORE* (all copies of *EXPLORE* can be downloaded for free from AAG's website at www.appliedgeochemists.org), I discussed the geographic diversity of the association's membership, which is currently drawn from over 50 countries. This membership is drawn from government, academia and industry, and includes some of the foremost practitioners in the development and application of geochemical techniques. Many of these are current AAG officers, and some have held one or more such positions in AAG for significant periods during its 40-year history. Despite the commitment shown by a number of members, the future health of the association can only be guaranteed if we continue to add younger members, who will eventually take on leadership roles in the association. Although this is now happening, there is an ongoing need to attract and retain student members who have an interest in applied geochemistry. We are concerned that the membership includes only a small number of students. Like other professional organisations, AAG offers financial incentives to attract and support students, such as subsidised membership and financial help to a number of students to attend its biennial International Applied Geochemistry Symposium (IAGS). However, in order to foster applied geochemistry and boost AAG's student membership, a new initiative by AAG's Education Committee is being developed and is nearing completion. By means of this initiative, AAG will connect applied geochemistry students with analytical laboratories that will provide geochemical analyses to support the student's research work. The initiative is seen as being of benefit to all parties. Those interested in following up on this approach – and other planned areas of support for applied geochemistry students – are advised to keep a watch on *EXPLORE*. I am sure that students who participate in these AAG programs will realise the collateral benefits of belonging to the oldest applied geochemistry professional body, and some will take up the opportunity to steer it in the future.

Paul Morris (paul.morris@dmp.wa.gov.au)
Geological Survey of Western Australia
AAG President

NEWS FROM AAG REGIONAL COUNCILLORS

EuroGeoSurveys Geochemistry Expert Group Activities

The EuroGeoSurveys Geochemistry Expert Group (EGS-GEG) has at present 53 official EGS members, and, including associate members from outside organisations, more than 70 scientists participate in the activities of the group. The group closely cooperates with colleagues from the USGS (David Smith) and Geoscience Australia (Patrice de Caritat), where comparable continental-scale geochemical mapping programmes are being carried out.

The mission of EGS-GEG is to provide high-quality geochemical data for near-surface materials, to develop harmonised databases for multipurpose use and to provide independent expert advice to the European Commission. To achieve this mission, systematic geochemical data for the whole of Europe are being generated by harmonised methods of sampling of near-surface materials (soil, stream or floodplain sediment, water), sample preparation, chemical analysis, quality control, data processing and presentation. The systematic geochemical information is published in the form of geochemical atlases, which are freely available and can be used for (1) state of the environment reports, (2) mineral exploration, (3) agriculture, (4) forestry, (5) animal husbandry, (6) medical geology, (7) determination of natural background values for environmental risk assessment, and other purposes.

EGS-GEG succeeded the FOREGS Geochemistry Group, which at the end of its activities had produced the *Geochemical Atlas of Europe*. The EGS-GEG is currently carrying out two large projects, the Geochemistry of European Agricultural and Grazing Land Soil (GEMAS) and Urban Geochemistry (URGE), which will keep the group busy for the next three years. The EGS-GEG has just completed a project on European groundwater geochemistry using bottled water as the sampling medium. The results of this project have been published in an atlas (Reimann and Birke 2010), whereas several more detailed national interpretations have been published in a special issue of the *Journal of Geochemical Exploration* (volume 107, issue 3, pages 217-422). The latter volume includes 15 contributions from national teams in Croatia, Serbia, Slovenia (2), Greece (2), Slovakia, Hungary, Italy (2), Fennoscandia, Germany (2), Portugal and Estonia.

Other activities of EGS-GEG for the period 2010–2013 include (1) publication of a book on urban geochemistry studies in April 2011 (Johnson et al. 2011), (2) data elaboration and publication of GEMAS project results, and (3) publication of new results from the *Geochemical Atlas of Europe* project. It is noted that because of industry restrictions the GEMAS atlas will be published in 2013.

The URGE project is being carried out by a sub-group of the GEG led by Rolf Tore Ottesen of the Geological Survey of Norway. The aim of URGE is to carry out urban geochemical mapping of 10–12 European cities using a common sampling and analytical protocol, ensuring that results are directly comparable across the continent. The sampling is being carried out during 2011, all analytical results will be available in 2012, and "final reporting" will occur around the end of 2014.

Benedetto De Vivo (bdevivo@unina.it)
Università di Napoli Federico II

RECENT ARTICLE PUBLISHED IN *EXPLORE*

Stephen Amor (2011) Responses in lake sediments and waters to occurrences of rare earths and rare metals in the Canadian Shield. *EXPLORE* 151 (September 2011)

A number of deposits of rare earth elements (REE) and rare metals (RM) in the Canadian Shield are compared in terms of their geochemical response in lake sediments and waters. The geochemical data were drawn from the Geological Survey of Canada's National Geochemical Reconnaissance (NGR) lake-sampling program and from programs carried out by the geological surveys of Ontario and Quebec. Most of these data are available for free download. Mineral-occurrence data were derived from online mineral deposit databases for the provinces and territories and from company websites.

Responses vary from strong and focused, through regional and not directly associated with known deposits, to none at any scale. For occurrences that do have a geochemical signature, fluoride in lake water (Fw) and Mo in lake sediment frequently show an anomalous response, as do the REE (and certain RM). Therefore, Fw and Mo constitute useful pathfinders for these occurrences, particularly where analyses of REE and RM have not been carried out on the sediments. Occurrences of Li show little or no response, even in Li itself, although there is no lake-sampling coverage over certain important Li camps.

There are many untested anomalies in the Canadian Shield suggestive of the presence of REE/RM mineralization, particularly in northeastern Saskatchewan, northern Manitoba, southeastern Nunavut and Labrador. Many are situated in ground that is currently unstaked. However, in the presence of other favourable indicators, the absence of a REE/RM anomaly in lake sediments and waters is not a reason to write off an area's prospectivity.

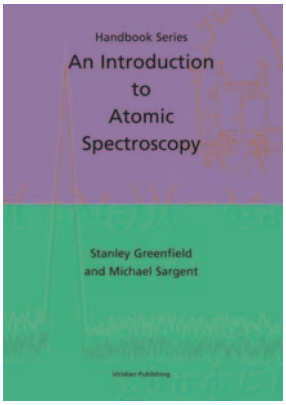
Stephen Amor (StevenAmor@gov.nl.ca)
Geological Survey of Newfoundland and Labrador

International Association of Geoanalysts

http://geoanalyst.org

VIRIDIAN PUBLISHING

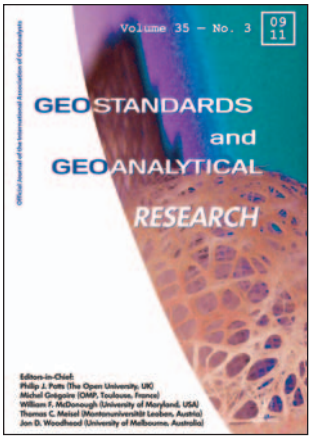
The International Association of Geoanalysts has renewed its tie-up with Viridian Publishing (www.viridian-publishing.co.uk), allowing IAG members to enjoy a 20% discount off the cover prices of a range of texts devoted to analytical (geo)chemistry. Viridian has long specialized in the reissuing of classical texts devoted to specific aspects of geoanalysis. Their current offering consists of six volumes issued in paperback format, thus allowing both professionals and students access to works detailing all aspects of, for example, ICP–AES, neutron activation analysis and atomic absorption and fluorescence spectroscopy. A full 40% discount on the already modest cover prices will be provided to IAG members wishing to purchase the full suite of six volumes. Further information is available on the IAG's web page under "membership."



Published earlier this year, *An Introduction to Atomic Spectroscopy*, by Stanley Greenfield and Michael Sargent, is the latest offering from Viridian Publishing. This newly released 128-page volume provides an overview of nearly all aspects of atomic spectroscopy, with a particular emphasis on the historical development of this key analytical field. As this book was written by two of the founders of modern analytical spectroscopy for the quantitative determination of metallic species, the reader would expect much insight into the thought processes which led to key advances during past centuries and recent decades. And here the reader is richly rewarded. Written for both the professional analyst and advanced-level students, this text also discusses various designs which have been employed in both atomic emission and atomic fluorescence instrumentation, and includes detailed descriptions of the physical theories governing a given process. Other chapters are devoted to critical aspects of the quantification process, including both the fundamentals of spectra generation and the methods by which quantitative data can be acquired. For analysts interested in the history of atomic spectroscopy or in a well-balanced review of the physics on which this family of methods is based, this latest publication from Viridian Publishing will be a welcome contribution.

GEOSTANDARDS AND GEOANALYTICAL RESEARCH

Geostandards and Geoanalytical Research, the official journal of the International Association of Geoanalysts, has recorded yet another success towards its goal of being *the* key information source devoted to all aspects of geoanalysis. With the release of the latest ISI report for the year 2010, *GGR* has increased its impact rating to 3.015, placing the journal 21st out of 165 in the field of multidisciplinary geoscience. As president of the IAG, I would like to congratulate the board of Editors-in-Chief of *GGR* as well as Wiley-Blackwell Publishers, which has supported the journal since 2007. In conjunction with steadily decreasing times for the review of submitted articles and earlier release of accepted manuscripts via the Wiley-Blackwell "Early View" system, *GGR* continues to attract top contributions in a broad range of topics related to the chemical characterisation of natural materials.



Another strength of *GGR* is its presence within the Wiley online library. The journal's web presentation has been significantly expanded in recent months to include such new features as a list of "Virtual Special Issues," Editors' Choice papers from 2009 to 2011 and a report of the most cited articles from the journal. These features are in addition to the classical content, such as author guidelines and online manuscript submission. Society members are reminded that they have full access to all the content of the Wiley online library, not to mention full electronic back issues of the journal reaching back to 1977, via their society membership. Find the link at www.geoanalyst.org.

Michael Wiedenbeck (michael.wiedenbeck@gfz-postdam.de)
President, International Association of Geoanalysts

THE SIX MOST CITED PAPERS FROM *GGR* (2008–2010)

- Nasdal et al. (2008) Zircon M257 – a homogeneous natural reference material for the ion microprobe U-Pb analysis of zircon. GGR 32: 247-265 (26 citations)
- Sims et al. (2008) An inter-laboratory assessment of the thorium isotopic composition of synthetic and rock reference materials. GGR 32: 65-91 (19 citations)
- Abraham et al. (2008) δ^{30}Si and δ^{29}Si determinations on USGS BHVO-1 and BHVO-2 reference materials with a new configuration on a nu plasma multi-collector ICP-MS. GGR 32: 193-202 (14 citations)
- Petit et al. (2008) Development of Cu and Zn isotope MC-ICP-MS measurements: Application to suspended particulate matter and sediments from the Scheldt estuary. GGR 32: 149-166 (7 citations)
- Verma et al. (2009) Relative efficiency of single-outlier discordancy tests for processing geochemical data on reference materials and application to instrumental calibrations by a weighted least-squares linear regression model. GGR 33: 29-49 (5 citations)
- Bolou-Bi et al. (2009) Magnesium isotope compositions of natural reference materials. GGR 33: 95-109 (5 citations)

German Mineralogical Society

www.dmg-home.de

PERALK-CARB WORKSHOP 2011

The international PERALK-CARB 2011 workshop on peralkaline igneous rocks and carbonatites took place on June 16–18, at the Institute of Geosciences at Tübingen University. For everyone working in this field, the PERALK-CARB workshop, initiated by Gregor Markl (Tübingen) and Anatoly Zaitsev (St. Petersburg), was a highlight in this year's conference program. Given the list of invited speakers, from Canada, Australia, and various European countries, it was no surprise that the community responded in style and filled the institute in Tübingen to its limits. Unlike the PERALK meeting of 2005, when the focus was on peralkaline rocks alone, this meeting was broadened by including carbonatites, with a special session dedicated to carbonatitic and associated silicic volcanism in the Gregory Rift. The participation of several representatives of exploration companies from Namibia, Canada, and southern Germany underlined the fact that the genesis of peralkaline and carbonatitic rocks is highly relevant to the mineral exploration industry.

The PERALK-CARB 2011 workshop started on Thursday with an ice-breaker party in an Ethiopian restaurant. The scientific program began the next day with a warm welcome by Gregor Markl, head of the petrology group in Tübingen. The concept of a single oral session and a single poster/coffee location ensured that all participants had opportunities to discuss the more than 60 presentations in a relaxed and friendly atmosphere. The first scientific session on Friday morning dealt with melt generation and magma sources for kimberlites and carbonatites. In the afternoon, the focus of the talks was on the magmatic and postmagmatic evolution of peralkaline rocks. Aspects covered included the roles of water, halogens, and oxygen fugacity in peralkaline melts; stable isotopes in amphiboles; hydrocarbons as tracers for melt and fluid evolution; and experimental studies on phase equilibria and the behavior of metals in peralkaline melts. At the poster session, participants perused the more than 35 posters on the mineralogical and geochemical peculiarities of peralkaline and carbonatitic rocks from around the world.

On the following day, the morning session was dedicated to the Gregory Rift. At this session, the unique natrocarbonatite volcanism of Oldoinyo Lengai and its relationship to associated silicate volcanic rocks was a key theme. The general consensus was that the natrocarbonatite lavas formed by liquid immiscibility from a carbonated silicate parent magma. Even though the spectacular landscape of natrocarbonatite activity was destroyed by explosive eruptions in 2007, recent photographs point towards renewed carbonatite activity in the crater. The afternoon session on carbonatites included experimental studies on liquid immiscibility, computer models, mineral chemistry investigations, structural aspects of metamorphosed carbonatites, and the physical volcanology of carbonatite eruptions. Later, the numerous helpers from Tübingen's petrology group held a barbecue in front of the institute, so that the lively discussions could continue uninterrupted. Even some minor rain showers did not disturb the good mood of the participants.

Without doubt, the PERALK-CARB 2011 workshop was a great success, as evidenced by the participants' enthusiasm on all questions related to peralkaline rocks and carbonatites. Thanks go to Gregor Markl and Anatoly Zaitsev, who, with financial support from the Alexander-von-Humboldt Society, initiated this workshop as part of a partnership between the institutes in Tübingen and St. Petersburg. In particular, Michael Marks is thanked for the perfect organization of the workshop; he and his helpers ensured that everything went smoothly and according to plan. That said, the community assembled in Tübingen is hopeful that a repetition of the PERALK-CARB workshop will be possible in the future!

Ralf Halama, Kiel

Participants of the DMG petrology section meeting. Photo: Kathi Faack

DMG PETROLOGY SECTION MEETING

This year's meeting of the Petrology Section of the DMG was held on July 1–2 at the Ruhr-University in Bochum. Scientists and students from Germany and beyond convened for a scientific program divided into four blocks, each with four to five talks. The talks in the first session focused on field-based petrology and metamorphic reactions. The following blocks dealt with experimental petrology, including processes in the upper oceanic crust, reactions deep in the mantle, the formation of minerals and rocks, the partitioning of elements between minerals and melts, and alteration phenomena. The meeting was also used to present and discuss some new tools and experimental setups, for example, an in situ sampling device for low-pressure and high-temperature experiments and the use of boron nitride as a possible container material. An afternoon poster session allowed young scientists to present their work. After the talks, a guided tour of the laboratories gave participants a closer look at the implementation and sputter facilities at Ruhr-University Bochum. The meeting ended with the traditional Saturday evening BBQ. We thank the organizers for putting on a perfect meeting and we especially thank the backstage helpers. The next meeting will be hosted by the Institute of Mineralogy at the University Münster.

Christof Kusebauch (Münster) and **Rauno Baese** (Kiel)

DMG PhD COURSE: XAFS SPECTROSCOPY

X-ray absorption fine structure (XAFS) provides information on the valence and the local atomic structure of selected elements. XAFS spectroscopy requires synchrotron radiation and therefore the course X-ray Absorption Fine Structure (XAFS) Spectroscopy: Theory, Measurement, Data Evaluation took place at the electron accelerator ANKA of the Karlsruhe Institute of Technology (KIT). On 23–25 November 2010, fifteen students, mainly PhDs and postdocs, participated in this course, held in English. The first day started with an introduction to the generation and properties of synchrotron radiation and to the theory of X-ray near edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) spectroscopy. A tour through ANKA gave participants an overview of the beamlines and their techniques and applications. In the exercises held afterwards, participants measured samples at the three ANKA XAFS beamlines. The day closed with discussions during dinner in a nearby restaurant.

The second day focused on data evaluation. Using different examples and the measurements from the previous day, participants became familiar with processing raw data and evaluating data on individual computers. The third day was reserved for independent data processing and helping participants with their questions. Thanks for insights into the XAFS technique go to the organizer, Joerg Goettlicher, and to the lecturers and supervisors, David Batchelor, Kathy Dardenne, Stefan Mangold, Joerg Rothe, Ralph Steiniger, and Tonya Vitova, from the KIT Institute for Synchrotron Radiation and Institute of Nuclear Waste Disposal.

Financial support from the German Mineralogical Society and KIT enabled this course to be held. The next course takes place at the end of November, 2011, and is announced at www.dmg-home.de/kursprogramm.html and http://anka.iss.kit.edu/english/622.php.

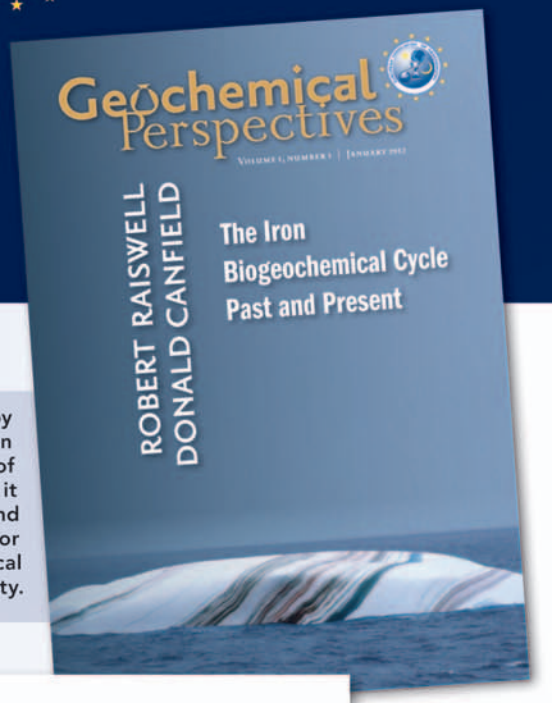
Christian Selleng, TU Bergakademie Freiberg

European Association of Geochemistry

www.eag.eu.com

Geochemical Perspectives

New journal in January 2012



Each issue of *Geochemical Perspectives* presents a single article with an in-depth view on the past, present and future of a geochemical field, as seen through the eyes of highly respected members of our community. The articles combine the research and the history of the field's development, the scientist's opinions for future research and can even include personal glimpses into the author's scientific life. *Perspectives* articles are intended to appeal to the entire geochemical community, not only to experts of one theme. They are not reviews or monographs, but provide perspectives about where the field is going and opinions about where it should go.

Published by the European Association of Geochemistry, it is entirely run and edited by and for the geochemical community.

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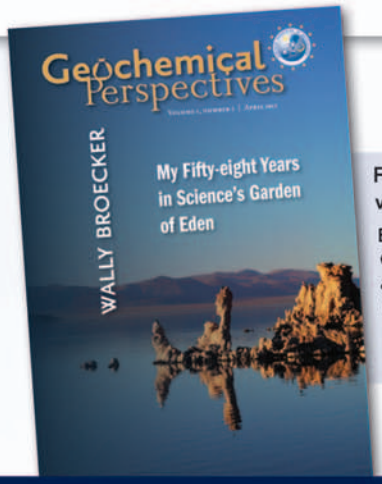

Future issues written by:

Bruce Yardley, Gordon Brown & Georges Calas, Charlie Langmuir, Bjørn Jamveit and Fred MacKenzie.

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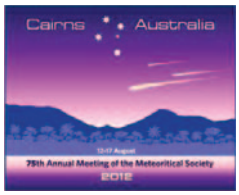
2012 ANNUAL MEETING



The 75th annual meeting of the Meteoritical Society will be held in Cairns, in the far north of Queensland, Australia, at the Cairns Convention Centre in 2012. The organizers invite you to attend the meeting and visit our city. Cairns, located close to the Great Barrier Reef and tropical rainforests, will make a spectacular location for our conference. The meeting will be held on August 12–17, which is in the dry season of the tropics.

We expect to have a wide variety of interesting scientific sessions, and we are also looking at running a field trip to notable craters in Australia. We are still in the planning stages, so please let us know if you are interested in participating. Full details as given in the first announcement are available on the LPI website, www.lpi.usra.edu, and more information is available on the local website, http://shrimp.anu.edu.au/metsoc2012. For information not available on the websites, please contact organizer Trevor Ireland at Trevor.Ireland@anu.edu.au.

We look forward to seeing you in Cairns in 2012.

STUDENT TRAVEL AWARDS

Over 40 students attending the annual meeting of the society in Greenwich, UK, in August received travel grants. We are most grateful to the many organizations and society members who contributed generously to the travel grant fund, especially the Barringer Crater Company, NASA (Cosmochemistry Program), the European Space Agency, the Meteoritical Society Endowment Fund, Dr. Lucy McFadden, and an anonymous donor. The awardees are listed below, together with the funding organization.

THE BARRINGER CRATER COMPANY

Alexandra Blinova, University of Alberta • Chelsea Brunner, University of New Mexico • Hana M. Chappell, University of New Mexico • Jangmi Han, University of New Mexico • Hatsumi Ishida, Tohoku University • Nataliya V. Kychan, Institute of Environmental Geochemistry, NAS of Ukraine • Seann J. McKibbin, Australian National University • Heba Tag Elsir Meadni, University of Khartoum • Ghada Mohammed Taha Osman, University of Khartoum • Xuchao Zhao, Institute of Geology and Geophysics, Chinese Academy of Sciences

NASA – COSMOCHEMISTRY

Andrew Beck, University of Tennessee, Knoxville • Eve Berger, University of Arizona • Maitrayee Bose, Washington University • Gregory A. Brennecka, Arizona State University • Melanie B. Channon, California Institute of Technology • Kathryn Gardner-Vandy, University of Arizona • Evan Groopman, Washington University • Ellen Harju, University of California, Los Angeles • Katharine Robinson, University of Hawai'i, Manoa • Matthew Sanborn, Arizona State University • Adam Sarafian, University of Georgia • Xiaoyu Shi, University of California, Davis • Rachel L. Smith, University of California, Los Angeles • Samantha E. Smith, Texas Christian University • Devin Schrader, University of Arizona • Driss Takir, University of Tennessee, Knoxville • Myriam Telus, University of Hawai'i, Manoa • Mark Tyra, University of New Mexico • Curtis Williams, Arizona State University

EUROPEAN SPACE AGENCY

Pia Friend, Institut für Geologie • Maartje Hamers, Utrecht University • Sanna Holm, Lund University • Matthew Huber, University of Vienna • Emmanuel Jacquet, Museum National d'Histoire Naturelle de Paris • Anna Losiak, University of Vienna • Sihane Merouane, Institut d'Astrophysique Spatiale • Veerle Sterken, Max-Planck-Institut für Kernphysik

METEORITICAL SOCIETY ENDOWMENT FUND

Arbab Ibrahim Arbab, University of Khartoum • Rogelio D. Acevedo, Centro Austral de Investigaciones Cientificas, Argentina • Hasnaa Chennaoui Aoudjehane, Université Hassan II, Aïn Chock, Morocco • Kuljeet K. Marhas, Physical Research Laboratory, India • Jayanta K. Pati, University of Allahabad, India • Vira P. Semenenko, Institute of Environmental Geochemisty, NAS of Ukraine • Pablo Munayco Solarzano, Universidad Nacional Mayor de San Marcos, Brasil

INTERNATIONAL METEORITE COLLECTORS ASSOCIATION – BRIAN MASON TRAVEL AWARD

Florian J. Zurfluh, Institut für Geologie, University of Bern

Brian Mason Award

In 1997, Joel Schiff, the first editor of *Meteorite* magazine, created a travel award in honor of Brian Mason. The award is given to a student attending the annual meeting of the society who submits an abstract that presents clearly explained, exciting results of particular interest to readers of *Meteorite* magazine. The recipient is required to write a popular account of his or her work for the magazine. Since 2008, the award has been generously funded by the International Meteorite Collectors Association.

This year the program committee for the Greenwich meeting selected **Florian J. Zurfluh** as the winner of the Brian Mason Award. Florian is a student at the University of Bern in Switzerland. He submitted an abstract entitled "New insight into the strontium contamination of meteorites," authored by F. J. Zurfluh, B. A. Hofmann, E. Gnos, U. Eggenberger, I. M. Villa, N. D. Greber, and A. J. T. Jull. This paper focuses on understanding the strontium uptake of meteorites found in hot deserts (Oman).

CALL FOR AWARD NOMINATIONS

Please consider nominating a colleague for one of the society's awards. Nominations should be sent to Secretary Greg Herzog (herzog@rutchem.rutgers.edu) by January 15 (January 31 for the Pellas–Ryder Award). For more information and details on how to submit a nomination for any of these awards, please see the latest Newsletter on the society website or e-mail the secretary.

The society presents a number of awards each year. The **Leonard Medal** honors outstanding contributions to the science of meteoritics and closely allied fields. The **Barringer Medal and Award** recognize outstanding work in the field of impact cratering and/or work that has led to a better understanding of impact phenomena. The **Nier Prize** recognizes outstanding research in meteoritics and closely allied fields by young scientists (under 35). The **Service Award** honors members who have advanced the goals of the Meteoritical Society to promote research and education in meteoritics and planetary science, in ways other than by conducting scientific research. The **Paul Pellas–Graham Ryder Award** is given for the best student paper in planetary science and is awarded jointly by the Meteoritical Society and the Planetary Geology Division of the Geological Society of America.

Geochemical Society

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THANK YOU VOLUNTEERS!

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Earth in Evolution

24-29 June 2012 | Montréal, Canada

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List of Sessions Finalized: 30 November 2011

Abstract Submission Opens: 1 December 2011

Abstract Submission Deadline: 1 February 2012

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A conference of the Geochemical Society and the European Association of Geochemistry, hosted by GEOTOP and UQAM

EARTH IN EVOLUTION

GOLDSCHMIDT MONTREAL JUNE 2012

CALL FOR EXECUTIVE EDITOR

Frank Podosek, who has been executive editor of *Geochimica et Cosmochimica Acta* for the past 12 years, will retire from this position at the end of 2012. The Geochemical Society and the Meteoritical Society, joint sponsors of the journal, are now looking for a replacement for Frank. Elsevier, which publishes *GCA*, has advertised the position on its website (http://recruitment.elsevier.com/jobs/view/197005-executive-editor-position/). If you are interested in being considered as the next executive editor of *GCA*, please send a resumé and cover letter to the chair of the Joint Publication Committee (JPC) of the two societies, Brigitte Zanda (zanda@mnhn.fr) before December 31, 2011. After the JPC has made its recommendation, the two societies will propose a candidate to Elsevier which will appoint the next executive editor for a three-year term, renewable for a second three-year term.

Société Française de Minéralogie et de Cristallographie

www.sfmc-fr.org

MEETING ANNOUNCEMENTS

State of Knowledge about the Geology and Ore Deposits in Madagascar in the 21st century

A meeting with the above title will be held at the Geological Society of France (SGF) headquarters in Paris, France, on December 6–7, 2011. It is part of the *Journées Géologiques* conference series of the SGF and is sponsored by a number of institutions, such as the Centre National de la Recherche Scientifique (CNRS), the Institut National des Sciences de l'Univers (INSU) and the Bureau de Recherches Géologiques et Minières (BRGM).

As its title suggests, the meeting is meant to be a state-of-the-art summit on recent advances by Malagasy researchers and their partners in the Earth sciences in Madagascar, particularly as applied to ore deposits. In addition to classic topics in economic geology, the meeting will cover environmental and social aspects, such as mine-related pollution and the socio-economic impact of mining activities on the population. This meeting follows from an INSU initiative and coincides with the review phase of a six-year PGRM (Projet de Gouvernance des Ressources Minérales) project, sponsored mainly by the World Bank for the Ministry of Mines and Energy of Madagascar, which was aimed at updating the geological mapping and mineral potential of the Precambrian basement of the island.

The scientific program will include a number of keynote presentations by scientists who have been particularly active in the country. It will conclude with a round-table discussion on future prospects for the scientific community working in Madagascar.

Organisers: **Stefano Salvi, Daniel Ohnenstetter, Didier Béziat,** and **Gaston Giuliani**

More information about the meeting can be found at: http://sgfr.free.fr/seance/Mada2011/

Contact: stefano.salvi@get.obs-mip.fr

Serpentine Days 2012 – Second Announcement

After the success met by the "Serpentine Days" meeting in Grenoble in 2007, a new edition will be held on 2–6 September 2012. The conference will take place in Porquerolles, a very welcoming island in the south of France. The meeting will be sponsored by the SFMC. More details will be given in the next issue of *Elements*. Further information will soon be available on the SFMC website at www.sfmc-fr.org/.

Organizing Commitee: **M. Andreani, A.-L. Auzende, A. Delacour**

BOOK ANNOUNCEMENT

Le cristal et ses doubles

Dr Jean-Claude Boulliard, éditions du CNRS, Paris, 350 pp and 247 figs

This book (in French) is devoted to crystal twinning (mainly) and epitaxial growth (briefly) in the mineral world. It is divided into three parts. The first part gives complete information on the history of research devoted to twinning. It starts with the first observations by Gautron de Robien and Romé de L'Isle and finishes with the work of Friedel, at the beginning of the 20th century, which included his well-known theory of twinning and the first attempts at a theory on epitaxy. The second part is an exhaustive survey of the scientific fields concerned with twins and twinning. The different theoretical (morphological, algebraic, etc.) and physical (growth, transition and mechanical twins) approaches used for the analysis of twinning are described. In this part, the author revises and minimizes the importance of Friedel's theory, and shows how a two-dimensional approach can explain the main results of Friedel's hypotheses. He also discusses the concept of pseudo-symmetry. The third part is more descriptive. It includes many photos of twinned and epitaxial minerals from the mineral collection of the UPMC-Sorbonne (campus Jussieu), which is managed by the book's author.

The First **European Mineralogical Conference** will be held at the Goethe-University in Frankfurt, Germany, **2–6 September 2012**.

planet earth
from core to surface
emc2012
2 - 6 September
european mineralogical
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The contributing societies currently are:

DMG	**Deutsche Mineralogische Gesellschaft**
MinSoc	**Mineralogical Society of Great Britain & Ireland**
ÖMG	**Österreichische Mineralogische Gesellschaft**
PTMin	**Mineralogical Society of Poland**
RMS	**Russian Mineralogical Society**
SEM	**Sociedad Española de Mineralogía**
SFMC	**Société Française de Minéralogie et de Cristallographie**
SIMP	**Società Italiana di Mineralogia e Petrologia**
SSMP	**Swiss Society of Mineralogy and Petrology**

Suggested themes for the meeting are as follows: Mantle petrology and geochemistry; Magmatism and volcanology; Metamorphism; Applied mineralogy; Clay mineralogy; Mineral physics; Mineralogical crystallography; Planetary materials; Mineral deposits and raw materials; Low-T geochemistry; Geochronology; Geobiochemistry; Advanced analytical techniques; Archaeometry, care and preservation; Open session.

There will be a series of invited lectures, notably including the acceptance speech of Prof. D. H. Green, recipient of the IMA Medal.
The scientific committee will consist of one representative from each society.
The local organizing committee: Gerhard Brey, Heidi Höfer, Sabine Seitz

WEB: emc2012.uni-frankfurt.de MAIL: info-emc2012@uni-frankfurt.de

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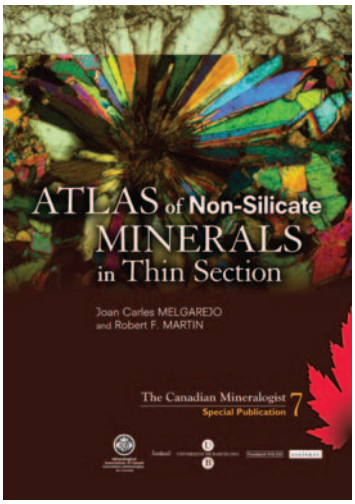
AT LAST, SPECIAL PUBLICATION 7!



MAC's Special Publication 7 is the long-awaited *Atlas of Non-Silicate Minerals in Thin Section*. When I first set eyes on *Atles d'Associacions Minerals en Làmina Prima* by Joan Carles Melgarejo in 1997, I was convinced that this monumental Atlas must be repackaged and published in English. I undertook to work with Joan Carles to make this a reality. We both invested the time necessary to bring the material up to date; we added important non-silicate minerals not covered in the 1997 version; and we chose to present the 408 minerals according to the time-honored Dana classification. In this way, the halides are presented together, as are the carbonates, sulfates, phosphates, organic minerals, etc. We refined the very useful section describing the mode of occurrence of the minerals chosen.

SP7 contains pertinent references keyed to those modes of occurrence, to which the reader can turn for additional information. I can imagine the boost that such an encyclopedic coverage of phosphates will provide a budding pegmatologist; for example, thin sections of assemblages containing all the likely primary and secondary phosphates are illustrated! The Quensel–Mason sequence is illustrated and explained! The same thing can be said about the complex assemblages resulting from the oxidation of ore deposits, which is of such great environmental concern. We added references to the latest investigations of the crystal structure and crystal chemistry of each mineral described. We added a DVD version of all illustrations in the book as a resource for those in the teaching profession still convinced that the study of minerals in thin section is a cornerstone in the investigation of natural assemblages of minerals in sedimentary, igneous, and metamorphic rocks, and in mine wastes. The book was created with both senior-level students and seasoned investigators in mind.

Unfortunately, a serious "dumbing down" is well under way; many students emerge from some prestigious universities without an appreciation of the diversity of minerals and their importance in a wide variety of terrestrial environments. Mineralogy has even been discarded as a core discipline in some Earth sciences curricula. The graduating class will thus be ill-prepared for the challenges that lie ahead. Part of the reason may well lie in the unavailability of adequate teaching materials and illustrations. Joan Carles and I, with the help of several contributors to SP7, have scoured the literature to provide the necessary information from a broad variety of fields and to highlight the exciting developments in the study of minerals. A careful petrographic analysis is an eye-opening experience; textural relationships among minerals are a fascinating area of investigation, where a researcher can begin to formulate working hypotheses about important petrological processes.

The Mineralogical Association of Canada and the authors are most grateful to the Osisko Mining Corporation for a grant-in-aid of publication. Thanks to their generous grant, this full-color book is offered at an affordable price to students and professionals. Work is under way to produce the sequel on silicate minerals.

Robert F. Martin
Earth and Planetary Sciences, McGill University

2012 MINERALOGICAL ASSOCIATION OF CANADA AWARDS

CALL FOR NOMINATIONS

Deadline to submit nominations for the Peacock Medal, the Young Scientist Award, and the Berry Medal is December 31.
Check our website for additional details
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PROFESSOR LESZEK STOCH, HONORARY MEMBER OF THE POLISH MINERALOGICAL SOCIETY, BECOMES AN HONORARY PROFESSOR

The rector of AGH, Prof. Antoni Tajduś, presents an Honorary Member diploma to Prof. Leszek Stoch (right). Photo Zbigniew Sulima

The title of Honorary Professor was conferred upon Prof. **Leszek Stoch** by the Senate of his alma mater, the AGH University of Science and Technology in Krakow. The ceremony was held on 4 July 2011. Leszek Stoch was born on 6 June 1931, the son of teachers. In 1949 he began his studies at the Academy of Mining and Metallurgy (AGH) in Krakow and in 1955, specializing in glass technology, graduated as a chemist-ceramist with an MScEng degree. In 1951, still a student, he took the job of deputy assistant and until his retirement in 2001 worked at his alma mater. He defended his doctoral thesis in 1960 (in the Faculty of Ceramics) and in 1966 presented his second-degree dissertation, which gave him the title of *doctor habilitatus*. In 1976 Leszek Stoch was nominated full professor. In the years 1971–1980 he held the post of Deputy Director at the Institute of Mineralogy and Deposits of Mineral Raw Materials. In 1980 he moved from the Faculty of Geological Prospecting to the Faculty of Materials Engineering and Ceramics, where he became the Chair of Glass and Enamels (1980–2001) and for six years (1984–1990) was the Dean.

The wide scientific interests of Professor Leszek Stoch were focused on the problems of clay minerals and mineral materials as well as on the technology of glass and biomaterials. He has authored about 260 papers, published mainly in scientific journals of international merit, and has obtained 14 patents. Particular attention should be paid to his book *Minerały ilaste* (*Clay Minerals*), published in Polish in 1974. His investigations on special glass types earned him in 1998 the prize of the Foundation for Polish Science (the so-called "Polish Nobel") in the technical sciences. He supervised 30 DSc students, seven of whom are now independent academics (five being university professors).

Professor Stoch is one of the founders of three scientific societies: the Mineralogical Society of Poland (and its clay minerals section), the Polish Ceramic Society, and the Polish Society of Calorimetry and Thermal Analysis. Since 1995 he has been the corresponding member of the Polish Academy of Arts and Sciences. Although reaching retirement age in 2001, Professor Stoch has remained active, continuing interdisciplinary research in the Earth sciences (mineralogy and the science of mineral raw materials), solid-state chemistry, materials science, and glass technology. Congratulations from the Mineralogical Society of Poland, dear Professor.

Krzysztof Bahranowski
AGH University of Science and Technology, Krakow

1st SCANNING ELECTRON MICROSCOPE WORKSHOP: APPLICATIONS IN EARTH SCIENCES (SEMWORKSHOP '11)

A three-day short course and workshop meeting was held on March 11–13, 2011, at the University of Silesia in Sosnowiec, Poland. It was organized by the Department of Geochemistry, Mineralogy, and Petrography of the Faculty of Earth Sciences, University of Silesia, and the Mineralogical Society of Poland. Key members of the SEMWORKSHOP '11 organizing committee were Radu Bailau, Eligiusz Szełęg, Ewa Teper, and Beata Zych. The meeting brought together 51 experts, professionals, and students from Estonia, the Netherlands, Romania, and Poland to review the applications, current state, progress, and challenges in the field of scanning electron microscopy. The short course included both theoretical aspects and practical training in this analytical method through a series of expert-led interactive teaching sessions, which were followed by group discussions on instrumentation, tools, and the capabilities of the technique. Participants were given the opportunity to analyze their own samples. Attendees also had a chance to examine the collection in the faculty's mineralogical museum.

The workshop program comprised eight oral presentations and six practical sessions. Invited speakers were Janusz Janeczek ("Introductory remarks on SEM"), Dirk van der Wal ("Recent developments in SEM and DualBeam instrumentation," and "Introduction to automated petrography and use cases in the geosciences, oil and gas, and mining"), Marek Michalik ("SEM in environmental geoscience"), Michał Zatoń ("Application of SEM in paleontology"), and Zbigniew Sawłowicz ("SEM [BSE and EDS] in taphonomy and more: practical remarks"). The practical sessions were conducted by Arkadiusz Piersa and Tomasz Kępiński (LabSoft), Artur Gazewski (Comef), and Ewa Teper (University of Silesia).

After their hard work, the happy participants enjoy a beer tasting at Tyskie Brewery.

In addition, two postconference field trips were held: (1) Tyskie Browarium Tour (Tyskie Brewery) with a beer tasting, and (2) Tarnowskie Góry silver mine—observing the silver and lead ores exploited from the 13th century up to the 1930s. The next workshop, SEMWORKSHOP '12, will take place in the spring of 2012 in Sosnowiec, Poland.

Radu Bailau and **Eligiusz Szełęg**

ECROFI XXI

On August 9–11, 2011, the 21st European Current Research on Fluid Inclusions (ECROFI XXI) meeting was held at the University of Leoben, Austria. The meeting was organized by Dr. Ronald Bakker and was preceded by a one-day field trip to the famous Sunk-Trieben magnesite deposit, led by Walter Prochaska and Amir Azimzadeh. The meeting was followed by a one-day workshop on applications of equations of state and computer programs in fluid inclusion research, taught by Ron Bakker. The alpine town of Leoben offered a convenient and relaxed atmosphere to host the conference, with many hotels, restaurants and pubs within a few minutes walk of both the conference site and the central square (Hauptplatz).

The ECROFI meeting and the related PACROFI (Pan-American Current Research on Fluid Inclusions) and ACROFI (Asian Current Research on Fluid Inclusions) meetings are small conferences that focus on research related to fluid and melt inclusions. They provide an excellent venue for beginning as well as experienced "inclusionists" to share and discuss research results with others. This year 85 researchers from 22 countries were in attendance, and 95 oral and poster presentations were delivered. The ECROFI/PACROFI/ACROFI meetings are especially beneficial to students, who are offered the opportunity to present and discuss their research results with experienced inclusionists in a setting that is encouraging and supportive.

Many significant advances in fluid and melt inclusion research were presented at ECROFI. Dominik Marti and co-workers and Rita Hidalgo-Staub and co-workers gave talks describing the effect of surface tension on the homogenization temperature of low-temperature inclusions, and the application to determining homogenization temperatures of inclusions in speleothems in order to extract paleotemperature information from cave systems for paleoclimate studies. David Banks (with Demange as senior author) spoke on the use of laser ablation ICP–MS for determining trace metal contents of hydrocarbon fluid inclusions associated with ore deposits and suggested that organics may be important for metal transport in some ore-forming systems. Bob Burruss discussed the application of coherent anti-Stokes Raman scattering (CARS) microscopy to produce high-resolution 3-D images and chemical maps of individual fluid inclusions. This application of CARS represents a major advance in our ability to image and analyze individual fluid inclusions and promises to significantly improve our understanding of fluid-mediated processes in the Earth. Volker Lüders described a new apparatus for analyzing both carbon and nitrogen isotopes of fluid released from inclusions, and Dublyansky and co-workers determined the hydrogen isotope composition of aqueous fluid inclusions in hydrogenic minerals and used this information to unravel the paleohydrogeology of the area near Yucca Mountain, Nevada, USA. Marta Berkesi and co-workers explained the application of focused ion beam (FIB) techniques to determine the compositions of crystallized melt inclusions in mantle xenoliths and documented that CO_2-rich fluids in the mantle transport significant amounts of incompatible trace elements. Alexandre Tarantola and co-workers described an experimental study in which fluid inclusions were subjected to deviatoric stress, and they also applied this method to study natural inclusions from the Central Alps. These workers showed that by determining the plane of flattening and the densities of intact and relict fluid inclusions, the magnitude and direction of maximum stress during low-strain deformation can be determined. Marta Sosnicka presented an excellent summary of fluid evolution during metamorphism of the Krivoy Rog iron deposit in Ukraine. In addition to oral presentations, a student poster competition was held at ECROFI, and graduate student Daniel Moncada was awarded first place for his poster on the application of mineral textures and fluid inclusions in exploration for epithermal Au–Ag deposits.

Overall, the ECROFI conference provided an ideal environment for experienced inclusionists and students to discuss new discoveries and applications of fluid and melt inclusions to better understand the geochemical evolution of the Earth system. We hope that you will join us at PACROFI 2012, to be held at the University of Windsor, Canada, immediately preceding Goldschmidt 2012 in Montreal.

Robert Bodnar (rjb@vt.edu), Virginia Tech

2011 EMU SCHOOL

The 2011 EMU School, Layer Silicates and Their Application in Advanced Technologies, took place in Rome from July 9 to 19. Teachers and students enjoyed the wonderful location of Villa Farnesina, made available by the Accademia Nazionale dei Lincei, the oldest scientific organization in the world. Lessons began with an introduction to the structural, crystal chemical, and disorder aspects of layer silicates, with a view to providing students with fundamental knowledge, a prerequisite for the more applied subjects to follow. These dealt with the interpretation of X-ray diffraction data, X-ray adsorption spectroscopy, adsorption and desorption phenomena, the organization of water molecules in the interlayer, surface features, and interaction with organic and biomolecules. Advanced applications of layer silicates were also treated in detail.

The 2011 EMU School was the result of an Erasmus Intensive Program proposed by a consortium of 21 European universities chaired by the University of Modena and Reggio Emilia. Fifteen highly qualified teachers and two tutors provided informative and stimulating lessons, which helped the students to gain a good knowledge of the state of the art in this field and also to learn about current research. All slides used during the lessons have been made available to the mineralogical community through the School's website, www.emuschool2011.unimore.it.

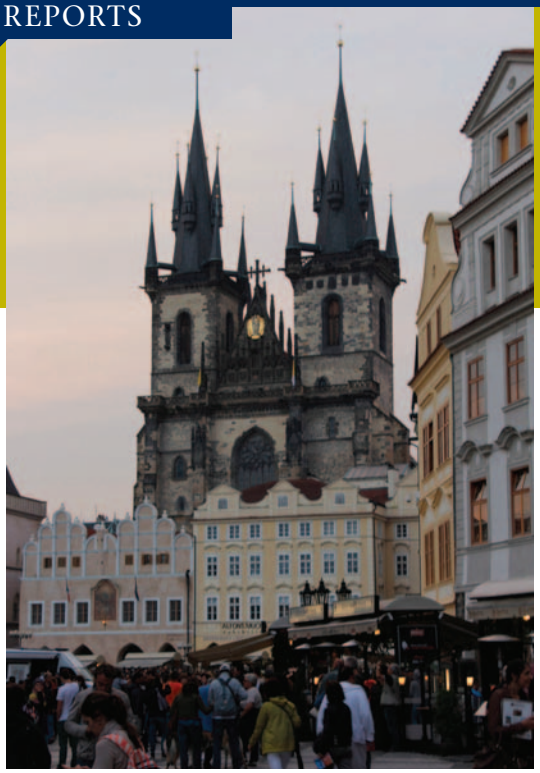
The volume *Layered Mineral Structures and Their Application in Advanced Technologies* is now part of the EMU Notes in Mineralogy series and is available online from the copublisher, the Mineralogical Society of Great Britain and Ireland, at www.minersoc.org/pages/EMU-notes/EMU-notes.html.

From left to right, Annibale Mottana, Daniele Malferrari, Maria Franca Brigatti, and Chiara Elmi

The EMU is very grateful to the organizers of the School and the editors of the volume, Maria Franca Brigatti and Annibale Mottana, for their excellent work; all the teachers and authors; and also the two youngest but very active members of the organizing staff, Chiara Elmi and Daniele Malferrari. Special thanks go to the Accademia Nazionale dei Lincei, which gave unstinting support to the organizing team.

Roberta Oberti, EMU President

GOLDSCHMIDT 2011 CONFERENCE REPORT



Old Town Square, Prague. Photo courtesy of Teresa Roncal-Herrero

The 2011 Goldschmidt meeting was held in the beautiful city of Prague, Czech Republic. This conference, held alternatively in North America and Europe, is sponsored in Europe by the European Association of Geochemistry (EAG). The Prague meeting set a new record: with a total of 3711 abstracts submitted and 3312 registered delegates (30% students), this was the biggest Goldschmidt conference to date. Delegates came mostly from the USA (600), Germany (437), the United Kingdom (280), France (233), Japan (153), China (144), Switzerland (121), Australia (119), Canada (97) and the Czech Republic (96). A total of 1970 oral presentations were given, and 1741 posters were displayed. And a total of 20,000 glasses of the famous Czech beer were drunk during four evening poster sessions!

ORGANIZING THE CONFERENCE

The European Goldschmidt conferences are now organized directly by the EAG, as the increasing size of the meeting made it hard to find local institutes or local consortia willing to take on this responsability. The EAG searched for a site that would be both attractive and able to provide an infrastructure suitable for 20 or so parallel sessions and 3000 plus delegates and at a reasonable cost. Paul Beattie, CEO of Cambridge Publications, the conference organization company, investigated possibilities in Europe with representatives of the EAG. Prague's downtown Congress Center, built in 1989 during the communist era mostly to host meetings with brother communist states (in fact it was used only once for this purpose before the fall of the Berlin wall), met the meeting specifications in terms of space and number of rooms. Prague is an exceptionally attractive city, boasting an outstanding historical center, reasonably priced accommodation, and numerous downtown restaurants and bars.

The principal convenors were the Organizing Committee chairman, Bernard Marty, EAG's past president, Eric Oelkers, EAG's current president, Bernard Bourdon, the local convenor, Martin Novák (from the Czech Geological Survey), and the chairman of the 2009 Goldschmidt meeting, Chris Ballentine. The administration of the conference was run by Cambridge Publications, which also had a place on the Organizing Committee (Paul Beattie), with help from the EAG Council.

A science committee composed of Bernie Wood, Sue Trumbore, and the convenors defined 22 science themes and identified scientists worldwide to handle these themes. Special effort, not always successful, was made to have two chairpersons of different genders and from different continents for each theme. The theme chairs then identified 4 to 7 sessions in their themes and selected scientists to convene these sessions. In total, 135 sessions were defined by fall 2010, and then a call for sessions was opened to the geochemical community, which resulted in about 100 more proposals. Of these, about half were retained, the others being merged with already-defined sessions or, more rarely, rejected. We ended up with 182 sessions that were advertised at the end of 2010.

Because of the large number of abstracts received (3711), it was decided that there would be no morning and afternoon breaks and that sessions would be run on all five days with no free half day in the middle of the meeting. The rationale was to privilege science, with an approximately 50:50 distribution between orals and posters.

During the final steps of organization, the earthquake–tsunami disaster struck northern Japan, claiming the lives of more than 20,000 people. The tsunami also resulted in the Fukushima Daiichi nuclear accident, which contaminated areas around the power plants with radionuclides. Evaluating and mitigating the consequences of this event were clearly in the realm of our competence, so we proposed to the Geochemical Society of Japan (GSJ), through its president, Mitsuru Ebihara, that we organize a special session on the mechanisms of the accident and on its local- to global-scale aftermaths. The GSJ responded enthusiastically, and a day-long session was thus organized in parallel with the regular sessions.

THE CONFERENCE

After a well-attended icebreaker on Sunday afternoon, the conference was opened on Monday, August 15, 2011, by EAG president Bernard Bourdon and a plenary talk by Sam Musaka, the Geochemical Society's president. Each morning began with a plenary talk, featuring distinguished speakers Marc Hirschmann, Edouard Bard, Franck Selsis, and Victoria Orphan. These talks were followed by oral presentations in 18 parallel sessions. The new medalists of the Geochemical Society (GS) and EAG were introduced between the plenary talks and the beginning of the sessions, and the awardees gave their '"medal" scientific talks in the relevant sessions. On each day (apart from Friday) poster sessions were held from 5 to 7 pm, with plenty of snacks and drinks to sustain the discussions along the crowded rows.

Poster session

Four field trips before or after the conference explored the environmental and cultural heritage of the Czech Republic and attracted over 100 delegates.

The special Fukushima session was attended by 150 to 300 people. Presentations included the seismic context, the causes of the accident, the local and global dispersion of short-lived isotopes, and future prospects for the damaged nuclear power plant. At the end of the session, GSJ president Mitsuru Ebihara presented a statement requesting more transparency in the treatment of information and more involvement of the geochemical community. This statement was endorsed by the presidents of the GS and the EAG and can be found on the EAG website.

GOLDSCHMIDT 2011 CONFERENCE REPORT

Banquet at the Municipal House. Photo courtesy of Teresa Roncal-Herrero

Social events held during the week included classical music concerts in three of Prague's most beautiful churches, a dinner at the Brevnov Abbey, and a free rock/blues concert in the Forum Hall of the Congress Center given by CRPG-based Double Scotch band (with Bernard Marty on guitar). The banquet, attended by 1029 guests, was held in the magnificent Municipal House, in the heart of Prague. Due to its sumptuous Art Nouveau style, the building has been the scene of several blockbuster movies, including *Mission Impossible* and *La Vie en Rose*.

A well-attended ice-breaker party. Photo courtesy of Teresa Roncal-Herrero

Double Scotch performing at the Goldschmidt concert

A FEW SCIENCE HIGHLIGHTS

Great science was naturally the focus of the conference. Dating precisely the birth of the Solar System, a long-standing controversial issue, seems to have gained maturity: both the short-lived (e.g. ^{26}Al–^{26}Mg) and long-lived chronometers are now consistent once other nuclear effects are taken into account. The debate about a chondritic, or not, Earth continues, fuelled by new meteorite data used to explore the origin of matter that made the Earth. The Late Veneer hypothesis has gained traction, with independent lines of evidence emerging for post–Giant Impact accretion to Earth of possibly oxidized planetesimals. Furthermore, evidence is accumulating that this late accretion delivered significant volatiles to Earth. Geochemical evidence seems to support a warm (>30 °C) early Earth, even if physical modeling of different ancient atmospheres does not. Although geodynamical and petrologic models for the early Earth support the view that the first crust was mafic (or ultramafic) in composition, this crust appears to have been essentially destroyed by Eoarchean time (>3.6 Ga). Tungsten isotope anomalies are now found in 3.8 Ga old terrestrial rocks, which puts important constraints on the early evolution of Earth. Direct ion probe evidence for "fast" (600 My) recycling of seawater in the source areas of mantle plumes was presented.

A tribute to George R. Tilton (1923–2010), who pioneered U–Pb dating of the Earth's rocks and minerals, included a collection of presentations in the fields of the age and chemical evolution of Earth, the Moon and meteorites; mantle dynamics in rifting and intraplate settings; terrestrial Pb isotope evolution; and novel U–Pb applications in geochronology.

Presentations on mineral deposits concerned their geochemistry; the links between mineral deposits and the evolution of the oceans, atmosphere, biosphere, and lithosphere; metal distribution in melts and fluids; and state-of-the-art analytical techniques for dating mineral deposits. The GEOTRACES sessions considered several new isotope techniques for studying marine biogeochemical cycles—in particular, the presence of anthropogenic ^{236}U in the ocean was reported for the first time. It was also noted that the physical concepts for understanding the occurrence of noble gases in terrestrial waters might help to constrain the dynamics of radon in the ocean.

Many presentations were also given in the vibrant and developing fields of molecular environmental geochemistry and geobiology. For example, talks about "the ash that closed Europe's airspace..." highlighted how only a detailed understanding of the processes governing the interaction of mineral surfaces and fluids can lead to reliable predictions of air-traffic safety. Various talks also highlighted the links between careful experiments on the nucleation, growth, and dissolution of mineral phases and atomistic modeling, and showed how these links are crucial for our understanding of macroscopic and even global-scale (bio) geochemical processes.

NOW AND THEN

Several issues could be improved upon at future conferences. For example, there were technical problems with Wi-Fi and the audiovisual equipment at the beginning of the conference, and some rooms were overcrowded during some of the most popular talks. However, despite these glitches, it was generally agreed that the conference was a great success, both scientifically and socially. The success of the conference reflects a scientific discipline that is thriving and of increasing importance to society, because geochemistry encompasses data, techniques, and skills important for confronting some of the major issues the world faces today. These include climate change, the disposal of nuclear waste, the management of the Earth's water resources and the discovery of new mineral resources.

Plans are progressing well for the next two Goldschmidt conferences, Montréal in June 2012, and Florence in August 2013. These will be exciting meetings and will continue the tradition of effective conferences serving the geochemical community.

Bernard Marty, with **Bernard Bourdon**, **Martin Novák**, **Chris Ballentine**, and **Paul Beattie**

ION PARTITIONING IN AMBIENT-TEMPERATURE AQUEOUS SYSTEMS[1]

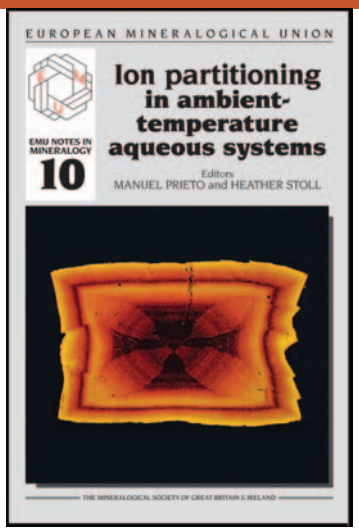
Water–rock interactions are at the heart of many of the processes that make the Earth (so far) a habitable planet[2]. Understanding and quantifying these processes help us to study, control and potentially remediate some of the anthropogenic interferences and disturbances affecting the delicate balance that makes life on Earth so unique. Natural and man-made systems are seldom simple, and this also applies to the interactions between complex solid solutions and multicomponent aqueous systems. In spite of this complexity we have to seek solutions because, as the late Werner Stumm used to say, "Everything that is interesting in Life happens at interfaces."

In this context, I responded with trepidation to the challenge posed by *Elements* of reviewing this book, which touches on a subject that has entertained me for many years. The same theme was treated in a book I co-authored, in 2007, with some of the contributors to this one[3]. Reading the book, the questions I asked myself were: How much has the field advanced in the last four years? Have we filled in some of the knowledge gaps we identified earlier?

The emphasis of the present book is broader, in the sense that the work edited by Manuel Prieto and Heather Stoll is not exclusively concerned with trace elements and radionuclides in aqueous solution–solid solution systems. The strength of the book resides in its overview of ion partitioning research in low-temperature systems.

Carbonates are the most often referred-to system in the 12 chapters of the book. In chapter 1, Prieto uses the Cd(II)–Ca(II) carbonate system to illustrate the effect of ionic strength and aqueous composition on measured distribution coefficients and the Zn(II)–Ca(II) carbonate system to point out non-ideality effects on solid solution behaviour. In chapter 2, Putnis uses the Cd–Ca carbonate system to illustrate the departure from equilibrium, and the divalent carbonate system to explain the effects of crystal anisotropy and surface structure on the kinetics of ion partitioning and the consequences for oscillatory zoning. The comprehensive chapter 3, by Kulik, touches on the carbonate system only in the discussion on regular interaction parameters. Divalent carbonates are central in chapter 4, in which Böttzer and Diechtel describe metal-ion partitioning during low-temperature precipitation and dissolution of anhydrous carbonates and sulphates. The equilibrium partitioning of divalent cations in calcite, aragonite, rhodochrosite and siderite is used to introduce various empirical and modelling relationships. Magnesian calcites are discussed with regards to the effect of congruent and incongruent dissolution on metal-ion partitioning. The formation of diagenetic carbonate from evaporitic sulphate is mentioned in some of the sections in chapter 5, by Putnis and Fernández-Diaz. In chapter 6, by Monnin and Herau, a full section is devoted to the carbonate system in the marine environment, in which the authors discuss some of the fundamental and experimental challenges regarding the carbonate system in seawater. In chapter 7, Fairchild and Hartland portray the influence of changing composition, colloid content and temperature of the contacting waters on the trace element content of speleothems. Godselitas and Astilleros in chapter 8 present the interaction of carbonates with heavy metals and actinides. The carbon cycle is introduced in chapter 9, by Oelkers and Gislason, who postulate that divalent carbonate formation is the main driving force for the long-term sequestration of injected CO_2. The interaction of trivalent actinides with calcite is discussed by Bosbach in chapter 10. In chapter 11, Cohen and Gaetani investigate the partitioning of divalent cations (Mg, Sr, Ba) in coral and abiogenic aragonite. They consider factors that influence the growth of biotic and abiotic aragonites, with implications for the use of coral skeletons as paleothermometers.

In chapter 12, Stoll uses the Cd–Ca carbonate system to illustrate ion partitioning in foraminifera and coccoliths, the largest producers of carbonate in the oceans. The Ca/Ba ratio in coccoliths is used to explain the influence of seawater concentrations on the partitioning of these elements in biotic carbonates. The Mg/Ca ratio in foraminiferal calcite records temperature variations in the ocean, and borate to carbonate partitioning in the same species gives some insights about the bicarbonate concentration and consequently the pH. Underlying all these discussions is a fundamental knowledge of the thermodynamic and kinetic controls of ion partitioning in carbonates, a theme that percolates through all the chapters in the book.



The second most studied systems in the book are the sulphates. Ca(II) and Ba(II) sulphates are ubiquitous in nature, and the interaction of Sr(II) and Ra(II) with them are at the heart of the development of aqueous solution–solid solution thermodynamics. This is largely reflected in the book, where these systems are described in chapters 1, 4, 6, 8 and 10.

In this book, the reader will find a large amount of up-to-date information regarding ion partitioning and its interaction with the carbon and sulphur cycles. The fundamentals are thoroughly developed in chapter 1, and some interesting applications are found in many of the chapters, particularly applications that interface between abiotic and biotic systems. While the broad scope of the book is one of its strengths, it also constitutes its weakness. Chapter 3 on geochemical modelling is too broad and too ambitious; many systems are modelled, but not a single experimental datum is used to contrast the plausibility of the models. Chapter 8 is also too broad, attempts to cover too many systems, and avoids the in-depth analysis that would be required for some issues. Chapter 9 on CO_2 sequestration is simply disappointing. The proposed "mechanisms" of CO_2 trapping are accepted at face value, and there is no discussion of geochemical processes that would address some of the key challenges related to CO_2 injection into geological media and to perturbations in the carbonate system and their consequences for ion partitioning. While chapter 10 is a good introduction to the applications of aqueous solution–solid solution thermodynamics to the disposal of nuclear waste, the reader will find a more thorough discussion of the subject in reference 3.

Some of the challenges we identified in our previous book remain unanswered, particularly the one concerning the identification of key processes at the molecular and atomic levels. These processes should constitute the basis for any firm understanding and quantification of the mechanisms and thermodynamics of ion partition processes at ambient temperatures.

In essence, this is a useful book for anyone interested in low-temperature geochemistry, particularly as it relates to the carbon and sulphur cycles and trace element interactions.

Jordi Bruno, Spain

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THE PHOTOGRAPHIC CHALLENGE OF ELBAITE

As a professional mineral photographer, tourmaline provides some of the most spectacular specimens for work. Elbaite, a lithium-bearing variety of tourmaline, is one of my favorite minerals and not too difficult to photograph, but it does provide some challenges. This sample, from the famous Pederneira mine, near São José da Safira, Minas Gerais, Brazil, is a good example (FIG.1).

The first problem was its size. While not really very large, it was too big to fit on the nonglare glass used for my typical photograpy. In order not to foreshorten the specimen by shooting down on it, I set it on a 4 × 8 foot sheet of black laminate with a slight orange-skin texture. With a very slight upward curve at the far end, I was able to get a low angle and shoot at close to right angles to the main crystals. Luckily, the sample required only minor propping with a little bit of putty to get it to stand upright.

Lighting is critical to an excellent photograph. I usually use studio flash (strobe) for my lighting. The main light was diffused through a "soft box" and was above and slightly in front of the specimen. Another light was to camera right with a 10° honeycomb spot grid on it and was aimed directly at the specimen. A spot grid severely reduces the angle of coverage of the light and comes closer to being a point light source. This "kicker light" gives the specimen life and dimensionality and also saturates the colors. The final light I used was diffused and was placed opposite the camera on the far side of the specimen. Aimed at the bottom of the specimen, it creates the halo around its base. It

FIGURE 1 Elbaite, Pederneira Mine, Minas Gerais, Brazil (19.6 cm high). SCOTT RUDOLPH COLLECTION

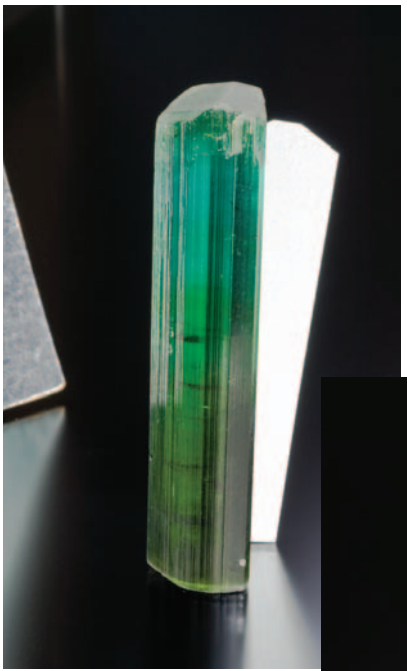

FIGURE 2 Elbaite, Paprook, Kunar, Afghanistan (9.5 cm high). THE CRYSTAL CIRCLE

is necessary to backlight gemmy tourmalines to reveal their colors, zoning, and transparency. I usually accomplish this by placing tall, narrow reflectors behind each of the crystals. A simplified version of this can be seen in FIGURE 2. This setup gives me even backlighting along the full length of the crystal, with no burnt-out areas or spillover of the light along the edges or termination. The final step in lighting the crystal group was to place specular, metallic reflectors to the upper left, upper right, and lower right of the specimen. These were carefully placed so as to bring out the characteristic elbaite striations.

The camera used was a Nikon D2xs with a 60 mm Micro Nikkor lens set at f32, and the shutter speed was 1/80 second. I was tethered to a MacBook Pro computer and used Nikon's Cameral Control Pro 2 software. With some knowledge of mineralogy, an artistic bent, and good equipment, you too can take great mineral photographs.

Jeff Scovil (jeffscovil@earthlink.net)
Scovil Photography

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Elbaite crystal from Cruzeiro, Minas Gerais, Brazil. Image by Jeff Scovil from *The Photographic Guide to Mineral Species* CD, available exclusively from Excalibur Mineral Corp.

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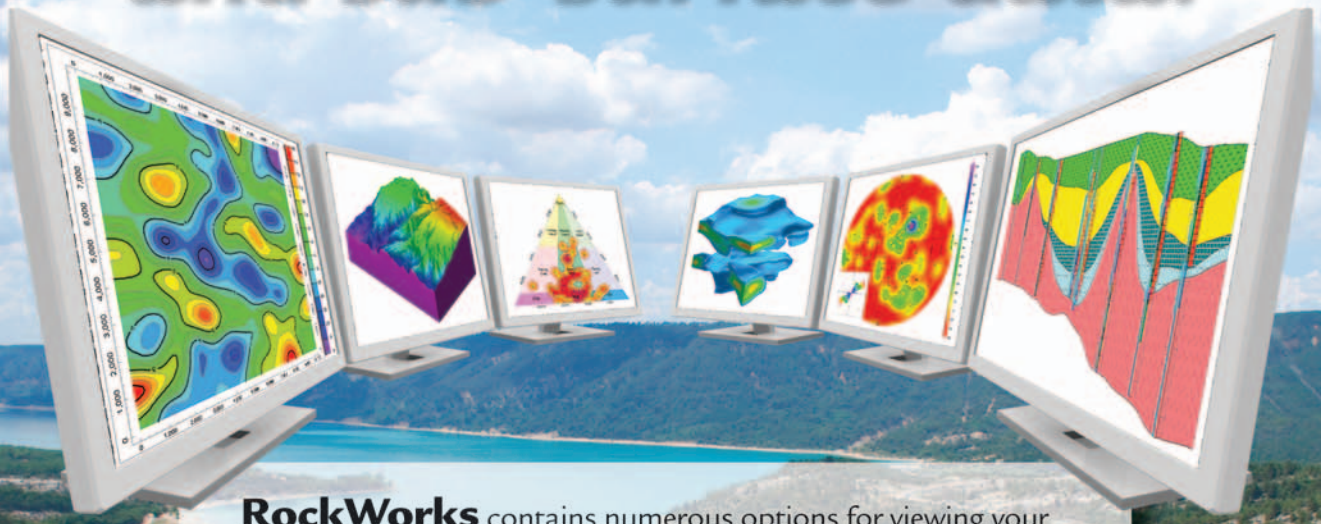

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