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Mineral Resources and Sustainable Development
Georges Calas

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Cover Image: The nickel mine of Tiebaghi is developed on an ultrabasic massif in Northern New Caledonia. A former chromium mine, it is now mined for nickel silicate ores. Its mountaintop location overlooks the New Caledonian lagoon listed by UNESCO on the World Heritage List. This illustrates the development of a mining activity in an environmentally vulnerable situation. In the background, the Barrier Reef makes a clear boundary between the lagoon and the open Pacific Ocean. Photo credit: Société Li Niels, Nouméa (New Caledonia)
MINERAL RESOURCES AND THE LIMITS TO GROWTH

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In writing an editorial for this issue on mineral resources, I was immediately reminded of The Limits to Growth (Meadows et al. 1972), a book that I read avidly from cover to cover as a young post-doc. For anybody interested in humanity’s effect on the environment and its near-term consequences, it is still a fascinating read. The authors summarised a computer model of the likely effects of sustained economic growth on the Earth and the human population. Based on historical data from 1900 to 1970, they observed exponential growth in total human population, resource consumption, food consumption, industrialisation and environmental pollution. They fitted exponential growth curves to the data and assumed in their “standard model” that there was a 250-year supply of all resources at 1970 rates of consumption. They then developed what they considered to be appropriate feedback loops between the different parameters, such as between resource consumption and rate of industrialisation, food consumption and available arable land, gross national product (GNP) per capita, and birth rate. These feedback loops were added to the model, which was constructed to project how the global system would develop out to the year 2100. The results were startling. In the standard model, the global system collapses because of resource depletion, which leads to increased diversion of industrial capital into resource extraction, which, in turn, reduces industrial growth. The industrial system collapses for lack of investment, taking with it the service and agricultural systems. The global population continues to rise for a while and then declines as death rates increase due to lack of food and health services. When does this start to happen? According to the 1972 study ... about 2015; global population starts to decline from around 2030.

Of course, the authors recognised the large uncertainties and didn’t put great emphasis on the timescale. But they did note that, even making large allowances for increased resource availability and improved industrial efficiency, collapse still occurred before 2100. If, for example, they double the amount of available resources, collapse would be delayed by a few years, but then occurs due to increased pollution (including climate change), which damages food production and the health of the population.

The Limits to Growth has been subject to intense scrutiny and criticism since its publication. By allowing consumption to increase exponentially but with fixed or slowly increasing resource availability, the authors ensured that the system would collapse at some point. Furthermore, it has been argued that the authors made insufficient allowance for technical innovation. Some of the detail (such as the GNP per capita of China) has been invalidated by political and technological changes. Nevertheless, as shown in a recent study (Turner 2014), many of the projections made by Meadows et al. (1972) were remarkably accurate. As can be seen in Figure 1, population, industrial output, food and services per capita, which are relatively straightforward to measure, all follow the predicted curves closely. Resources and pollution are less easy to measure, requiring the use of energy reserves and atmospheric CO2 as proxies (Turner 2014), and it is these which

![Figure 1](image-url) Projections of the standard model in The Limits to Growth (dashed lines) compared to pre-1970 data (light solid lines) and updated results (bold solid lines; Turner 2014). Shown are the projections out to 2100 for (A) population, (B) economy, and (C) natural resources. Figures from Turner and Alexander (2014), courtesy of The Guardian UK.
The concept of mineral resource sustainability and development weighs heavily on the mind of the international community, given that our Earth has a fixed quantity of mineral resources needed by an ever-increasing human population (currently ~7.5 billion), all of whom want modern comforts and amenities. Although this issue of Elements can’t come close to addressing all the complexities of mineral resources and sustainable development, the authors have provided articles that introduce us to the origins and economics of mineral resources, the different mining methods required to sustainably extract these resources, plus the different processing techniques needed to refine them. We are also provided with examples of how geochemical research can help solve the complex environmental legacies of mining. And, we are challenged to educate the next generation of geoscientists who will be responsible for finding and developing the resources needed to sustain a nation’s standard of living, its domestic national product, and its position in the world.

**2017 ANNUAL EDITORIAL TEAM MEETING**

On Sunday, 13 August 2017, the Elements editorial team held their annual staff meeting in Paris (France). The meeting was an invaluable opportunity for our international team to discuss, face-to-face, editorial matters. We addressed the problems and logistics of handling manuscripts, evaluating proposals, setting the topical lineup for the first half of 2019, and we explored the challenges and opportunities for our magazine in this digital age of the internet, social media, and YouTube. We also met with the Elements Executive Committee. The members of this committee represent the 17 participating societies and it is they who oversee the financial aspects of our publication. It was a long but productive day.

One of the most time-intensive discussions for the editorial team involved the evaluation of the 13 thematic proposals submitted for the Elements 2019 lineup. This was a challenging task because the team only schedules three to four issues at a time. We evaluated each proposal with respect to the potential interest and relevance of the topic for our diverse readership; we assessed how well the proposed topic would be covered by the suggested articles; and we considered the qualifications and diversity of the proposed authorship. On the basis of these discussions, we accepted the following thematic proposals: “Planet Mercury” (February 2019), “Reactive Transport Modeling” (April 2019), “The South Aegean Volcanic Arc” (June 2019), and “Weathering: A Unifying Process in the Geosciences” (August 2019).

If you missed our last proposal deadline, we invite you to submit your ideas to us by 15 January 2018 when we will finalize the remainder of the 2019 lineup.

_Bernard J. Wood, Friedhelm von Blanckenburg, Nancy L. Ross, and Jodi J. Rosso_
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NanoSIMS high resolution trace element images contribute to the understanding of the role of biofilms in forming or transforming platinum-group mineral grains, and in the dispersion and re-concentration of platinum-group element in surface environments.

Signature of biophilic elements in botryoidal Brazilian Pt-Pd-grains.

From: Biological role in the transformation of platinum-group mineral grains.
Frank Reith et al., NATURE GEO SCIENCE, 21 March 2016.

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Meet the Authors

Gordon E. Brown Jr. is at Stanford University (California, USA) where he is the D.W. Kirby Professor of Geological Sciences in the School of Earth, Energy & Environmental Sciences and also the Professor of Photon Science at the SLAC [Stanford Linear Accelerator Centre] National Accelerator Laboratory. Over the past 30+ years, Brown and his students have studied the chemical and biological processes that sequester and/or transform contaminant species, particularly heavy metals, at mineral–aqueous solution interfaces in both natural and synthetic systems using synchrotron radiation and other experimental and theoretical methods. He has enjoyed many research collaborations over the past 35 years with Georges Calas and Mike Hochella.

Georges Calas is Chair of Mineralogy at the University Institute of France and a professor at Université Pierre et Marie Curie, Paris. He held the chair Sustainable Development – Environment, Energy and Society at Collège de France between 2014 and 2015. His research interests concern how the molecular-scale organization of minerals, glasses, and melts controls their properties and can provide invaluable information on the formation conditions of geomatics. His current interests include environmental mineralogy, materials science, nuclear waste management, cultural heritage, and the use of mineral resources in a sustainable manner. He is a member of Academia Europaea and a Foreign Fellow of the Royal Society of Canada.

Johan de Villiers is a professor in the Department of Materials Science and Metallurgical Engineering at the University of Pretoria (South Africa). He obtained his bachelor’s degree at the University of the Orange Free State (South Africa) and his PhD in geology at the University of Illinois (USA). He served as General Manager, Research and Services at the South African mining and minerals research company Mintek. He was Research Associate investigating phase chemistry at Pennsylvania State University (USA) and worked on transmission microscopy at Arizona State University (USA). His interests are in applying mineralogy and crystal chemistry to solve metallurgical challenges. He is a Fellow of the Mineralogical Society of America and of the Geological Society of South Africa.

Cyril François is a PhD student in Earth Sciences at Grenoble-Alpes University (France). His research focuses on the management of knowledge and data through the development of new data architectures, as well as integrating life-cycle assessments with economics-based input–output tools. The purpose of his work is to estimate the energy and material intensities, as well as the geographical supply chains, of the raw materials involved in the manufacture of energy-producing technologies. He obtained a master’s degree in Defense and Geopolitics from Paris-Sorbonne University (France) and worked for two years in industry.

Gaël Giraud is a CNRS researcher in economics, specializing in the theory of general equilibrium, game theory, finance and energy issues. He is the chief economist of the Agence Française de Développement, a professor at the École Nationale des Ponts et Chaussées, where he also holds the chair of Energy and Prosperity. He was also a member of the French government’s Steering Committee for Energy Transition and of the Stern–Stiglitz High-Level Economic Commission on carbon tarification. Gaël is a former student of the École Normale Supérieure of Paris (France) and the National School of Statistics and Economic Administration (Paris). He obtained his PhD (1998) in mathematics at the École Polytechnique (France). In 2009, he was named Best Young French Economist by the Le Monde newspaper and by the French think-tank group, Le Cercle des économistes.

Michael F. Hochella Jr. is a University Distinguished Professor in the Department of Geosciences at Virginia Tech, and is Founding Director of the Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth), both in Blacksburg (Virginia, USA). He is also a Laboratory Fellow in the Geosciences Group at Pacific Northwest National Laboratory in Richland (Washington, USA). He works in the fields of nanoscience and technology, and specifically in the areas of nano-bio-geo-environmental science at local, regional, and global scales. He obtained his PhD at Stanford University (California, USA) under Gordon E Brown, Jr.in 1981, and has known Georges Calas for almost as long.

Michel Jébrak received his DSc in Orléans (France). He is a professor at the Université du Québec à Montréal in Montreal (Canada) where he has also served as Vice-President, Research and Art. He teaches at the Université du Québec en Abitibi-Témiscamingue (Canada) and in the Université de Lorraine (France). His research focuses on epigenetic ore deposits and on social impacts of the mining industry. He has been involved in the development of several mineral exploration research groups: Divex, Consorem, Canada Mining Innovation Council. He holds the Chair in Mining Entrepreneurship in Canada and is a member of the Mines and Society network in France and of the Quebec-based climatology group Ouranos.

Jean-Marc Montel is a professor at the University of Lorraine (France). He graduated in 1982 from the École Nationale Supérieure de Géologie (ENSG) in Nancy (France). He received his PhD in Nancy in 1987. Subsequently, he became a CNRS researcher at the Laboratoire Magmas et Volcans in Clermont-Ferrand (France) (1988–1999), professor and head of Géosciences Environnement Toulouse (France) (1999–2008), and then returned to Nancy in 2008 as head of ENSG. His expertise lies in the mineralogy of accessory minerals, partial melting of the continental crust, radioactive waste management and U–Th–Pb geochronology. And because ENSG graduates about 120 high-level students at master’s level in geological engineering, he has also become an expert in fundamental and applied geoscientific education.

Robert S. Pell is a PhD candidate at the Camborne School of Mines, University of Exeter (UK). His research aims to quantify the environmental performance of rare-earth production, using a life cycle assessment approach, and to incorporate the concept of raw material criticality into life cycle assessments. Prior to his current research, he received a BSc degree in geology from the University of Birmingham (UK) and then worked as Assistant Editor for International Mining, a monthly publication for mining technology news and project developments. More broadly, he is interested in the responsible sourcing of raw materials, particularly the social and environmental challenges associated with technology metals.

Alain Rollat is an independent consultant in rare-earth processing and technology. He is a graduate of the École Nationale Supérieure de Chimie de Strasbourg (France) and Doctor in Chemistry from University of Strasbourg. He has spent most of his career in the rare-earth business of the Solvay Group where he held various research and develop-
ment and industrial positions in the Research Centre of Aubervilliers and in the factory of La Rochelle (France). During this period, he developed several processes in the field of rare-earth separation and purification and participated in the design of new production units of rare earths in France and China. Coauthor of 12 patents, he currently works for several junior mining companies in the rare-earth field.

**Fatma Rostom** started a multidisciplinary PhD in economics and geosciences in 2014 at the University Paris 1 Panthéon-Sorbonne (France). Her research focuses on the economic modeling of natural resources, especially how resource depletion can be a limiting factor for economic growth. Fatma holds a master’s degree in engineering from the École des Mines (Paris, France), and a bachelor’s degree in geosciences from the École Normale Supérieure Lyon (France).

**Olivier Vidal** is a CNRS researcher in mineralogy at the Institut des sciences de la Terre at Grenoble-Alpes University (France). He obtained his PhD (1991) in Earth sciences at Paris University (France) and spent two years at the Institut für Mineralogie at Bochum University (Germany). He worked at France’s Commissariat à l’Energie Atomique and at the Southwest Research Institute in San Antonio (Texas, USA). He is interested in the thermodynamic modelling of mineral reactions and the modelling of the energy–raw materials nexus in the context of energy transition.

**Frances Wall** is Professor of Applied Mineralogy at Camborne School of Mines, University of Exeter (UK). She has a BSc in geochemistry and PhD from the University of London (UK). Frances became interested in how rare-earth deposits form in carbonatites whilst working at the Natural History Museum in London, and her research interests currently centre on the formation of high-technology metal deposits, applied mineralogy, mineral processing, and responsible sourcing of mined raw materials. Frances joined Camborne School of Mines (CSM) in 2007, was Head of CSM from 2008 to 2014. She was also named one of the 100 Global Inspirational Women in Mining 2016.

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WHAT IS SUSTAINABILITY IN THE CONTEXT OF MINERAL DEPOSITS?

Robert Bowell

Sustainable development is a term that all too often has been hijacked within our society by politicians and business promoters eager to endorse their “green” credentials. Yet human society requires sustainable growth in order to continue. However, in the context of much of society’s mineral resources what does sustainability actually mean?

In the interest of complete disclosure, I have been a miner from the age of 16 and still own my own mining operations, so I am unapologetically pro-mining. However, I also appreciate the planet we live on. The context and concept of mineral development being sustainable is one that intrigues me. By its very nature, mineral deposits are rarely “sustainable”. The activity of mining consumes a resource as the development progresses. At some point, a given mineral deposit will be physically or, more commonly, economically exhausted. Other than marine evaporates, guano phosphate and some soda ash deposits, mineral deposits are not renewed on a human timescale of true sustainability (Fig. 1).

This is nothing new. Georgius Agricola in his mid-16th century book De Re Metallica [On the Nature of Metals (Minerals)] commented on the waste of resources in many of the mines around Freiberg, St Andreasberg and the Harz Mountains (Germany) and how they would cause problems for future generations. Yet, despite the consumption of resources, many mines continue for many generations. For example, the base metal–sulfide deposits of the Iberian Peninsula have been continuously mined for 5,000 years; the mines of Laviron in Greece were mined over a period of 3,000 years; and Bingham Canyon in Utah (USA), although just over a hundred years old, has seen the extraction of over 19 million tonnes of copper ore and continues to produce approximately 300,000 tons of copper, 500,000 ounces of gold, 4 million ounces of silver, 30 million pounds of molybdenum and 1 million tons of sulfuric acid every year! So, although not sustainable, certainly long lived (Fig. 2).

There is a growing interest in defining sustainability in the minerals industry. The papers in this volume highlight some of the research interest. Another recent and excellent publication on the topic focuses on the sustainability and historical development of global coal and copper resources, defined by the authors as “critical components in our species development” (Golding and Golding 2017).

Despite often long and active periods of mining, most mines do not close as a result of the exhaustion of all ore. Mines close because the ore that is left costs more to extract at prevailing metal prices than will be realized in revenue. As many ore bodies reach this maturity or are abandoned, potential negative environmental impacts can and do occur.

It is conceivable that the mining legacies of previous generations can, through new technology, be considered as providing an alternative ore source, possibly in perpetuity: truly “sustainable mining”. A recent publication by Nordstrom et al. (2017) addressed the potential methods that could be applied to offset environmental impact mitigation and produce critically required metals from contaminated water discharged from mine sites. But is there really value in such an exercise?

An evaluation on mine waters discharged from Iron Mountain (California, USA) (Fig. 3) indicates “ore grade” concentrations up to 650 mg/L copper and 2,600 mg/L zinc in water with a pH less than 1.5 at a flow rate up to 50 L/s (Alpers et al. 2003). The calculated value of the water in terms of metals (primarily as copper and zinc) could be in excess of US$12,000 a day, making it a mid-size base-metal producer. This water also has a wide range of other potentially valuable trace metals.
Mine-water discharge from Iron Mountain (California, USA). The pH of the water ~1.5; copper content in this water is ~0.5–0.6 g/L; zinc content is ~2 g/L.

components as well (such as Ag, Pb, Cd, Li, Be, Ga, Ge, Sn, Te, TI, and rare-earth elements). However, the reality is that the total metal value can be very different from the economic value because it does not account for the cost of metal extraction, refining or transport. These costs can be on the order of 60% or more of total metal value. So, despite the attractive costs, if it costs $8,000 to $10,000 per day to recover these metals then the operation is less attractive as a commercial concern but could be driven by other factors, such as environmental clean-up.

Metal recovery from mine waters, such as at Iron Mountain, represents a potential source of revenue to offset water treatment costs and, in some places, may even represent an economic project in its own right.

A caveat exists, however: even if the “ore potential” can be proven and the technology can recover economic amounts of metal, there may still be little incentive to “re-mine” many old mining districts.

Companies that attempt such re-mining ventures may be held responsible for all past mining legacy, as well as any new disturbance. Furthermore, the mere mention of metal value from these old districts could result in legal action from property owners or bankruptcy trustees who will lay claim to any recovered value. It is quite conceivable that potentially “sustainable” developments could become unattainable simply due to legal quagmires. So, despite the potential for extractable minerals, in some cases they could become “legally off-limits”.

Nevertheless, in the current environment of high-metal demand and exhaustion of historically important metal sources, different sources of metals or technologies to extract metals will have to be found. This could be from mining deeper primary mineral resources, using new types of ore (such as bauxites) providing rare-earth elements or returning to recover extractable minerals from abandoned mines. These challenges will require a good understanding of the mineralogy and geochemistry of the target metals and minerals in order to identify such “sustainable” opportunities. The geological community must be suitably trained and equipped to characterize such “sustainable” opportunities.

REFERENCES


COMBINED XRD AND SAXS ANALYSIS OF NANO-MAGNETIC MATERIALS

Nano-magnetic materials have a variety of potential applications. For example, they can be used in high-density data storage and in biomedical research and clinical diagnosis. Fundamentally, it is important to understand that the nano particle size is not always the crystallite size. One particle may contain several differently oriented crystallites or domains.

In the figures below, we demonstrate the analysis of both the crystallite size and nano particle size of magnetic FePt materials. XRD is sensitive to the crystal structure; hence it is suitable for crystallite size analysis. On the other hand, SAXS is not sensitive to the crystal structure, but it is to particle size. Both the XRD and SAXS analyses were performed on the SmartLab multipurpose diffractometer. The XRD and the crystallite size results are shown in Figure 1.

![Fig. 1](image1.png)

![Fig. 2](image2.png)

The SAXS measurement and fitting results are shown in the left panel of figure 2. The resulting particle size distribution is shown in the right panel of Figure 2. For the particular sample analyzed here, the crystallite size is identical to the particle size, 2.9 nm. This indicates that each particle contains just a single domain.
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Mineral resources have been used for millennia and are a key to society’s development. With the growing importance of new technologies and the energy revolution, questions have arisen regarding the future availability of resources of metals and industrial minerals. As discovering large high-grade deposits has become increasingly rare, the concept of “sustainable development” will become viewed as essential to extract metals/minerals from new low-grade deposits. In addition to economic considerations, it is essential to reconcile mining activity with environmental protection and to allay the concerns of local populations. This issue of Elements highlights the progressive movement towards an active environmental and societal strategy for sustainably harnessing mineral resources.

INTRODUCTION

What are mineral resources? They are resources that encompass ores, industrial minerals, building stones and aggregates. They have been formed through a diverse range of geological processes, which are often unique and raise questions about the history of our planet and the nature of its past and present environments (Arndt et al. 2017). Indeed, mineral resources bring “messages” about the way our planet works, from the deep magmatic to the surficial environments. Human civilizations have been based, since the earliest times, on a progressively more sophisticated use of mineral resources: so it is that we define the Stone Age, the Bronze Age, the Iron Age, the industrial revolution of the 19th century, or the “Silicon Age” of today. More than ever, our economic activity relies on mineral resources, which provide everyday metals and mineral materials, as well as (in the wider sense) ceramics, glasses, cement and plaster, tiles and bricks, pigments, and so on. Mineral resources and the materials that we derive from them shape our everyday lives: we need them for buildings and public works, cars and planes, communication technologies and renewable energy sources, fertilizers, papers, cosmetics and drugs, etc. In fact, we live side-by-side with minerals and metals so frequently that we often forget their ubiquitous presence.

For many countries, the exploitation of mineral resources is a driving force for economic development. Ores – mined for base-, critical- or precious metals – have to be processed to extract the metals, and sometimes this extraction has to be from low-grade ores mined in remote places. Every year, a considerable quantity of ore is extracted: for example, more than 3.3 billion tons of iron ore were mined worldwide in 2015 (U.S. Geological Survey 2016). This has led to the development of dedicated transport networks, which are a major contribution to the international trade. Industrial minerals constitute a more heterogeneous domain. They may be used as raw materials for finished products by melting (e.g. glasses) or by the formation of new phases (e.g. ceramics, tiles and bricks, cement). Minerals as additives also provide specific properties to certain end products, e.g. papers, plastics and composite materials. Industrial minerals illustrate how atomic-scale structural properties govern their properties, and, hence, their use and economic value. Finally, aggregates and building stones, which are used as building materials and for public works (e.g. dams, bridges, roads), are characterized by the large volumes extracted: in 2012, the world’s use of aggregates for concrete was estimated at 25.9 to 29.6 billion tons a year (Peduzzi 2014). As a whole – including aggregates used in land reclamation, shoreline developments and road embankments – a conservative estimate is that mankind uses 40 billion tons of aggregate/stone a year. This is twice the yearly global erosion rate and is one of the most dramatic examples of human impact on environment.

As an activity, mining still suffers from a bad public perception as a result of poor past practices. Mines have often been the site of tragic events and mass mortalities, with spectacular accidents and high levels of permanent and severe pollution, which sometimes have extended over decades or centuries and led to the deaths, in total, of several million people. It is not easy to forget the centuries of appalling conditions in the Potosí silver mines of Bolivia since the 16th century, or the Soviet Gulags in the Norilsk and Kolyma mines in Siberia, or the abuses of
human rights associated with the production of modern “conflict minerals” in Central Africa. There is a deep suspicion by the public about mining activity in general. This is not surprising when one considers the past behaviour of some companies who abandoned and left unrestored mineral exploration and mining sites or who cared little about the resulting pollution. In addition, the volume of rocks extracted or simply displaced by mining has necessarily increased due to a drop in the grade of ores. This also may increase the impact of mine waste. Mining activity must reconcile economic activity with environmental and societal imperatives, particularly when mining in fragile environments.

The extraction of mineral resources is inherently unsustainable. Resources, be they large or small, are finite. Eventually, most large high-grade deposits will be exhausted or depleted because demand is only increasing (De Villiers 2017 this issue). Questions are being asked about the finite aspect of the available reserves, as illustrated by crises highlighted in the media (e.g. for the supply of rare-earth elements in 2010–2011). Fortunately, the mining potential of Earth is still a long way from being exhausted, which is good news for our need to build, for example, specific devices for the production of energy that have low CO₂ emissions. As with other new technologies, such devices are based on the extensive use of critical raw materials, which are often exploited in a few deposits of economic importance. This overall industrial development implies that more metals will have to be produced by 2050 than during the last 100 years (see Vidal et al. 2017 this issue). Strategies for developing energy sources for the future must include considerations about the availability of mineral resources needed for energy production and for “clean” transport methods (Graedel et al. 2015; Ali et al. 2017).

The exploitation of mineral resources is irreversible, and minerals themselves seem non-renewable. However, unlike natural hydrocarbons, many metals and industrial minerals can be recycled. This ability of recycling is now contributing to the growing sector of secondary raw materials and is a major evolution towards mineral sustainability. Mineral resources illustrate the difficulty of satisfying the conflicting objectives of the “three pillars” of sustainability: economy, environment, and social equity.

Although sustainability is a topic that seems to belong exclusively to the domain of Earth and environmental sciences, many fields contribute to a broad overview of the sustainability problem and help to define future strategies: materials and engineering sciences, economics, social sciences, politics, and even history. The rising public awareness of environmental impacts, of equal sharing of the profits among the various stakeholders (companies, states, local populations) or of managing land use, prompts media discussion about mining activity. These discussions are often relayed by non-governmental organizations and it is a fact of modern life that societal acceptability is now central when discussing the development of mines. Beyond certification procedures based on the general principles of sustainable development, such as the ISO 26000 norm on social responsibility (ISO 2010), more specific certification standards are now being sought for the mining industry not only to address the concerns of local populations but also to increase the confidence of financial investors (Caron et al. 2016).

POORLY SHARED RESOURCES

Mineral resources are unevenly distributed between countries because geological diversity (or homogeneity) does not follow human political lines. Approximately 70% of the world’s platinum, for example, was produced in South Africa during 2015 (U.S. Geological Survey 2016) and was mined almost exclusively in the Bushveld (Mungall and Naldrett 2008). Considering that platinum-group elements (PGE) are important as precious metals and as vital components for catalytic converters (automotive exhaust, specialty and fine-chemistry industries, etc.), the strategic importance of South Africa is considerable given that it holds 80%–90% of the world’s PGE reserves (Pitchumani and Eppelbaum 2017). Other examples are also dramatic. About 85% of the world’s niobium, a critical metal used to make high-tensile steels, superconductors and electronic components, is produced by the Araxa mine in Brazil. Similarly, about 50% of the world’s production of rare-earth elements comes from the Bayan Obo mine in Inner Mongolia (Wall et al. 2017 this issue). These world-class deposits of critical metals have a major geostrategic importance. Moreover, they provide examples of the exceptional efficiency of unusual geological processes for concentrating specific elements, often revealing original characteristics of the regional geological history.

Base metals and iron ore resources are also unevenly distributed. For iron, only a limited number of world-class deposits are in operation because of the large size necessary to ensure profitability. The largest iron deposits are located in Australia and China, and, to a lesser extent, in Brazil (the world’s largest iron-ore mine is in Carajas), India and Russia. By contrast, a century ago, iron was produced by mines that served local or regional markets. This had been the case in Western Europe, following the discovery in 1878 of the Thomas–Gilchrist process for phosphorus removal from iron ore. Unfortunately, these iron mines closed a century later: their reserves were limited and the ore quality was no longer economically viable. These mine closures caused regional-scale social disasters in the countries affected.

The economic growth of China in the 2000s is spectacularly reflected in the production and use of mineral resources. World production of iron has been transformed over the last 20 years, with a dramatic increase in steel production by China. China only produced about 15% of the world’s steel at the turn of the 21st century, but, as of 2017, now accounts for about 50%. Figure 1 illustrates the importance of this growth, which has doubled world production in just 15 years while at the same time steel produced in the rest of the world stagnated. The importance of China in the mining sector is considerable: it holds a dominant

![Figure 1](https://www.worldsteel.org/)
position for many metals, the most salient of which are tungsten and antimony (with 82% and 77% of the 2015 world production, respectively), and also aluminium, vanadium and titanium (55%, 53% and 47% of the 2015 world production, respectively) (U.S. Geological Survey 2016).

As a result of the concentration of mining activity in a few world-class deposits, the unequal distribution of natural resources has led to an increase in the transport of ores on a global scale. The quantity of ores extracted from the largest mines justifies the vertical integration of the value chain within major groups in order to reduce costs and improve efficiency. Mining companies themselves have developed autonomous railway and sea transport routes, major ore processing and metallurgy centres, and, sometimes, even trading activities.

**QUALITY AND VARIABILITY: THE EXEMPLARY CASE OF INDUSTRIAL MINERALS**

Industrial minerals are not seen by the public as being in any way “glamorous” and may even be perceived as trivial. Yet, no in terms of basic societal needs, they are some of the most important of all. This is the case of sand. It is often coloured by coatings of nanoscale Fe-oxides, which limits its use as a raw material for “noble” uses such as glazing because the iron brings unwanted colouration. Yet it was the search for pure sand that led to its exploitation around the village of Saint-Gobain in Northern France 350 years ago that gave rise to the eponymous and now multinational company of Saint-Gobain (S.A.). During the diagenesis of the Saint-Gobain sands, most iron oxide coatings were leached away, vastly improving the quality of the resource. Similarly, sedimentary deposits of technical grade kaolin have benefitted from the dissolution (during diagenesis) of the Fe-oxides that were bound to the clays: a low impurity content makes kaolin suitable for many applications. Clay minerals have been hugely important since antiquity, mainly as a raw material for the manufacture of ceramics. Their distinctive properties arise from their two-dimensional crystal structure, which provides a lamellar morphology and some very specific surface properties, leading to applications discussed in two previous issues of *Elements*: the “Bentonites” issue (Bain 2009) and the “Kaolin” issue (Schroeder and Erickson 2014).

Industrial minerals illustrate how, under the same name, a resource can have different qualities, uses, and values. Kaolin, for example, can be used both as a filler and a coating in the paper industry or as a raw material for the production of ceramics and glasses. Its use depends on characteristics such as brightness or the size and shape of the kaolinite crystallites (Murray and Kogel 2005). Coating paper sheets with flat kaolinite platelets results in smoother, whiter surfaces that improve the paper’s optical and printing properties. It is one of the most important uses of kaolin (Fig. 2). However, most raw kaolins occur as books or stacks of platelets that are usually aggregated because of crystal defects. Kaolin delamination is a process by which these stacks are sheared to produce the thin plates of high aspect ratio (diameter to thickness) that are needed for coating uses. Calcination of kaolin increases light scattering and improves the brightness and opacity, providing low-cost pigments for the paper industry. Other treatments, such as centrifugation, can select for specific particle size fractions, down to a few tens of nanometers thick, opening up new applications in areas of catalysis, medicine and agriculture. The elaboration of more sophisticated industrial minerals illustrates a quest for a more sustainable use of the kaolin resource, by improving the quality of the extracted material.

**THE ENVIRONMENTAL IMPACTS OF MINING**

The environmental impacts of mining are a major concern. The local environment can be affected either from extraction and smelting operations or because of the considerable quantities of waste that is produced (Brown and Calas 2011; Hudson-Edwards et al. 2011). At the extraction stage, major impacts are caused by mineral dusts from unwanted ancillary minerals, such as silica or asbestos. Atmospheric contamination by heavy metals and arsenic is mostly caused by smelters releasing metal-bearing dust or elements with low vaporization temperatures, such as arsenic, lead, zinc or mercury. Groundwater contamination can also be a major problem at some mining and metal processing sites (Fig. 3).
Waste rocks and tailings around mines can also be problematic. Waste rocks are those with metal concentrations too low to be economic or that have to be removed to access the mineralized body. Tailings result from mineral processing and contain only residual metal concentrations; nevertheless, tailings are reactive due to previous milling and chemical processing. The confinement of tailings in impoundments (tailing ponds) may be at the origin of some catastrophic dam failures (see Brown et al. 2017 this issue). The exploitation of increasingly low-grade ores leads to a considerable increase in the volume of both waste rock and tailings, the high surface areas of which favour their reactivity during exposure to running waters. Over time, water runoff oxidizes metallic ores and, thus, mobilizes heavy metals, which can become bio-available.

Contamination of the environment from “historic” mines can potentially impact areas with a long mining history when there was no environmental regulation in place. These sites are often abandoned as “orphan sites”, which have no legally responsible party attached to them. The media regularly mention contamination at a local or regional scale by hazardous minerals (e.g. asbestos) and toxic elements such as arsenic, antimony, cadmium, mercury, uranium or lead. Sometimes, the contamination comes from associated impurities, as in arsenian pyrite: under surface conditions, arsenic is released from mine wastes, a process enhanced by biological activity (e.g. Morin and Calas 2006). These examples show the need for monitoring mine sites after their exploitation, especially in populated regions.

Speciation is a major parameter in environmental sciences: it controls the bio-availability of soil-bound metals. This is illustrated in the case of soil contamination by lead. Figure 4 shows that there is no correlation between soil lead and blood lead for local populations. The lowest lead levels are actually observed at mining sites themselves due to the presence of low-solubility lead minerals (e.g. lead sulfide or sulfate) in the soil and waste rock. By contrast, higher blood-lead levels are observed in sites close to smelters, possibly related to the lead being in a more bio-available form, such as sorbed lead (Smith and Huyck 1999). A complementary example is provided by geochemical anomalies: these naturally high concentrations of potentially contaminating elements (e.g. As, Pb, Zn) do not correspond to any anthropogenic activity but result from the weathering of bedrock. Despite the fact that they contain concentrations of toxic elements similar to those encountered in smelter-impacted soils, these areas have often been inhabited for centuries. These abnormal areas are interesting because they provide examples of the ways by which heavy elements can be stabilized in soils (Morin et al. 2001). The relevant parameter for monitoring the environmental impacts of heavy metals is, thus, not the elemental concentration in the soils or waters as such but the speciation of the elements of concern. Fortunately, an element’s speciation state can be directly evaluated by molecular-scale approaches (Brown et al. 2017 this issue).
MINERAL RESOURCES AND SUSTAINABILITY

Population growth and a reduction in general poverty levels go along with industrialization. The increases in urban populations and improved standard of living are associated with the growth in the consumption of energy and raw materials. The development of new technologies has outpaced our knowledge of how to extract the available resources to match the demand.

As is the case for other mining sectors, China has played a major role in the rare-earth element market over the past 30 years. By the end of the 20th century, China controlled most of the world’s rare-earth production (Chakhmouradian and Wall 2012). When the Chinese suspended its rare-earth exports following a maritime incident off the Senkaku Islands between China and Japan in September 2010, a high-profile international crisis resulted. Figure 5A shows the price spike in dysprosium prices caused by the Senkaku incident, a situation similar to the other rare-earth elements. Uncertainties over supply led to a significant increase of the price in the early 2010s. These prices fell once China had resumed its exports, but the present-day prices are still higher by about a factor of five relative to the low levels observed in 1998. Rare-earth reserves, however, are distributed more widely than only where current production is taking place (Fig. 5B). A recent illustration is brought by the discovery of world-class deposits of the rare element scandium in an unusual lateritic context (Chasse et al. 2017). The situation is, therefore, different from that of the platinum-group metals, discussed above, where reserves are highly localized. After the 2010–2012 rare-earth crisis, Eugene Gholz, Senior Advisor to the US Pentagon at the time and a specialist in national security and economic policy wrote, “Policymakers should not succumb to pressure to act too quickly or too expansively in the face of raw materials threats” (Gholz 2014). This example illustrates that a strategic-minerals risk does not necessarily correspond to an inherent lack of resources for that metal or mineral. The volume of a resource present in the Earth’s crust might be considerable. The problem is a lack of exploitable deposits at a given moment, until potential resources can be converted into exploitable reserves. Indeed, the development of a viable mine often requires several years, which makes reacting to political or economic forcing of a resource a complex matter.

The sustainability of a given resource could potentially be improved using innovative mineral processing technologies, such as hydrometallurgy or other wet processing techniques. This approach will allow diverse and selective extractions of the various metals or industrial minerals present in an ore, thereby optimizing the use of the initial resource. However, such as for recycling (see below) the recovery of by-products is developed only when economically feasible, i.e. when the price of metals and industrial minerals is high enough.

Recycling activities continue to gain in importance as the demand for raw materials and energy savings increases. Recycling in a broad sense, including re-use, is a major component of sustainable development. It is a complex domain, because the technical possibilities for recycling are very different between the various materials. Some metals have high recycling rates: transition elements, such as copper or iron, as well as precious metals, gold, platinum-group metals and silver. They are relatively easy to melt and refine because of their chemical stability. Most materials are, in fact, inherently recyclable: the stocks used by our society can result in “urban mines” from which metals and other mineral materials can be reclaimed (Ciacci et al. 2017). However, unless future end-of-life recycling rates are dramatically stepped up and the price of raw materials is high enough, the recycling rates of rare elements – such as the rare earths, zirconium, and tantalum – may continue to be desperately low, which currently applies to some metals used in minute quantities in mobile phones, computers, battery packs or fuel cells. There is a consensus that it should be a requirement to include the concept of recycling at the design stage of modern high-tech products, which would make it possible to recover genuine “secondary raw materials” at the end of a product’s lifetime.

Among success stories, the 28 [at the time of writing] European Union (EU) countries are achieving a successful recycling of glass, with an average recycling rate of 70%, exceeding 90% in some countries. This saves both energy and considerable quantities of raw materials. However, quality losses after recycling mean that recycled glass can be used only for the production of packaging glass or for aggregates in the building industry, all of which are materials of lower intrinsic quality than the transparent glasses needed for glazing. The increased importance of recycling is also illustrated by the contribution of recycled aluminium to total aluminium production, growing from 19% in 1950 to 36% in 2014, despite global aluminium production increasing from 1.5 Mt to 49 Mt during this timeframe. Projections for aluminium production in 2020 predict a recycling rate of 40% for a global production of 70 Mt, sharing the burden with primary aluminium ores in this fast increasing aluminium production.

It is necessary to maintain a fundamental research activity on mineral resources, with the objective of ensuring the knowledge needed for the development of future generations. This involves strengthened exchanges between academic research and industrial research and development to best use the natural resources and to find substitutes for the most critical materials. Sustainability requires control-

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**Figure 5**


(B) World reserves in megatons (Mt) for the rare earths in 2016, showing that this resource is shared between several countries and not the monopoly of one or a few. Data from U.S. Geological Survey (2016).
ling the environmental, human and societal impacts of mining activities. All these activities cover the entire field of knowledge and require the involvement of the scientific community to guarantee the development of this area, which remains discreet but vital for our economy.

**IN THIS ISSUE**

This issue of *Elements* illustrates some recent concepts emerging from a sustainable perspective on mineral resources. De Villiers (2017 this issue) demonstrates the inventiveness of the mining sector, which continues to develop in a changing societal and legislative environment and continues to meet the challenges raised by commercial competitiveness. Recycling and process optimization are central to the long-term sustainability of resource development. Wall et al. (2017 this issue) discuss the rapidly expanding field of the critical metals, which are of increasing importance in the fast-developing field of new technologies. These authors show how responsible sourcing may be an environmentally friendly approach to analyze how the supply chains of our goods meet acceptable standards after the mining stage. The questions raised by the exponential increase in the demand for mineral resources, which themselves need to be responsibly sourced, are covered by Vidal et al. (2017 this issue): more metals will have to be produced by 2050 than during the last 100 years. The industrial expansion necessary for the development of low-CO₂-footprint technologies is also analyzed from the viewpoint of the socio-economic sciences. Brown et al. (2017 this issue) focus on the impacts of past mining activities, the mitigation of which requires knowledge of nano- and molecular-scale speciation of the contaminants. Understanding mining-related impacts is necessary for limiting contaminant transport and bio-availability and to design effective remediation strategies. Jébrak and Montel (2017 this issue) describe and illustrate how the modern resource geologist should be educated, especially in becoming familiar with 3-D models that can integrate all the data from a mining project, from exploration to post-mining. In the industrial chain, the resource geologist is the first contact with the environment, and he/she will also have to deal with any societal issues related to exploration operations, mine opening and closure, site rehabilitation, impact mitigation and long-term monitoring.

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How to Sustain Mineral Resources: Beneficiation and Mineral Engineering Opportunities

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The sustainability of a mineral resource depends, among other aspects, on what the mineral in question will be used for, price fluctuations, future resource requirements, and downstream manufacturing. A balance must be struck between the long-term commitment of developing a mineral deposit against the short-term threats of a changing commercial and social environment. Long-term resource sustainability is dependent both on increased efficiency, which improves profitability, and on revitalizing marginal mines. This is illustrated through breakthroughs in the processing of low-grade copper and refractory gold ores, as well as nickel laterite ores. Retreatment of mine wastes and tailings can also increase the sustainability of mining activity. Ongoing research and development is also helping to sustain mineral resource exploitation.

KEYWORDS: resource usage, process optimization, recycling, research and development

INTRODUCTION

The sustainability of mineral resources is a subject that is increasingly being discussed at various levels: from local communities associated with mining and mineral processing, to regional and national governments, and at international conferences. These discussions address resource availability, utilization and consequential environmental risks, and the social impacts that accompany the exploitation of commodities. Because of mining’s substantial impact on the environment and its generation of large quantities of potentially hazardous waste, it has been, and will be, the subject of intense debate. As a consequence of the increased population and the reduction in poverty, illustrated by “Nearly 1 billion people taken out of extreme poverty in 20 years” (The Economist 2013), there will be an inevitable increase in production of mineral commodities to meet the increased needs for a better quality of life.

In response to the realization that a secure supply of raw materials is essential for the competitiveness of the European economy, the European Innovation Partnership (EIP) on Raw Materials was established in 2012 and published the Raw Materials Scoreboard in July 2016 (European Commission 2016). This document outlines the future resource requirements of the European Union (EU). To strengthen the security of supply, the EU will invest in the diversification of supply, improve conditions for domestic production, and stimulate the recycling of raw materials.

Mining and processing necessarily exploit dwindling resources. Minerals extraction is inherently unsustainable and, eventually, most currently known large high-grade deposits will be developed or depleted. This is most evident in the case of the South African gold industry, which contracted from being, in 1970, the biggest producer of gold, at 1,000 tons (Rockerbie 1999) down to sixth place in 2016 with a production of 140 tons: global gold production in 2016 was 3,100 tons (U.S. Geological Survey 2017). This contraction was due to the fact that many of the large high-grade mines had been depleted and had closed (Limpitlaw 2004). Gold reserves in South Africa are still substantial (Viljoen 2009), but the extreme depths (3,900m at the Mponeng Mine) make exploitation expensive and dependent on available energy and water resources.

Minerals extraction is a human activity that is highly visible, extremely invasive, and often damages the environment. Open cast mining, together with mine waste disposal, can sterilise large tracts of land, which in many cases can be impossible to reclaim. Acid mine drainage often results from sulfide ore mining and is difficult to control, and, in many countries, remediation is often neglected. Unfortunately, most public perceptions of the mining industry are negative and reinforced by media coverage of major catastrophic events, such as coal mine disasters, tailings dam collapses, cyanide leakage in rivers, and acid mine water spills. None of these were more dramatically and publicly portrayed in the media than the successful rescue of 33 trapped Chilean miners at the San José Mine near Copiapó during the summer/autumn of 2010. This emphasized the inherent dangers associated with mining. Conversely, downstream industry has managed to convey a positive image of environmental awareness, with examples of the reduction of fossil fuel use by electricity generation using wind or photovoltaic sources.

That there will be increased use of raw mineral commodities is inevitable. To address the issues surrounding this situation, this article will evaluate the sustainability of the minerals industry; discuss future resource requirements and the factors influencing resource development and sustainability and the recycling of commodities; examine sustainability with respect to the efficient and novel processes for the extraction of mineral commodities;...
and discuss some commodities and waste materials that are currently under-exploited and that research could make more accessible.

**RESOURCE REQUIREMENTS FOR THE FUTURE**

A condensed and graphic history of raw materials extraction is given in the Raw Materials Scoreboard (European Commission 2016). This highlights the dramatic 40-fold increase in the use of construction materials from 1900 to 2009, as compared to ores and industrial minerals which saw a 31-fold growth over the same period. During the period 1950–2010, raw material consumption levelled off for most countries, except for some countries in Asia where the increase in consumption has been exponential, rising approximately 14-fold in this period (Fig. 1).

This means that the Asian region will dominate consumption during the next few decades, with resource use expected to double between 2010 and 2030. However, the largest increases in global mineral resource production in the near future will be for elements needed for the low-carbon technologies (e.g. wind power, solar-photovoltaic cells, electricity generation), and biofuel technologies. Some of the elements needed for all these technologies include dysprosium, chromium, cobalt, gallium, indium, neodymium and silicon.

**FEATURES OF RESOURCE DEVELOPMENT AND EXPLOITATION**

There are three factors that currently limit the development and exploitation of resources: (1) global pricing of the raw ore, (2) time, and (3) cost of environmental compliance.

The global price of ore can dictate the success or failure of a mining company. The economic importance of global prices on the mining industry, as compared to a downstream industry (those that convert an ore into derivative products) is graphically illustrated in Figure 2A. On this diagram, it can be seen that the raw ore is the predominant source of revenue (86%) for the mining company. In contrast, for downstream companies, the cost of the ore can be a mere fraction (<1%−20%) of the overall production costs. This dramatically shows that the cost of ore for downstream industries can be truly insignificant, and the price of the ore does not strongly impact on their profitability. On the other hand, the price of the ore has a huge direct impact on the source mine’s profitability and sustainability. This was dramatically shown during the recent sharp drop in iron-ore prices (Fig. 2B). The price of iron ore dropped from $154 per ton in February 2013 to $41 per ton in December 2015, causing many mining companies to shut down or drastically curtail production. Furthermore, this price drop significantly and negatively impacted the national economies of the major producing companies operating in Australia and Brazil.

Time is another major factor in resource development. The development of a major new mineral resource can take 10 years or more. There needs to be a large commitment by a company to a resource’s eventual implementation, but with that are the concomitant risks of a changing commercial environment, funding challenges, and societal responsibilities. An example is the development of the world-class Voisey’s Bay Nickel deposit (Canada), which was discovered in 1993. It was auctioned off in 1996, but mining only started in 2005 (Gibson 2006). Mine development also carries short-term risks, such as commodity price volatility as exemplified by the oil price collapse of 2015–2016, which took place over 6 months, and the iron-ore price decline over 12 months. In addition, production disturbances, such as strikes and work stoppages due to unforeseen technical problems, can further disrupt production. Thirdly, legislative actions, such as licensing changes,
can delay production for months, as happened earlier in 2017 at the Grasberg copper (and gold) mine in Indonesia. Resource rental taxes and local beneficiation (increasing mine product quality) demands can further impact on the profitability of resource development. All these short-term risks can have negative impacts on the long-term developmental sustainability of a mining project.

One other important factor affecting the sustainability of a mining operation is the cost of environmental and social responsibilities associated with the operation moving increasingly towards sustainable development. Because the profitability of the mining industry is poor – an average rate of return is only 5% (Humphreys 2001) – estimated environmental costs that amount to an additional 3% of operating costs can be difficult to sustain. In some countries, environmental costs can amount to 23% of development costs. These costs can, however, be offset by increased productivity and increased efficiency of extraction by adopting low-cost technologies, such as bioleaching and solvent extraction.

**RECYCLING**

Increased recycling is seen as an essential component of the ‘circular economy’, where commodities are used and re-used on a continuous basis. Recycling has been practiced in the steel and aluminium industries for many years, and the logistics for recycling are well in place. In a recent study of the extent of recycling of selected major-element commodities (UNEP 2011), a number of metals showed high recycling rates, whilst others are recycled to a lesser extent. Table 1 summarises the extent of metal recycling. In the case of ferrous metals and steel, as well as for the precious metals, the recycling rates are quite high. But recycling rates drop to less than 1% for many metals such as the rare earths, vanadium and zirconium. It is clear that for the major metallic commodities, recycling can ensure the continued availability of major resources. However, this carries a commitment to select, collect and accumulate specific commodities so that they can be re-used. This function is not necessarily carried out by either the primary producer or the user and is difficult where the commodities are present in small or trace amounts or are widely distributed among various products.

**PROCESS OPTIMIZATION**

Optimization of extraction processes can enhance the profitability of mining activities, thereby extending the life of mining and metallurgical operations. For example, worldwide platinum-group element production in 2013 was 12.9 billion ounces, which was valued at US$14.4 billion (Johnson-Matthey 2013). Recovery of the metals from the primary ore mined varies from 75% to 85% and ongoing efforts are made to increase this figure. A 1% increase in recovery translates to an increase in revenue of $140 million per year, usually at little extra cost. At the platinum-group metals Lonmin mine in South Africa it was stated that, “underground and overall concentrator recoveries increased to 85.1% and 85.0% from 80.5% and 79.0% respectively year on year” (Lonmin 2010). This translates to an increase in revenue of $64 million for the company. From the same company, key features of platinum-group processing are given and shown in Table 2. The biggest cost factor is mining itself (at 65%–70% of total costs), with milling and flotation coming in second (at 9%–12% of total costs). On the other hand, the biggest potential increase in revenue could come from the milling/flotation step where recovery is only 80%–90%. Compare these figures to the very efficient process steps involving in smelting/converting and in base-metals refining and precious metals refining, all of which have efficiencies of 95%–99.8%. Increases in efficiency in mining and milling/flotation will, therefore, contribute most to increases in profitability and sustainability. Mineralogical methods, such as liberation analysis, have also contributed significantly to increasing the recovery of valuable elements (Cabri 2010). Additionally, by-products such as copper, nickel and gold, as well as minor elements such as selenium and tellurium, can also add to the profitability of platinum-group mining.

Increased efficiency in copper-ore processing is exemplified by the application of the two-stage hydrometallurgical process of solvent extraction/electrowinning, together with heap leaching, both methods having effected huge improvements on the profitability and sustainability of many mines and transformed the copper industry (Bartos 2002). This has been especially the case in the treatment of low-grade, otherwise uneconomic, ores and mine discards, as well as in revitalising abandoned mines.

The application of bio-hydrometallurgy involving bacterial leaching is hailed as the next revolutionary breakthrough in both gold and copper recovery processes (Bartos 2002; Clark et al. 2006). In the case of gold processing, this involves the leaching of gold-containing sulfide minerals, such as arsenopyrite and pyrite, to liberate the occluded gold, which is then leached with cyanide. In copper

### Table 1 Key Features of Platinum-Group Element (PGE) Extraction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mining</th>
<th>Milling &amp; Flotation</th>
<th>Melting &amp; Converting</th>
<th>Base Metal Refining</th>
<th>Precision Metal Refining</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of Total Cost (%)</td>
<td>65–75</td>
<td>9–12</td>
<td>6</td>
<td>7</td>
<td>4–5</td>
<td>100</td>
</tr>
<tr>
<td>PGE Grade</td>
<td>4–6 g/ton</td>
<td>100–600 g/ton</td>
<td>640–6,000 g/ton</td>
<td>30–65%</td>
<td>&gt;99.8%</td>
<td>—</td>
</tr>
<tr>
<td>PGE Recovery (%)</td>
<td>—</td>
<td>80–90</td>
<td>95–98</td>
<td>&gt;99</td>
<td>98–99</td>
<td>75–85</td>
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<tr>
<td>Concentration Ratio</td>
<td>—</td>
<td>30–80</td>
<td>20</td>
<td>75</td>
<td>2</td>
<td>200,000</td>
</tr>
<tr>
<td>Processing Time (days)</td>
<td>—</td>
<td>2</td>
<td>7</td>
<td>14</td>
<td>30–150</td>
<td>Up to 170</td>
</tr>
</tbody>
</table>

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processing, the leaching of chalcopyrite, which is poorly soluble in dilute sulfuric acid, can be greatly improved by bioleaching. This will make the solvent extraction/electrowinning treatment of chalcopyrite-containing ores a viable and sustainable process. This technology has been implemented at a number of mines up to a scale of 1 million tons per annum (Clark et al. 2006). Again, advanced mineralogical methods are important to identify and quantify the various readily and poorly soluble copper minerals, as well as the location of gold in the pyrite, arsenopyrite or both. Where and in what form the gold actually is would influence the choice of processing methods to be used.

Iron-ore sintering is a technology that has been in operation for decades, but its use is now increasing in importance. The increasing use of soft goethitic ores and fine-grained upgraded ores has led to the need for agglomeration in order to use these ores in blast furnaces (Cores et al. 2010). Sintering is the preferred method to achieve a suitable blast furnace feedstock and, as such, is extensively used worldwide. Again, this technology ensures the utilization of ores that were previously deemed unsuitable. Additional benefits include better feedstock quality, more suitable blast furnace operation and better steel quality, all because sinters are now the preferred feed for blast furnaces worldwide. Figure 3 illustrates the sintering process by showing the combustion bed in the background and the moving sinter bed in the foreground.

Iron-Ore Mining Waste Utilization

At many iron-ore mines (Fig. 4), the ores are usually beneficiated to a grade of 62% Fe or 65% Fe. As a result, large amounts of ore that do not meet these specifications (e.g. that in the range of 50%–60% Fe or below) are discarded. This discarded material can be potentially upgraded to a higher quality, more valuable, commodity that can have a grade of +60% Fe. Extensive research is ongoing into upgrading such waste iron ore. At present, this is done by pulsed gravity separation (jigging) instead of heavy media separation (Naudé et al. 2013). Clearly, the life of the mine can be extended without incurring large additional mining expenses. The fine particles generated by comminution of the ore can also be beneficiated, usually by flotation followed by pelletisation, to make the product suitable for blast furnaces.

Waste Processing

To decrease the environmental impact of concrete production and reduce associated CO₂ emissions ground granulated blast-furnace slag, which is a glassy by-product of pig iron and steel manufacturing, is commonly used to produce blast-furnace slag cements and slag–concrete mixtures (Flower and Sanjayan 2007). Another potentially important recycling process is the recovery of titanium and residual vanadium from waste steelmaking slag produced from titaniferous magnetite. This slag contains appreciable amounts of titanium compounds that could be upgraded by flotation, gravity separation or chemical treatment by acid leaching. Figure 5 shows coarse-grained reduced M₃O₅ (where M = metal) with a pyroxene and perovskite.

Tailings Reprocessing

Reprocessing gold-containing tailings dumps has been practised for many years in South Africa, and extensive dumps are still available. This practice recovers gold that is usually associated with sulfide minerals and that is not easily accessible through direct cyanidation. The cost of processing is normally very low because the tailings are already mined, comminuted and lying on the surface. All that is required is excavation, gentle milling or attritioning followed by flotation to recover a gold-bearing concentrate that can contain 1.3–1.9 g/ton Au (Fleming et al. 2010). Tailings as low as 0.3 g/ton Au can be economically recovered. Again, the viability of gold mining can be extended by reprocessing (Viljoen 2009).
Recently, reprocessing tailings that contain platinum-group elements (PGEs) has also commenced (notably in South Africa). These tailings arise from the upgrading of chromite ores, all of which contain PGEs to a variable extent (Naldrett et al. 2009). The products are PGE concentrates that are toll-smelted and a chromite concentrate that is sold to ferrochrome producers. Additionally, large tonnages of tailings from the processing of the platiniferous Upper Group 2 (UG-2) chromite ore from South Africa are also being investigated for re-treatment and recovery of residual PGEs and iron-rich chromite.

Titanium Production

Titanium is a lightweight metal, is the fourth most abundant metal element after Al, Fe and Mg, and is used for applications that demand high strength-to-weight ratios, especially in the aerospace industry. It is still produced using the Kroll and Hunter processes, which are batch processes. Both processes are based on the metallothermic reduction of TiO₂ by magnesium or sodium, respectively, and are costly and time-consuming (Zhang et al. 2011). These processes are followed by re-melting and purification of the titanium sponge to remove magnesium (or sodium) and oxygen, again in batch processes. This makes titanium 40 times more costly than steel and 20 times more costly than aluminium, with little likelihood of cost reduction. Can these costs come down?

Table 3 gives a comparison between the global production of these metals. It is clear that the high cost of titanium prevents its widespread use. A viable lower-cost alternative for the Kroll and Hunter processes has yet to be developed, the US Department of Energy having already investigated 17 different “emerging reduction technologies” (Kraft 2004). The FFC Cambridge process – an electrochemical process developed during 1996/1997 by Tom Farthing, Derek Fray and George Chen at the University of Cambridge (UK) – was hailed as a highly promising, potentially low cost, new method of producing titanium metal, but no large-scale facility has been forthcoming despite millions of dollars of investment. Metal powder technology company Metalysis (based in the UK) built a small industrial facility to demonstrate tantalum and titanium production in 2014, but whether any larger-scale facilities will appear in the future remains to be seen.

Major research and development opportunities certainly exist for the development of this significant under-exploited resource with a market value estimated to be worth ~$10 billion per year.

Processing of Titaniferous Magnetite

This resource is largely untapped because of its poor suitability as feedstock for blast furnaces: the main smelting route is by using electric arc furnaces. The blast furnace method is used for smelting titaniferous magnetite mainly in China and Russia. It is estimated that some 20 million tons of crude steel is produced from this resource (total world steel production in 2015 was 1,622 million tons). This amounts to approximately 1.2% of total output. Valuable by-products include vanadium and a potential titania slag, both of which could contribute to an increased cash flow.

So, this major resource of more than ~50 billion tons (Fischer 2015) is vastly under-utilised, and research and development is needed to make it more amenable to blast furnace operation. Electric arc furnace smelting is expensive and cannot compete with blast furnaces unless cheap hydro-electric power is available. The titanium-rich electric arc furnace slag that currently contains the fluxes used in the production of pig iron is discarded, despite containing >30% TiO₂. Some efforts have been made to recover the titanium oxide and the residual vanadium either by hydrometallurgical treatment or by nitridation.

Lateritic Nickel Mining and Processing Technologies

Lateritic nickel constitutes approximately 60% of known nickel resources, and because of the low nickel content (1%–2% Ni) its processing presents a number of challenges. Firstly, the ore does not lend itself to upgrading because of the low-grade distribution of nickel among different, often dispersed, very fine-grained phases (Butt and Cluzel 2013). Consequently, in the pyrometallurgical production of ferronickel, the high slag-to-metal ratio (40 to 50) due to the low nickel content and the high magnesium content results in a high power consumption during the processing procedure.

High-pressure acid leaching has been attempted in a number of localities, with limited success; a number of plants that attempted the process were forced to close. The low nickel content is also a big cost factor and an impediment to profitability. In addition, costly titanium pressure vessels have to be used and the disposal of the leach residues remains a challenge. Recently, Chinese technology has been developed for the low-cost production of nickel pig iron using blast furnace technology. This pig iron product can then be used for the production of alloys and stainless steel (von Krüger et al. 2010).

Significant opportunities exist, then, for upgrading low-grade nickel ores. If the grade can be increased from 1% to 2% by upgrading, the slag-to-metal ratio can be halved with a huge saving in electricity cost and slag disposal cost. In addition, metal production can effectively be doubled with the same throughput. Mineralogical input to assist upgrading technologies such as flotation will be crucial in this regard.
A better understanding of the mineralogy, together with improved processing technologies can affect the process economics of Ni-laterites. This is the case of the Ni-laterites of Eastern Australia, which contain rare earths and scandium (Chassé et al. 2017). The development of appropriate hydrometallurgical technologies yields high purity oxides (a purity better than 99% Sc₂O₃) as the final products. This would not be possible with other processing techniques and could result in the exploitation of a new generation of deposits developed in laterites and exploited for commodities such as Ni and rare metals. The selective extraction of these critical metals has been the key to considering these deposits as candidates for development.

**FACTORS AFFECTING FUTURE RESOURCE SUSTAINABILITY**

Sustainability of mineral resources is dependent on a number of factors (listed below) that can affect the viability and development of future mining activities and investment in this sector.

- The time it takes to develop a new mine. The development of a new mining operation carries a long-term commitment that can take as long as 10 years. Short-term factors, such as commodity price fluctuations, changes in the regulatory environment and social perceptions can seriously undermine this commitment, to the detriment of the industry.
- The maturity of national economies. The future sustainability of mineral resources is considered to be adequate as a result of increased recycling and levelling off of demand as economies become more mature.
- The rise in reprocessing mineral processing waste and tailings. Reprocessing existing waste can extend the production of a commodity, whilst also reducing heavy-metal pollution and acid mine drainage.
- The need to recycle rare metals. Such recycling will increase substantially as the use of rare metals expands, providing an adequate means of scrap collection can be developed.
- The development of novel cost-effective technologies. These will prove essential to process low-grade orebodies and the waste materials derived from mining operations.
- The increasing need to develop lower-grade open cast orebodies. Such orebodies will inevitably be brought onstream, but their development will also impact significantly on the environment.
- The rise in opportunities for researchers to better process unexploited and low-grade ores.

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Most critical raw materials, such as the rare-earth elements (REEs), are starting products in long manufacturing supply chains. Unlike most consumers, geoscientists can become involved in responsible sourcing, including best environmental and social practices, because geology is related to environmental impact factors such as energy requirements, resource efficiency, radioactivity and the amount of rock mined. The energy and material inputs and the emissions and waste from mining and processing can be quantified, and studies for REEs show little difference between ‘hard rocks’, such as carbonatites, and easily leachable ion-adsorption clays. The reason is the similarity in the embodied energy in the chemicals used for leaching, dissolution and separation.

INTRODUCTION

Current technologies use a wider range of elements in their fabrication than ever before. The manufacture of a computer chip demands 44 different elements (Graedel et al. 2015). Touch screens need a thin film of indium tin oxide; capacitors used in electronics need tantalum; permanent magnets of all types, ranging from the tiny speakers in smartphones to huge tonne-weight magnets in large wind turbines, are made of NdFeB. Lithium ion batteries, which also contain cobalt and graphite, are now widespread and are rapidly increasing in use. The total amounts needed of many of the aforementioned elements, despite their many uses, are often only in the tens to thousands of tonnes per year, orders of magnitude less than those of mainstream commodities such as copper. This means that just a few mines can be sufficient for supply and, thus, the choice of source mines at any one time is limited. For commodities such as indium, there are no mines: smelter by-products are the only source. Recycling rates are often low. The potential supply risk is high, and such elements are called ‘critical’. The concept of ‘criticality’ is usually calculated from a combination of the economic importance of the raw materials, the difficulty of substituting another raw material, and the supply risk (European Commission 2014; British Geological Survey 2015; Graedel et al. 2015).

Because many of these critical metals are used in technologies that improve our care of the Earth’s environment, it seems appropriate to try to ensure that their production does not itself harm the environment, nor the local communities and people that produce them. Responsible mining is about minimising the negative effects of mining and maximising the positive outcomes (e.g. Goodland 2012). Responsible mining takes into account environmental protection, community interaction, workforce health and safety, transparency in economic contributions (such as taxes), and also energy use, carbon footprint, water use, resource efficiency, and resource and reserve reporting. Responsible sourcing is about all of these issues and how we, as final consumers, can be assured that the supply chains, including the ultimate sources, for our goods meet acceptable standards. Responsible sourcing was noted as a key stakeholder requirement of the mining industry in the seminal Breaking New Ground: Mining, Minerals and Sustainable Development report (IIED 2002) and again more recently by multinational mining companies (ICMM 2015).

In this article, we consider the issues involved in critical raw materials, using the example of rare-earth elements (REEs), and draw attention to the challenges relevant to geoscientists.

RESPONSIBLE MINING AND SOURCING SCHEMES

Most mining companies seek to demonstrate their commitment to responsible mining practices. In order to be able to distinguish ‘window dressing’ from effective and comprehensive action, however, some kind of assurance is required. Examples include the Global Reporting Initiative used by multinational companies who are members of the International Council on Mining and Metals (ICMM) (www.icmm.com), and the Responsible Jewellery Council scheme (www.responsiblejewellery.com). Some schemes for gold and gemstones, such as Fairmined (www.fairmined.org), are similar to the well-known fair-trade schemes for tea and coffee. To date, only a few raw materials, such as the conflict mineral ‘coltan’ (columbite–tantalite; the main ore of Ta) are covered under legally binding social regulations. Some manufacturers, such as Fairphone (a manufacturer of smartphones free of conflict minerals) have attempted to understand their supply chain and to connect consumers with the raw materials used. For most complex products, though, it is hard for the consumer to make a connection to the mines that have produced the raw materials. The main drivers for responsible mining of most critical metals are not responsible sourcing initiatives from consumers but the need for mining companies to (1) satisfy investment banks in order to raise capital, (2) gain informal approval (social licence to operate) from
SOLVENT EXTRACTION OF RARE-EARTH ELEMENTS

Perhaps the most complex chemical challenge for producing REEs is that applications need individual high REE purity. The separation of the natural mixtures into an individually pure REE is particularly difficult, chemically intensive and has always been a challenge in terms of science, technology and economics (Lucas et al. 2015). A breakthrough in developing a separation process that could use more environmentally friendly chemicals and/or can be applied at the same time as first-stage processing, or during in-situ leaching, would be a major advance in responsible sourcing of REEs. Historically, REE separation was done first by selective crystallization, then ion exchange methods, and now it is mostly done by solvent extraction. A number of new techniques have been proposed but none are being used commercially.

Solvent extraction is currently the only industrial scale REE separation process. The separation is done step by step, with a mixer-settler technology and each step performed in equipment called a solvent extraction battery. Each solvent extraction battery can separate one group of REEs into two sub-groups, or a mixture of two REEs into two pure individual REEs. So, the separation of mixture of n REEs into n individual REEs will need n-1 solvent exchange industries. Industrially, REE separation processes are all done in a battery of mixer-settlers with counter-current flows; the purification of each REE can reach as high as 6N (i.e. 99.9999% pure).

The choice of solvent depends on the following: selectivity (for the REE valency), loading capacity, and how the extracting molecule affects the energy and chemical reagent consumptions. The classical extractants used are 2-Ethylhexyl phosphonic acid, mono-2-ethylhexyl ester (HEHEHP or H(EH)EHP), tributyl phosphate (TBP) and Aliquat 336 (N-Methyl-N,N,N-trioctylammonium chloride). It is the extractant HEHEHP that gives the highest total difference of partition coefficients between REEs: \( P(\text{Lu}^{3+})/P(\text{La}^{3+}) > 10^6 \) (Fig. 1 Box). It is the most selective extractant along the lanthanoid series and can be used for all REE separations. Nevertheless, tributyl phosphate in a nitrate medium can be used for La/Pr/Nd separation, and Aliquat 336 in a nitrate medium can be used for some light and heavy REE separations (Fig. 1 Box). The loading capacity of a solvent, defined as the maximum quantity of REE that this solvent can load, can be improved by lower molecular weight and lower viscosity of the solvent.

The chemical and energy consumptions depend on the extraction mechanisms. All the solvents can be classified into three different types of extracting molecules: solvating agents or neutral extractants (e.g. TBP), which consume steam and water; anion exchangers (e.g. Salts of triauryl methyl ammonium and their host communities, and (3) comply with the laws of the countries in which they operate. These drivers and controls all apply to critical-metal mines, as well as to the production of mainstream commodities. There are so many different management and reporting systems that it is still difficult to identify any clear ‘responsibly mined’ mark that could penetrate and influence the long supply chains in which critical metals are normally involved.

RARE-EARTH SUPPLY

An introduction to the REEs has been given by Chakhmouradian and Wall (2012) in a previous issue of Elements. Other reviews of REEs as critical metals are given in Wall (2014) and Verplanck and Hitzman (2016). As mentioned above, the REEs (the term is used here to include 15 elements: Y, plus La through to Lu, but without Pm which has no long-lived isotope) are essential in many technologies owing to their magnetic, redox and luminescent properties. They are classed as critical because supply is dominated by just one country, China. Prices for REEs rose dramatically in 2010 and 2011 when China threatened to cut supply quotas, but, more recently, the supply situation has eased and prices have now dropped back to 2010 levels. A complication of REE deposits is the propensity of the REEs to follow one another geochemically, such that there are no ore deposits of individual members of the REE series. Although some geological processes fractionate the light REEs from the heavy REEs (Chakhmouradian and Wall 2012) all members of the series occur together.

The production of REEs usually follows conventional mining techniques. Production starts with open pit mines; this is followed by comminution (crushing and grinding) of the ore; then comes separation of the ore from waste by physical methods, such as gravity and magnetic separation, or by froth flotation, or a combination of the two (Fig. 1). The REE minerals then need to be dissolved (‘cracked’) to release the REEs. An intermediate mixed REE carbonate or oxalate produced at this stage can now be shipped. The next step, required in all cases, is further processing to separate the REEs from each other, which is the most important step in adding value and leads to the high purity REE metals and oxides that are sold to the manufacturing industry (Fig. 1).

By far the largest REE mine is in altered and metamorphosed carbonate at Bayan Obo, Inner Mongolia (China), with smaller carbonate/alkaline rock and carbonatite mines at Weishan County in Shandong Province (China).
and the Maoniuping/Dalucao area in Sichuan Province (China), both important sources for the ‘light’ REEs (La–Sm) (LREEs). All are open cast quarries. The higher atomic number ‘heavy’ REEs (Eu–Lu) (HREEs) come mainly from about 200 small mines working ‘ion-adsorption clays’ in weathered granite across southern China, especially in Jiangxi Province. The mining methods used for these HREE deposits are either removal of the ore material to leaching tanks or in situ leaching with ammonium sulphate (Fig. 2). These leaching methods use very simple technology but cut out the comminution and physical upgrading stages and go straight to dissolution (Fig. 2).

The pollution damage from Bayan Obo and associated processing plants in nearby Baotou is significant, frequently featured in newspaper articles (Ali 2014). The extensive land degradation and pollution associated with mining the ion-adsorption clays is also a serious problem, as is illegal mining. The Chinese government is taking action to consolidate the REE industry throughout China and improve its environmental performance. Nevertheless, it is a sobering thought that we are all implicated in this environmental damage through everyday pieces of equipment that almost certainly contain Chinese REEs.

There are, however, few alternative supplies. Outside of China, there are only three substantial active mines. The loparite mine in nepheline syenite at Lovozero, Kola Peninsula (Russia) produces REEs as a co-product with Nb. Ore treatment is done in Solikamsk (Russia). Mineral sands at Orissa (India) are mined by Indian Rare Earths Ltd. This ore is treated on site and the REE separation is also done in India, through a joint venture between Indian Rare Earths Ltd. and Toyota Tsusho. There is little public information on the environmental performance of either of these operations. The third mine is in weathered carbonatite at Mount Weld (Western Australia) operated by Lynam Corporation Ltd, with ore treatment and REE separation in Kuantan (Malaysia). The mining operation itself has not been controversial but the Lynam Advanced Materials Plant (‘LAMP’) in Malaysia, which was needed to separate the REEs, was subject to considerable protest on environmental grounds during its development because of fear of pollution from Th and U in the monazite ore (Ali 2014). The company now publishes details on their website (www.lynascorp.com) of environmental monitoring around the plant and uses international auditable management systems (e.g. ISO 14001, OHSAS 18001). The company is also developing their own chain of assurance with magnet manufacturers. The Mountain Pass (California, USA) carbonatite mine re-opened in 2012. It also made an issue of being a more environmentally friendly source of REEs than the Chinese producers (Loye 2015) but did not survive the recent low REE prices and closed again in August 2015. So, since the crisis of 2010/11, the choice of major supplier has only widened by one mine (Mount Weld). Processing and separation of REEs is becoming progressively more concentrated in China. For example, Solvay, a chemical company based in Belgium and one of the few processors outside of China, has moved to downstream applications rather than processing REE raw materials. Its two Chinese plants have stopped their REE separation lines, and its separation lines at La Rochelle (France) are only partly used. The plant at NPM Silmet AS in Sillamae (Estonia) only produces separated LREE products.

**CONNECTING GEOLOGY AND GEOCHEMISTRY TO RESPONSIBLE SOURCING**

Despite the difficulties in current REE supplies, a wide range of REE deposits are being, or have recently been, explored, providing a particular opportunity to consider how the geology and geochemistry of a deposit can affect responsible mining and sourcing. Deposits include carbonatites (both hydrothermally altered and weathered varieties), alkaline igneous rock (including nepheline syenite and granite), other types of hydrothermal deposits, high-temperature igneous monazite veins, mineral sands, and REEs as by-products of other ores. Even deep-sea muds are being explored (Chakhmouradian and Wall 2012; Wall 2014)

A qualitative comparison of the intrinsic properties of the main varieties of REE ore deposits shows wide variation (Table 1). Five factors have been chosen to characterise the different types of REE deposits: (1) the presence of radioactive minerals, because this is the main reason for restrictions on shipping and processing of REE ores and concentrates, as well as the main public fear; (2) the amount of environmental disturbance likely, considering the size of the likely mine (assumed to be open cast, few REE mines...
are proposed as underground operations) and the amount of rock that needs to be processed to obtain the REE; (3) the energy needed for crushing and grinding, which is the main energy use in mining, according to whether the deposit is a hard rock that requires considerable energy for comminution or is a friable placer or weathered deposit; (4) the resource efficiency, based on how easy it usually is to recover a high proportion of the REEs from the type of deposit in question; (5) the measure of whether the REEs are a by- or a co-product of another commodity.

Light REE-enriched carbonatites are generally low in Th and U, even if the ore mineral is monazite (see above). As these are some of the highest-grade ores, the amount of land disturbed is likely to be low compared to other REE deposits. The energy required for comminution is variable. Carbonatites, for example, are not particularly tough rocks, but even weathered deposits require comminution to a fine grain size (~50 μm) if flotation is used to recover the REE minerals.

The nepheline syenite alkaline rock deposits are large, low grade, hard rock deposits, requiring large amounts of energy for comminution. The mineralogy is complex, and attaining good separation and thus resource efficiency is difficult. There are possibilities for multiple products, and an intermediate rating has been given for this situation (Table 1). The radioactivity of eudialyte as the REE ore mineral in nepheline syenite is low and is a particular advantage of these deposits. Other minerals, such as stenstrupine, may, however, contain higher amounts of Th and U. In alkaline granites, the amount of Th and U can be much higher, hence the ‘variable’ label in Table 1.

Mineral sands, being unconsolidated, easy to process, and shallow deposits score well in all categories except radioactivity. With monazite and xenotime derived from granitic rocks, they are at the higher end of the range of Th contents, making derived concentrates significantly radioactive.

Ion-adsorption deposits (i.e. REEs adsorbed onto clays, which are usually the products of granite weathering) are the ones that tend to hold the HREEs and are easy to mine. They occur close to the surface in weathering profiles and are typically 15–35 m thick. They require disturbance of a large amount of land, owing to their low grade (typically about 800 ppm, but usually <4,000 ppm). On the plus side, the amounts of HREEs are small and near the surface, making high-quality remediation shortly after mining possible. Also, little energy is required for mining or processing. The recovery of exchangeable REEs is likely to be good, but insoluble REE minerals will remain in the waste. Values of Th and U are low, although the presence of Th- and U-bearing minerals in insoluble residual minerals such as monazite, xenotime, thorite or uraninite is likely to vary according to the protolith composition.

Production of REEs as by-products of ores such as apatite and bauxite is possible (Table 1) and the environmental impact of this depends on whether the production of the REEs is considered a bonus or whether, as is more usual, the overall environmental impacts (which may be large, see Figure 3) are apportioned to both the major products and the by-products.

Overall, the conclusions from this comparison are that mineral sands score well, apart from the radioactivity of the ore minerals. Most mineral sand operations ship concentrates from their mine to separate processing factories, but their monazite and xenotime concentrates are likely to be too radioactive for transportation, or even for storage. However, this is a challenge that could be overcome if a processing method was installed on site so that Th and U (and Ac) were removed from the ore concentrates. Then, an intermediate product could be shipped, and the Th and U stabilized and returned to source. Ion-adsorption clay deposits can also score well as environmentally favourable deposits, so long as good methods are designed to strip mine and remediate rapidly or to carry out safe in-situ leaching. Carbonatites generally appear more environmentally favourable than alkaline rock deposits because of their higher grade. Alkaline rock deposits have the advantage of higher proportions of HREEs.

**Table 1** Examples of rare-earth element (REE) deposits and qualitative analysis of their mining and processing characteristics. Characteristics shaded green and in bold are generally advantageous to responsible sourcing, grey are less so and unshaded cells are less favourable.

<table>
<thead>
<tr>
<th>Ore type</th>
<th>Energy for crushing and grinding</th>
<th>Grain size/ Difficulty of beneficiation</th>
<th>Chemicals (acid, flotation reagent)</th>
<th>Radioactivity: ore mineral and host rock</th>
<th>Amount of rock to be moved*</th>
<th>By-products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonatite</td>
<td>Medium – High</td>
<td>Variable – 10 μm</td>
<td>Flotation – medium</td>
<td>Medium</td>
<td>Low</td>
<td>Not usually</td>
</tr>
<tr>
<td>Weathered carbonatite</td>
<td>Medium</td>
<td>10 μm and finer</td>
<td>Flotation – medium</td>
<td>Low–Medium</td>
<td>Low</td>
<td>Not usually</td>
</tr>
<tr>
<td>Alkaline rock</td>
<td>High</td>
<td>Variable 1 μm and larger</td>
<td>Variable</td>
<td>Variable</td>
<td>High</td>
<td>Co-products common</td>
</tr>
<tr>
<td>Ion adsorption clay (in-situ leaching)</td>
<td>None</td>
<td>Beneficiation not needed</td>
<td>Leaching, so can be high</td>
<td>Low</td>
<td>High</td>
<td>None</td>
</tr>
<tr>
<td>Mineral sand (placer)</td>
<td>None–Low</td>
<td>10 – 100 μm</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>from TiO₂, zircon etc production</td>
</tr>
<tr>
<td>By-product of igneous apatite</td>
<td>High</td>
<td>100 μm–mm</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>from fertiliser manufacture</td>
</tr>
<tr>
<td>Red mud processing</td>
<td>Bauxite processing</td>
<td>n/a REE from red mud</td>
<td>Medium?</td>
<td>Low</td>
<td>High</td>
<td>from Al production</td>
</tr>
</tbody>
</table>

* i.e. low grade = large amount of rock
QUANTIFYING THE COMPARISON OF DEPOSIT TYPES USING A ‘LIFE CYCLE ASSESSMENT’ (LCA) APPROACH

It is possible to compare the environmental performance of the production of critical raw materials by using the “life cycle assessment” (LCA) approach. An LCA is performed by calculating all the energy and material inputs, and the associated emissions and waste outputs, over an entire life cycle, from raw material acquisition to ultimate disposal [International Organization for Standardization (ISO) 14040 2006a]. This method has the advantage of incorporating a wide range of environmental issues into an integrated assessment framework, including climate change, ecotoxicity and resource depletion. Calculations are done with proprietary software that incorporate databases of previous LCAs for inputs such as chemical reagents and power generation. The assessments can stop part-way through a life cycle, and most studies of mined materials go ‘mine to gate’, encompassing mining and some parts of the processing to give an intermediate product used in the next stage of the value chain. To date, there have only been a handful of LCAs for REE production, primarily focusing on Bayan Obo (Sprecher et al. 2014; Koltun and Tharumarajah 2014; Zaimes et al. 2015). Sprecher et al. (2014) extended their LCA to the production of NdFeB magnets. These studies yielded different results (Table 2). For example, global warming impacts range from 12 to 35.27 kg CO₂ equivalent (eq) at Bayan Obo, and acidification has a range from 6.4 to 99.28 kg SO₂ eq. The variation of the REE results can be explained by the fact that different software packages, datasets and methods have been used and that different assumptions about the processing routes were made for each LCA. For example, Koltun and Tharumarajah (2014) used a two-step allocation procedure to deal with the co-production of iron ore at Bayan Obo. Comparison of two LCAs done at different times can also be difficult because the inventories in the software are updated periodically as new data become available for specific processes, and because of the need to reflect the changing mix of energy generation in the countries in the database.

An important point that comes from these analyses is the high contribution made by chemical reagents, especially when they are manufactured in countries with high fossil fuel use. Although crushing and grinding prior to mineral separation is energy intensive, it has a smaller contribution to greenhouse gas emissions than dissolving the REE minerals and separating the individual REEs from each other (Fig. 4). Various new processes have been proposed to separate REEs but none are in commercial production yet. Learning from nature in order to find novel ways to carry out these processing stages is certainly a challenge to which geochemists could contribute.

Recent work by Vahidi et al. (2016) has examined the environmental performance of ion-adsorption clays. The LCA results indicated that production of REEs from ion-adsorption clays has a similar global warming impact as production from Bayan Obo, a lower acidification rate than from Bayan Obo, and a higher cumulative energy demand. It should be noted that the difference in REE composition (i.e. higher HREE content in the ion-adsorption clays) and the use of an economic allocation in the comparison means that the potentially better environmental performance of the ion-adsorption clays is offset by its higher relative economic value. Comparisons could be improved by comparing LCA results for individual REEs, e.g. Nd, Dy, or Eu, rather than grouping the whole set together.

Other challenges specific to using LCAs in evaluating REE production are that there are often limited data available for specific processing steps. Therefore, surrogate information is required. This is especially true when comparing deposits that are still in the exploration and development phase. There is also the issue about what factor to measure environmental performance against. Should it be measured against an individual REE or against an economic value? Previous studies have tended to incorporate some economic criteria because this is more realistic when considering the high-value variation of the individual elements. Cerium

### Table 2

<table>
<thead>
<tr>
<th>Factor</th>
<th>Unit</th>
<th>Bayan Obo 1</th>
<th>Bayan Obo 2</th>
<th>Bayan Obo 3</th>
<th>Ion adsorption clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>kg CO₂ eq</td>
<td>12–16</td>
<td>32.29–32.49</td>
<td>22.98–35.27</td>
<td>20.9–35.5</td>
</tr>
<tr>
<td>Acidification</td>
<td>kg SO₂ eq</td>
<td>6.4–8.8</td>
<td>N/A</td>
<td>96.27–99.28</td>
<td>0.165–0.288</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>0.04–0.06</td>
<td>N/A</td>
<td>0.18–0.27</td>
<td>0.303–2.87</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM2.5 eq</td>
<td>N/A</td>
<td>N/A</td>
<td>0.16–0.18</td>
<td>0.026–0.045</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq x 10⁻⁶</td>
<td>2.0–3.5</td>
<td>N/A</td>
<td>3.8–20</td>
<td>2.4–3.2</td>
</tr>
<tr>
<td>Cumulative energy demand</td>
<td>MJ</td>
<td>174–232</td>
<td>169.2–179.5</td>
<td>315–578.8</td>
<td>255–388</td>
</tr>
</tbody>
</table>

Data from Sprecher et al. (2014), Koltun and Tharumarajah (2014), Zaimes et al. (2015), Vahidi et al. (2016)

All results are presented as a range from low to high

The eq units simplify all of the chemicals causing each factor into one equivalent unit, e.g. kg CO₂ eq includes other gases responsible for global warming such as methane. PM2.5 = atmospheric particulates smaller than 2.5 μm diameter. CFC-11 = ozone-depleting chemicals equivalent to trichlorofluoromethane.

N/A = no result available for this factor

### Figure 4

Greenhouse gas (GHG) emissions equivalent per kg of rare-earth oxide produced calculated from a life cycle assessment of a) mining, concentrating Bayan Obo REE ore; b) dissolving (cracking) the two ore minerals bastnäsite and monazite to release their REEs; c) separating the light (L), medium (M) and heavy (H) REEs from each other. After Koltun and Tharumarajah (2014).
Conclusions

Most critical raw materials contribute to the long supply chains used for the manufacture of complex devices such as smartphones, computers, and cars. It is much more difficult for consumers to engage with the original mining operations in these cases than for mining operations for gemstone products used in jewellery where the raw materials are more obvious. Only high-profile humanitarian issues, such as conflict minerals, have really penetrated these long supply chains to produce the action needed to help ensure responsible sourcing. As yet, there are no responsible mining schemes generally applicable to mid-size critical metal suppliers, although there are international management systems and other relevant information that companies can use and make directly available.

Production of REEs as whole (using data for Bayan Obo) performs slightly worse than average when compared against LCA results for other metals. For example, Graedel et al. (2015) used an LCA metric for environmental impact, based on the earlier studies of Bayan Obo contained in LCA inventories. Graedel et al. (2015) graded the LREEs (La, Ce, Pr, and Nd) as having low environmental impact, and three of the HREEs (Eu, Dy, Tb) as medium, when compared with other metals. All the REEs had a lower environmental impact (in terms of production) than gold, whereas the LREEs themselves were similar to copper and higher than iron.

A limitation of the LCA approach is that although the software packages have been developed to incorporate many factors, such as those discussed in the quantitative comparison above, the results tend to be presented in terms of energy use, global warming impact, and greenhouse gas emissions. Thus, the results either miss or apparently downplay all the other factors of responsible sourcing. The LCA approach also misses the behavioural element of whether a mining company is abiding by the regulations and following good practice guidelines. Despite the data that exist in LCAs, it can be a powerful tool in calculating the environmental performance of REE production and of offering insight into hotspots of production that need further research, as well as calculating values that can feed into full life cycle analyses of manufactured goods. At the moment, the only deposit information available in commercial inventories is for Bayan Obo (China), and this is a major limitation when considering future supplies. Further work will be needed to formalise a consistent process for LCA use in the context of REE production.

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References

Global Trends in Metal Consumption and Supply: The Raw Material–Energy Nexus

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INTRODUCTION

The consumption of mineral resources and energy has increased exponentially over the last 100 years. Further growth is expected until at least the middle of the 21st century as the demand for minerals is stimulated by the industrialization of poor countries, increasing urbanization, penetration of rapidly evolving high technologies, and the transition to low-carbon energies. In order to meet this demand, more metals will have to be produced by 2050 than over the last 100 years, which raises questions about the sustainability and conditions of supply. The answers to these questions are not only a matter of available reserves. Major effort will be required to develop new approaches and dynamic models to address social, economic, environmental, geological, technological, legal and geopolitical impacts of the need for resources.

Keywords: mineral resources, raw materials, energy

TRENDS IN MINERAL RESOURCE CONSUMPTION

The first stage in industrialization is characterized by the construction of infrastructures in the sectors of heavy industry, housing, transport and communication, and in the sectors of production, transport and use of energy. This development phase consumes mainly ‘structural’ raw materials produced in global amounts of more than one million tons/year, such as concrete, steel and iron, aluminium, copper, manganese, zinc, chromium, lead, titanium, and nickel. After a period of increased consumption, the yearly consumption of structural raw materials stabilizes when the gross domestic product (GDP) per capita reaches about US$15,000–$20,000 per capita for steel and concrete consumption, and US$20,000–$25,000 for aluminium and copper consumption (Bleischwitz and Nechitior 2016). Many countries with large populations (e.g. China, Indonesia, India, Pakistan and many African countries) currently have GDP/capita of less than US$15,000. Their industrialization will inevitably be associated with an increase in the consumption of raw materials. This has clearly been the case since the late 1990s with the rapid industrialization of China, which led to dramatic growth in the rate of global steel and concrete consumption (6%/year), Al (5%/year), Cu (3%/year) (Fig. 1 and 1C), and Cr (5%/year), Mn (6%/year), Ni (5%/year) and Zn (4%/year). The maximum stock of iron and steel in developed societies is estimated to be about 10 t/capita (Wiedmann et al. 2015). In order to increase the current stock of 2.7 t/capita for a population of 7 billion individuals to a stock of 10 t/capita for 9 billion individuals, it would be necessary to produce 71 Gt of iron, which represents 85% of the known crude ore reserves (USGS 2017). For this evolution to take place in 35 years, the average steel production must reach 3 Gt/year by 2050, twice the current production rate.

Subsequent to, or in parallel with, the building of its base infrastructure, a country’s economy will move towards high technologies. At the beginning of the 20th century, metal consumption was limited mainly to Fe, Cu, Pb, Zn, and Ag, which had the desired basic physical and chemical properties needed for the technologies of the time. High technologies now require new raw materials and mineral resources because they utilise many additional properties, including electronic structure, catalytic properties, quantum and semi-conductor properties specific to almost all the elements of the periodic table. The annual growth in the production of rare metals is at record levels: around

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10%/year for Sb, Be, Co, Ga, Ge, Li, Mo and some of the rare-earth elements (REEs) (Fig. 1D). These huge growth rates and the inevitable problems of supply have become a focus of attention during the last decade. But evaluating the future of rare metals is extremely difficult because the demand for such metals depends on the rapid development of new technologies. For instance, Hitachi in 2012 manufactured high-efficiency permanent magnet synchronous motors that are free of REEs. Reluctance motors using REE-free electromagnets instead of permanent magnets are also an option for the future. Thus, should the supply of REEs become an issue, then technological innovations might develop that do not require essential REEs in their manufacture. This is an important difference between the ‘high-tech’ metals and the ‘structural metals’ such as steel, copper and aluminium: it would be very difficult to find adequate substitutes for the latter group. Another difference is that rare metals are often extracted as by-products from the production of the major metals that are the economic basis for most mines. If the demand of a co-produced metal rises, mining larger quantities is not possible because the major metal determines the volumes.

Until now, industrial development has been possible due to the access to cheap and abundant fossil energy. This situation is likely to change because the emissions of carbon dioxide and other combustion-related components have worrying environmental consequences. The Paris Agreements of COP 21 (the 21st meeting of the Conference of the Parties), which plans to achieve ‘carbon neutrality’ sometime between 2050 and 2100, will involve a massive reduction of carbon dioxide emissions and an in-depth revision of the existing global fossil energy–based system. New low-carbon energy infrastructures require more raw materials per megawatt of installed capacity than the existing fossil fuel–based facilities (Kleijn et al. 2011; Garcia-Olivares et al. 2012; Vidal et al. 2013; Hertwich et al. 2015) (Fig. 2). Therefore, large amounts of structural mineral resources (Fig. 3) and high-tech metals will be consumed, such as REEs in the super-magnets of wind turbines; Ga, In, Se and Te in photovoltaic thin films; Li in batteries of hybrid or electric vehicles; and platinum-group metals (PGMs) in fuel cells. Garcia-Olivares et al. (2012) have estimated that a complete shift to electricity produced by renewable resources as the sole source of used energy could require as much as 330 Mt of Cu (almost 20 times the current global yearly production), 8 Mt of Li (190 times), 66 Mt of Ni (30 times) and 31 kt of Pt (15 times). The supply of such huge amounts of metals, while preserving the supply for other needs, hardly seems achievable by 2050. Even the more conservative scenarios of future energy production that maintain a share of fossil fuels point out that very large quantities of metals will be needed (Fig. 3). The amounts of steel, aluminium and copper required to build the infrastructure needed for energy production according...
to the BlueMap scenario of the International Energy Agency (IEA 2010) represent 0.7, 3 and 2 times the global 2010 supply of these metals, respectively. The amounts of steel, aluminium and copper required for the Ecofys–WWF scenario (see Deng et al. 2011) correspond to 2.5, 6 and 4.4 times the 2010 supply, respectively, in addition to 10 Mt of lithium. The ever-increasing need for rare metals is also worrying (Örlund 2011): forecasts for 2030 indicate that the yearly global demand in Ga, In, Se, Te, Dy, Nd, Pr and Tb for photovoltaic cells and wind turbines will require production levels of these metals to be increased by between 10% to 230% of the 2010 world supply.

Altogether, the overall stocks of all metals needed to be produced by 2050 and the use of these metals in all manner of products in 2050 could be 5 to 10 times the current stocks (Graedel and Cao 2010; Graedel 2011). This means that the cumulative amount of metals to be produced over the next 35 years would exceed the cumulative amount that has been produced to date. Is this possible?

WILL THE SUPPLY MATCH THE DEMAND?

Several studies suggest that the future supply of raw materials will not match the demand because the amount of mineable fossil resources apparently decreases with time (see counterargument below) and that the production of several metals has either already peaked or will peak in the foreseeable future (Meadows et al. 1972; Laherrère 2010; Kerr 2014; Northey et al. 2014; Sverdrup and Ragnasdottir 2014). Classical modelling of fossil resources assumes that production follows a symmetric bell-shaped curve of normal distribution (Hubbert 1956; Laherrère 2010; Frimmel and Müller 2011). The background to this assumption is that production continuously increases at an exponential rate when easily accessible resources can be extracted, and it later collapses when the stock of mineable resources (what is termed the ‘ultimately recoverable resources’) becomes depleted. According to these assumptions, the decline of the growth rate of base metals production between 1970 and 2000 (Fig. 1) could have been erroneously interpreted as a sign of reserve depletion – ‘reserves’ being the part of a resource that can be economically extracted using the technology of the time. In reality, the stabilisation of production after the strong growth that followed World War II resulted from a lower growth-rate in demand. China’s sharp increase in metal consumption starting during the late 1990s was matched by an equally strong increase in production, with no supply constraints due to depletion of reserves. It seems, therefore, nonsensical to assume that the demand and production of a mineral resource will continuously increase at an exponential rate until the reserves are depleted. The Hubbert peak theory (Hubbert 1956) assumes that the ultimately recoverable resources are finite and quantifiable. While it is true that the stock of mineral resources in Earth is finite and is not being renewed on a human timescale, it is also true that the whole continental crust is composed of minerals that could

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3 Ecofys is a Netherlands-based renewable energy consultancy organisation; WWF is the World Wide Fund for Nature (formerly the World Wildlife Fund), which is an international non-governmental organisation dedicated to conservation.
eventually be extracted to produce metals. Improvements in technology will allow new discoveries to be made and make economically viable the exploitation of resources that were previously impossible to extract. It follows that the ultimately recoverable resources and the reserves are, in fact, larger now than they were 50 or 100 years ago. The increase of ultimately recoverable resources with time is well illustrated by the case of copper: the recovery values estimated in 2010 were made by calibrating logistic functions on the historic data of global production, and the derived recovery values that were calculated ranged from about 1 Gt (Laherrère 2010) to 3.8 Gt (Frimmel and Müller 2011). At the same time, the US Geological Survey estimated copper resources at 1.5 Gt. Three years later in 2014, the US Geological Survey completed its geology-based assessment of global copper resources and suggested that an amount of ~ 3.5 Gt of undiscovered copper should be added to the 2.1 Gt of already identified resources (Johnson et al. 2014). Thus, the demand for a metal and the reserves of that metal both fluctuate over time.

At least two other points must be considered when dealing with the future evolution of metal production, and these are dealt with below.

**Energy Required to Produce a Mineral Resource and Associated Environmental Impacts**

Mineral availability is related to accessibility, which is tightly connected to the energy required to extract/produce that mineral. Currently, about 10% of the global energy consumption and about 25% of the energy consumed by industry worldwide is used for the production of steel, cement and aluminium (EIA 2013). The production of mineral resources is, therefore, very energy intensive. Because the production costs depend on the cumulative energy of production ($E_{cum}$) and because the reserves depend on the production costs, any future reserves are connected to the evolution of $E_{cum}$. To a first order, both $E_{cum}$ and the price of metals vary as a power-law of the dilution of the metal (inverse of ore grade) (Phillips and Edwards 1976; Johnson et al. 2007; Gutowski et al. 2013) (Fig. 4). It follows that, at constant technology, $E_{cum}$ is expected to increase exponentially with decreasing ore grade (Mudd 2010; Norgate and Jahanshahi 2010). This need for energy is often seen as a future limit to extraction. However, the increase in $E_{cum}$ can be compensated by improving the energy efficiency. For example, the $E_{cum}$ of steel has been reduced from about 50 MJ/kg in 1900 to 25 MJ/kg in 2010 and the $E_{cum}$ of primary aluminium has decreased from 50 kWh/kg in 1950 to 15 kWh/kg in 2010 (Gutowski et al. 2013). Further improvements in energy efficiency will likely be possible, even though the rate of improvement will necessarily decline as the thermodynamic limit of primary production is approached (about 10MJ/kg for steel, and 10 kWh/kg for Al). If we were to use less efficient, but nonetheless less polluting, renewable and free energy sources at a low price in the future, then the question of mineral scarcity must be viewed differently. When the infrastructure of renewable energy matures, the price of energy will drop and the contribution of $E_{cum}$ in the cost of raw materials production will drop as well. We could afford to exploit resources not currently open to development. It is not certain whether this constitutes real progress, however, because cheaper energy and resources would entail an increase in demand and consumption, and a concomitant increase in environmental impacts other than those deriving from energy use. The 5 November 2015 Samarco company tailings dam collapse in Brazil is an illustration of the risks of large-scale mining. The decision in April 2017 by El Salvador to ban all metal mining on its territory is another example of popular mobilisation against environmentally destructive projects that had been responsible for heavily polluting the country’s surface waters. The future production of mineral resources will depend on social acceptance, which requires improvement of the levels of environmental protection and governance (Ali et al. 2017), the respect of safeguards and the systematic use of cutting-edge, although expensive, technologies that reduce the damage from mining and mineral processing activities.

**The Potential of Recycling**

The stabilization, or even the decline, of primary production does not mean that the world will suddenly run out of metals. In contrast to fossil fuels, primary metals are not lost when they are used, and metal-bearing goods that are manufactured today can be viewed as the reserves for tomorrow’s recycling. An increase in recycling, however,
will not be sufficient to meet demand during future periods of economic growth because we can only recycle some of the consumer goods and equipment that were created within the last few decades. But when most countries in the world reach a GDP/capita that corresponds to the saturation level, then recycling of many metals may, in theory, become the most important source of raw materials. In practice, recycling potential is limited by economic factors, such as the difference between the price of metals and the cost of their recycling. Only the metals present in sufficiently high concentrations in their end-of-life products can be recycled; the recycling cost and $E_{\text{cum}}$ of the most diluted metals will remain uncompetitive compared to the costs of their primary production (Fig. 4). This is why most rare metals used in high technologies are not recycled today. There are also examples for base metals whose recycling is limited by prohibitive costs. Falconer (2009) estimated that 60% to 80% of the copper in the undersea cables that link offshore wind turbines to Great Britain will not be recycled at the present cost of copper. However, a future increase of price due to an eventual depletion of primary reserves will foster recycling, which is the good news about mineral resources scarcity.

**LONG-TERM FUTURE TRENDS**

Modelling of mineral resource should not rely solely on factors such as a knowledge of present geological availability, historical data of production, and amount of ultimately recoverable resources. Modelling also requires assumptions regarding the growth rate of demand and the increase in levels of technology. Dynamic models are urgently needed, ones that will integrate the full complexity of the value chain, from primary production to recycling, and that will link together the energy requirements with the economic, geological, environmental, engineering, social and geopolitical dimensions. Such models are inherently complicated (Sverdrup and Ragnasdottir 2014), but it would be delusory to attempt to deal with the very complex issues with simple empirical and deterministic models such as that used by Hubbert for conventional oil in the 1950s. Olivier Vidal and Nicholas Arndt proposed a ‘prey–predator’ dynamic model to tackle some of these complexities (see S1 supplementary information in Ali et al. 2017). They showed that a business-as-usual scenario of copper demand and costs of production at constant price lead to a peak of primary production in 2040, followed by a collapse of primary supply. This evolution is consistent with estimates made by Northey et al. (2014), who based their model on geological availability and future mines capacity. However, many other scenarios of demand can be envisaged. If the demand stabilizes at about 30 Mt/year from 2030 onwards (16 Mt/year in 2015), no production peak is observed with the Vidal and Arndt model, and the primary supply stabilizes until 2100 at constant copper price. Recycling is predicted to compensate for the decline of primary production even in cases where primary production collapses: the cumulative flow of primary and recycled copper, for example, remains higher than twice the present level. The Vidal and Arndt model, when applied to other metals, suggests that the supply of most base and precious metals (except gold) should meet demand until the end of the 21st century. The situation for rare metals is not as clear because the historical data on reserves and production are either lacking, imprecise, or they span too short a period of time to be used as reliable constrains for the models.

**PERSPECTIVES**

Sustaining the supply of raw materials is not only a matter of primary resources and reserves. The Earth remains an immense reservoir of elements, even though their accessibility is limited by our ability to identify and access the resources when they are deep and hidden, by our ability to anticipate geopolitical risks, and by our ability to control the environmental and social impacts associated with element extraction. Energy issues must be taken into account in addition to the economic and social conditions of primary production, recycling, and the eventual depletion of reserves. The evolution of demand must also be analysed for the two kinds of mineral resources identified above. The supply of structural raw materials seems to be secured for the next 50 years because the reserves are huge. By contrast, the supply of most high-tech metals is often considered to be critical. However, it is the production of the structural raw materials that bear most of the...
environmental impacts and energy needs, and this is important because the long-term demand for structural raw materials is inevitable as poor countries become ever-more industrialized. The supply of rare metals is a shorter-term issue that results from four factors: 1) the decoupling of material and technological innovations from the reality of primary supply; 2) the difficulty of recycling complex and diluted products; 3) poor historical knowledge regarding rare-metal reserves, because these metals have not been in use for very long; 4) the fact that many high-tech metals are by-products of major metal production.

Despite the enormous stakes in, and complexities of, mineral commodities supply, simplistic empirical models are still being used to assess future supplies of mineral resources. Moreover, modelling to date has tended to focus on the catastrophic dimension of exponential growth. More accurate modelling must analyse the conditions and interactions that control the supply of particular materials. Thus, the multi-faceted nature of producing and using raw materials needs to be integrated into dynamic models that will combine together knowledge from different scientific disciplines – Earth and environmental sciences, material sciences, engineering, economics, social sciences, and others – to get a better idea of what the future for metal production of all types really holds.

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Improving Mitigation of the Long-Term Legacy of Mining Activities: Nano- and Molecular-Level Concepts and Methods

Gordon E. Brown Jr.¹, Michael F. Hochella Jr.², and Georges Calas³

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in activities over several millennia have resulted in a legacy of environmental contamination that must be mitigated to minimize ecosystem damage and human health impacts. Designing effective remediation strategies for mining and processing wastes requires knowledge of nano- and molecular-scale speciation of contaminants. Here, we discuss how modern nano- and molecular-level concepts and methods can be used to improve risk assessment and future management of contaminants that result from mining activities, and we illustrate this approach using relevant case studies.

KEYWORDS: mineralogy, environmental sciences, geochemistry, pollution, toxic elements, surface science, synchrotron radiation

INTRODUCTION

In 2015, a major release of mine waste occurred in the “Iron Quadrangle” of Minas Gerais (Brazil) when a tailings dam built to store wastes from the extraction of iron ore failed (Figs. 1A and 1B). This event, described as the worst environmental disaster in Brazil’s history, released ~60 Mm³ of waste and water—containing toxic levels of mercury, arsenic, copper, and zinc—into the Doce River. This river provides domestic water to hundreds-of-thousands of people. The tailings dam failure resulted in major economic losses to tens-of-thousands of people who depended on the river for their livelihoods. Locally, this event caused major damage to the village of Bento Rodrigues, resulting in the displacement of ~700 villagers from their homes, and caused the death of 19 people. Two-and-a-half weeks later the contaminated muds had traveled 850 km to the Atlantic Ocean, severely impacting one of the most important fish-spawning grounds in the world. Similar tailings dam failures have occurred in many mining districts around the world, causing major environmental, economic, and social impacts (Kossoff et al. 2014). Even in the absence of catastrophic events such as sudden tailings dam failures, mining activities and their long-term legacies often result in damage to local and regional ecosystems and impact the people who live in the affected areas.

An example of a far more extensive type of environmental impact, one stemming from thousands of years of mining activities going back to the Roman Empire, can be found in one of the world’s largest massive sulfide ore deposits: the Iberian Pyrite Belt (IPB), one of the world’s oldest massive sulfide ore deposits. Mining the IPB deposits for gold, silver, copper, lead, iron, and tin over so many centuries has left several hundred abandoned mines and resulted in dramatic levels of pollution that has been exacerbated by largely unchecked acid mine drainage (AMD) (Sarmiento et al. 2007). Surface water in these areas primarily drains into multiple streams/rivers in the adjoining and relatively small Rio Odiel and Rio Tinto river basins, which merge just before emptying into the Gulf of Cádiz and the Atlantic Ocean. Olias et al. (2006) estimated that the aforementioned river systems contribute 15.1% of the Zn, 3.13% of the Cu, and 0.15% of the As to the annual global riverine flux to the oceans. These are remarkable contributions, especially considering that these rivers are low discharge with moderate-sized drainage areas. A survey of 25 mining areas in the IPB by Sánchez-España et al. (2005) suggests that schwertmannite, a complex polyphasic oxyhydroxysulfate with crystalline areas spanning less than a few nanometers within amorphous nanometer-scale needles stemming from micron-sized cores (French et al. 2012), is “the most important mineral phase, both in controlling Fe solubility at pH 2–4, and as a sorbent of trace elements (As, Cu, Zn).”

The Brazilian and Iberian examples of the negative environmental impacts of mining activities do not adequately convey the magnitude of the problem worldwide. Approximately 20–25 Bt of solid mine wastes are being produced annually around the world (Lottermoser 2010), with open-pit mines producing 8 to 10 times as much waste as underground mines. Historic mining during a long period of limited (if any) environmental regulations until the 19th and 20th centuries has left a legacy of contaminated sites worldwide. Now, postmining operations, including remediation, cleanup, and/or monitoring, result from regulations and legal obligations. Remediation must utilize cost-effective technologies because mine waste brings no financial gain by itself. Waste types include mining wastes (overburden, waste rocks) removed to access the resource and processing wastes (tailings, sludges, waste water). In the absence of containment, both types of waste are sources of near-field or far-field contamination by chemicals, heavy metals, and/or radioactive elements, all resulting from chemical, biological, and physical processes that are best understood through nano- to molecular-scale approaches. In the specific case of tailings—the materials causing the most significant environmental impact in mining operations—evolution of their geochemistry, mineralogy, and physical state depends on the ore, ore processing, and storage conditions. Preventing the release of contaminants requires stabilization and rehabilitation.
of the tailings. In some cases, the evolution of metal prices may justify the recovery of some metallic components of tailings by reprocessing.

This article highlights the long-term legacy of mining activities in several localities that are exceptionally complex and heterogeneous at nanometer-to-kilometer length scales. An arsenal of nano- and molecular-level methods is required to characterize contaminant speciation, defined here as (1) identity and distribution of contaminant elements; (2) their physical states (crystalline, amorphous, or mixed materials, element/phase associations including natural organic matter (NOM), biomass, etc.); (3) oxidation states; (4) empirical formulas; and (5) detailed nano- to molecular-scale structures. Our principal focus is to illustrate how knowledge of contaminant speciation can lead to a more precise understanding of the transport, fate, and potential remediation of the chemically derived environmental damage associated with mining activities, especially how to limit contaminant transport and bioavailability. The terms contaminant (a chemical species at higher concentration than its background concentration) and pollutant (a chemical species that produces undesirable physical, chemical, or biological effects) differ, but here we use contaminant for both.

**NANO- AND MOLECULAR-LEVEL CONCEPTS AND METHODS**

To mitigate environmental impacts of mining and processing wastes, various types of knowledge are required: (1) the concentration of contaminants as a function of space and time; (2) the speciation of contaminants (see definition above); (3) the geology, geochemistry, mineralogy, and petrology of the mineral deposit and waste materials; (4) the local and (for larger mineral deposits) regional hydrology, including variations in rainfall and drainage; (5) the type of microbial community present at mine-waste sites. Examples of why such knowledge is important are presented in the case studies section below.

Heavy metal and radiogenic contaminants associated with mining activities can occur at major, minor, or trace concentrations in many different forms depending on redox conditions, pH, element concentrations, and other system variables, as well as on the types of processing used to extract the metals or radiogenic materials from ores and waste rock. In some cases (e.g. Hg-contaminated soils), concentrations are below detection for most nano- and molecular-level methods, and indirect, macroscopic methods such as selective chemical extractions are often used for contaminants and distribution. However, these methods are subjective, and important contaminant species can be overlooked. The waste materials generated from mining activities are typically highly complex due to the many different phases present and their heterogeneities over a large range of spatial scales. As a result, nanometer- to centimeter-level imaging is required to quantify compositional and structural heterogeneities.

One of the most important concepts used to assess the impact of contaminants on organisms and ecosystems is bioavailability, which is commonly defined in an environmental context as the measure by which various substances may enter into living organisms (Brown et al. 1999). The bioavailability of contaminants depends on their molecular-speciation and mode of ingestion. Solids have different solubilities in water: in general, the more soluble a solid, the more bioavailable the elements comprising it should be. For example, cinnabar is highly insoluble ($K_{sp} \sim 10^{-53}$ at 25°C), whereas eglestonite [(Hg$_2$)$_2$Cl$_2$O$_2$H] and montoydite (HgO) are orders of magnitude more soluble. Thus, when present as cinnabar, Hg is much less bioavailable than when present as eglestonite or montoydite, although cinnabar's solubility can be enhanced in the presence of certain types of bacteria (see below).

In addition to mineral solubility, another factor affecting bioavailability is sorption of aqueous contaminants on mineral surfaces. For example, Foster et al. (1998) used synchrotron-based X-ray absorption fine structure (XAFS) spectroscopy to determine the types of arsenic species in mine tailings at three gold mines in California (USA) and found that arsenate forms inner-sphere complexes on Fe(III)-oxyhydroxides and clay minerals at two of the sites, whereas arsenenate is mainly incorporated in precipitates at a third site, resulting in potentially greater bioavailability of arsenic at sites with adsorbed arsenate. Similar studies of lead contamination at mine sites in Leadville (Colorado, USA) and in smelter-contaminated soils near lead–zinc mines in Evin-Malmaison (northern France) showed the importance of sorbed lead in controlling its local molecular environment(s)—it would be difficult to determine the sorption mode of contaminants on the surfaces of minerals and poorly crystalline solids or on natural organic matter. Over the past 25 years, XAFS spectroscopy has been increasingly used to determine molecular-level speciation of contaminants, including sorbed species, in mining and processing wastes.

Many analytical methods are needed to provide information on contaminants in complex mining wastes. However, two in particular have proven to be very useful. Synchrotron X-ray–based spectroscopies (such as XAFS mentioned above) provide critical information on contaminant associations and distribution, including molecular and structural details. In addition, critical phases and reaction pathways involving mine-waste contaminants are often observable only at the nanoscale. This is one of the primary strengths of transmission electron microscopy (TEM) (see Caraballo et al. 2015, for a review relevant to mine-waste applications). Detailed phase characterization and elemental association, and electron-based imaging, diffraction, and chemical analysis techniques with spatial resolution down to sub-nanometer levels, make TEM an ideal method for unraveling the complexity of mine waste and contaminant behavior.

**CASE STUDIES**

**The Legacy of 120 Years of Mercury Mining in California (USA)**

The two largest mercury mines in North America—the New Almaden and New Idria Mercury Mines—are located in California and were operated for over 120 years. Environmental impacts of these mining activities are visible today as large volumes of Hg-bearing waste rock, roasted ore (calcines), and Hg-contaminated soils, where [Hg$_{tot}$] ranges from <100 mg/kg to >1,000 mg/kg. Although mining ended in the early 1970s, untreated mine wastes continue to release Hg to nearby streams and to the atmosphere. Native mercury [Hg(0)] from these mines was used to recover fine-grained gold in placer deposits in the Sierra Nevada foothills, resulting in the loss of ~3,600 t of Hg(0) to nearby soils and sediments. Surface waters have transported Hg-bearing wastes hundreds of kilometers from their sources, resulting in Hg contamination in the sediments of local drinking water reservoirs and the sediments of San Francisco Bay (Roth et al. 2001). Mercury contamination throughout these areas poses a significant challenge to regulatory agencies who are attempting to limit bioaccumulation of Hg in the food web, typically as monomethylmercury(I) which leads to toxic levels of Hg in some fish species and threatens human health.

Knowledge of Hg speciation in mine wastes is critical for determining its reactivity and bioavailability. Because different Hg-bearing species can have very different solubilities, the types and proportions of Hg species can...
greatly influence Hg release and transport. Kim et al. (2003) used XAFS spectroscopy to show that Hg speciation at different mine sites varies, although Hg-sulfides (cinnabar) and its high-temperature polymorph (metacinnabar) are dominant. The main Hg-containing phases found at the New Idria Mine, for example, are cinnabar, montoydite, eglestonite, and elemental mercury. As discussed earlier, montoydite and eglestonite are significantly more soluble than cinnabar, and thus pose a larger environmental problem than cinnabar.

Comparison of Hg speciation at mines with different geological histories indicates that speciation is influenced by the geological environment in which the Hg ore formed and by ore processing (Kim et al. 2004). For example, Hg-chloride minerals such as HgCl₂ (calomel) and corderoite (Hg₃S₂Cl₂) are found in hot-spring Hg deposits (where Cl concentrations are elevated), whereas Hg deposits in silicate-carbonate alteration rock generally lack such phases. In addition, calcined wastes, produced by roasting ores at 700°C to vaporize Hg(0), contain metacinnabar rather than cinnabar, which would be the dominant Hg-bearing phase in unroasted wastes from the same deposits. Kim et al. (2004) also found that total Hg in calcines increases with decreasing particle size. The proportion of Hg-sulfides also increases as particle size decreases, whereas soluble Hg phases are leached out as particle size decreases, resulting in release of Hg(II), which can be methylated by S- and Fe-reducing bacteria.

Using colloid fractions generated from column experiments and characterized by high resolution TEM and XAFS spectroscopy, Lowry et al. (2004) found that Hg₅ nanoparticles in tailings from the New Idria and Sulfur Bank Mines (California, USA) are the major Hg species being dispersed into local environments. Another surprising result was the discovery, using selective chemical extractions, that very little Hg(II) is sorbed on the abundant ferrihydrite or schwertmannite nanoparticles at the New Idria Mine site (Adam Jew pers. comm.), even though Hg(II) forms inner-sphere surface complexes on both phases in laboratory experiments. Additionally, Hg(0) used at placer gold deposits in the Sierra Nevada foothills to recover fine-grained gold was found to have transformed to HgS nanoparticles, and these are the major Hg-containing species now transported from these deposits (Slowy et al. 2005).

**Figure 1C** shows an acid mine drainage (AMD) pond below the main waste pile at the New Idria Mercury Mine. The pond sediment contains ferrihydrite and schwertmannite, as well as cinnabar and Hg(0) (Jew et al. 2014). A 16S rRNA gene clone library generated from water samples at this site revealed that the AMD microbial community is dominated by Fe- and S-oxidizing bacteria, which are capable of releasing significantly more Hg into solution than inactivated or abiotic controls. The microbial community was found to increase the solubility of HgS by ~25–30 orders of magnitude and is, thus, capable of releasing Hg(II) into solution. These findings have major implications for risk assessment and future management of abandoned Hg mines worldwide and demonstrate the importance of microbial processes in changing the speciation of Hg and other heavy metals at mine-waste sites.

Because of the low degree of structural order of liquid Hg(0), its XAFS spectrum is essentially featureless, making it impossible to detect Hg(0) in mine waste using conventional XAFS methods. However, when Hg(0)-containing samples are cooled slowly to 77K, Hg(0) is converted to crystalline α-Hg whose XAFS spectrum is well defined and out-of-phase with the spectra of cinnabar and metacinnabar. Thus, the proportion of Hg(0) in mine-waste samples can be quantified using this new method, provided [Hg(0)] >50 ppm. Using this approach, Hg(0) was found to comprise ~25% of the total Hg species at some Hg mines in the California Coast Ranges and ~12% at the New Idria Mercury Mine for size fractions <45 µm (Jew et al. 2011). This finding explains the correlation between the amount of Hg(0) evaded (i.e. escaped) into the atmosphere and the amount of Hg(0) at mine sites.

**Importance of Nanoparticle-Facilitated Transport of Contaminants**

The Clark Fork River Superfund Complex (western Montana, USA) is the largest contaminated site in the United States, apart from the nuclear fuel/weapons-contaminated sites managed by the U.S. Department of Energy. The contamination at Clark Fork is due to base-metal mining that started in this area in the 1860s and progressed over the decades; at one time it was the largest mining facility in the world. Toxic concentrations of metals (mainly Pb, Zn, Cu, and As) were spread atmospherically and also distributed down the hydrologic gradient from the mining areas and smelters. Eventually, over 300 square miles of floodplains, streams, rivers, and ponds were contaminated. The site includes 176 Mm² of tailings, 23 Mm³ of slag, and 382,000 M³ of flue dust. Remediation has been ongoing for decades at enormous expense.

Between 2007 and 2008, efforts to help stabilize the Clark Fork Superfund site were disrupted by removal of the Milltown Dam, which was built on the Clark Fork River in the early 1900s some 200 km downstream from the ore processing areas. Over the last century, thousands of
metric tons of Pb, Zn, Cu, and As accumulated behind the dam. The river was diverted and the accumulated metal-bearing sediment collected and removed. After dam removal, riverbed scouring occurred, releasing an unexpected amount of contaminant downstream. Subsequent analysis of fine riverbed sediments about 70 km downstream from the dam removal site revealed a three- to six-fold increase in Pb, Zn, Cu, and As compared to measurements taken before the dam was removed (Plathe et al. 2010).

It is important to study the fine, most mobile, sediment (down to the nanoscale) and identify the phases that transport the metal contaminants. This was particularly important because water in the Clark Fork River during periods of normal flow had metal concentrations within drinking water standards along with circumneutral pH levels; however, during flooding, fish kills were common, even in remediated areas. Hochella et al. (2005a,b) analyzed samples from contaminated riverbeds and adjacent floodplains that are separated by 80 river kilometers. Using TEM, the key secondary minerals that had formed from the breakdown of sulfides and silicates in the oxic, acidic soil–sediment–solution environments were identified. It was determined that As, Cu, Pb, and Zn were being transported by nanoscale secondary iron and manganese oxide minerals and amorphous aluminosilicates. In the anoxic portion of the riverbed, these secondary oxides and amorphous phases along with secondary sulfides were also found to contain the four contaminant metals. Clays also carried significant amounts of Cu and Zn.

Plathe et al. (2010) looked at the metal-carrying nanoscale and mobile sediment much further downstream than the Hochella et al. (2015a,b) studies. Riverbed sediment was collected 3 km downstream from the dam removal site (described above), a few years after the dam removal was complete. The toxic metals of concern were almost exclusively associated with nanoparticulate Fe and Ti oxides in the fine sediment fraction (20–400 nm hydrodynamic diameter). Unlike Hochella et al. (2005a,b) observations over 100 km upstream, these toxic metals were rarely associated with lower density minerals, including clays and other silicates (Plathe et al. 2010).

A subsequent study by Plathe et al. (2013) used a more sophisticated density fractionation technique to separate the higher density, more metal-rich, oxide particles from the lower density clay particles. This allowed the metal oxides to be studied more closely. In addition, all samples were analyzed using asymmetrical flow field–flow fractionation coupled with multi-angle laser light scattering and high resolution inductively coupled plasma mass spectrometry, as well as analytical TEM. This work confirmed that the toxic metals (Pb, Zn, Cu, and As) were being transported further downstream by nano-size iron and titanium oxides, specifically goethite, ferrihydrite, and brookite (Fig. 2).

**Speciation of Uranium in Mill Tailings**

The presence of low-level radioactive wastes located close to populated areas always raises concerns. More than 938 Mm³ of uranium tailings are stored worldwide, and surface remediation of mill tailing sites has been completed in many countries (Abdelouas 2006). Uranium speciation is a key parameter in modeling the fate and transport of uranium as a function of redox conditions, pH, the presence of organic and inorganic ligands such as carbonate or phosphate, and biogeochemical processes. Indeed, reduced U(IV) species are much less soluble than U(VI) species, though the mobility of (UO₂)²⁺ (uranyl) species can be retarded by adsorption and precipitation. We will comment here on the evolution of surface storage of U mill tailings under boreal and desert conditions.

The first example concerns the Gunnar Mine (Uranium City, Saskatchewan, Canada), operated between 1953 and 1964 and which left over 5 Mt of unconfined tailings that had to be remediated. Due to the complex mineralogy and geochemistry of these tailings and the possible presence of multiple uranium species, uranium XAFS analyses were complemented by selective chemical extractions, scanning transmission electron microscopy (STEM), and fission-track mapping (Othmane et al. 2013). The association of U with amorphous hydroxy ferric oxides and small particles of hematite was confirmed at the nanoscale using TEM coupled with high-angle annular dark-field imaging. Complementary XAFS data confirm that uranium
Uranium distribution in the tailings pile produced by the Compagnie Minière d’Akouta (COMINAK) mine, located in the Sahel desert in Niger. (A) Variation of U-concentration along the tailings profile showing the presence of anomalous U concentrations. The dark gray area indicates the range of uranium content expected from an average ore grade and process efficiency. (B) Analytical transmission electron microscope examination of secondary uranium minerals associated with V-rich clays (possibly chlorites), and sub-micron Fe-sulfides (in lighter greens at left of each of the four images). (C) Electron diffraction pattern showing that the sub-micron Fe-sulfides in (B) are greigite.

From Dejeant et al. (2016)

ASK THE RIGHT QUESTIONS: DISCOVER SOLUTIONS

Over the last few decades, we have used nano- and molecular-level methods and concepts to identify the underlying principles that control the speciation and movement of contaminant metals away from their sources in mining waste areas (waste rock, tailings, slag, and flue dust). Left unchecked, why do these sites “leak” metals into the surrounding environment for decades, centuries, and even millennia? What species of these contaminants are present? How does speciation dictate the bioavailability of these metals? What can be done to keep the metals from moving into the surrounding environment?

In our experience, illustrated in the case studies above as well as those of many others who have worked in this field, here is what we can say so far:

(1) Mining-, smelting-, and tailings-derived metal contaminants exist in postmining environments in complex ways, often only revealed clearly at the nano- to molecular/atomic-scale. Characterizing this complexity is challenging, complicated, and time-consuming, especially when considering the vast geographic distributions of contaminants often encountered.

(2) A variety of concepts and methods is the key (as briefly reviewed in this article). Detailed analyses using a variety of methods are needed: notably, synchrotron-generated X-ray techniques, ion beams, mass spectroscopies, nuclear magnetic resonance methods, electrochemistry, wet chemistry, organic chemistry (e.g. relevant to natural organic matter), molecular biology, thermodynamics, and computational science.

(3) This area of research is one in which fieldwork, which includes observing, studying, and measuring field samples as much as possible, is absolutely essential. These systems are simply too complicated at the nano- and molecular-scales to depend on simplified laboratory simulations and computational-based modeling, although a reductionist approach has proven to be of great value in deciphering some of the complexity. Nevertheless, sophisticated instrument-based materials observations continually broaden our horizons, often in surprising and unexpected ways.

(4) Understanding the association of contaminant metals with different phases, and the solubility of those phases under relevant conditions, has proven to be vital in understanding and anticipating the bioavailability of each type of metal in each regional-, local-, and micro-environment. It is necessary to quantify the speciation of contaminants to assess their environmental impact. Metals can be held in a sorptive state (where determining specifics of the sorptive state is also do-able and desirable) as truly dissolved species,
as species incorporated into nanoparticles, or as principal components of micron- to nanometer-sized phases that may be amorphous to highly crystalline.

(5) When information like that described above is available and combined with detailed geomorphic and hydrologic assessments of a mining site, it becomes possible to better understand how mining activities (including the effects of waste rock, the ore processing areas, and the dispersion into the environment of contaminants) have impacted and will impact the present and future ecology of that area.

(6) A relatively recent set of guidelines from the Office of Superfund Remediation and Technology Innovation of the U.S. Environmental Protection Agency (see USEPA in the reference list for a link to this publication) reviews best-management practices that mesh well with what we have reviewed in this paper. Concepts such as those presented here agree with previously considered remediation assessments in that responsible mining waste and tailings disposal must involve burial in geomorphologically stable and anoxic settings without the use of engineered structures such as dams, levies, and other unnatural landforms. For site-impacted water, passive treatment systems are still the methods of choice.

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Elements
Training geologists for a career in the mining industry has changed over the years. It has become at the same time more specialized and with a broader approach. The modern resource geologist needs to understand new styles of ore deposits, the impact of energy transition on the types of deposits and to implement mining processes, the increasing number of mining regulations, and the shift toward educating populations in countries that are new to mining. Based on observation and imagination, rooted in fundamental science, the education of a resource geologist has been transformed by the digital revolution and the integration of the principles of sustainable development. Training future resource geologists means changing the role of teachers to better develop the imaginations of their students and to increasing what students know about the social impact of mining.

**Keywords:** education, mineral resource, imagination, society

**INTRODUCTION**

Geology is a science traditionally based on field observations, often linked to basic laboratory studies. Geology has also been strongly connected to chemistry and physics, both disciplines being essential to better interpret field and laboratory observations. Even today, geology remains a combination of rigorous observation allied with imagination: geologists often use analogies because many geological processes are neither observable nor reproducible.

The education of resource geologists has evolved over the past 100 years with four distinct periods of change in the development of economic geology (Ronald 2016): the ‘early age’ (1916–1945), the ‘golden age’ (1956–1975), the ‘system age’ (1975–2005) and the ‘digital age’ (since 2005).

During the early age (1916–1945), there was no clear separation between a general geologist and a resource geologist. The science of ore deposits was still being developed, with numerous high-quality, field-based descriptions of the major deposits actively taking place. The subdisciplines of structural geology, mineralogy and the understanding of the succession of mineralization in time (paragenesis) were being united in an effort to understand mineral deposits. Therefore, the training of resource geologists was mainly based on field geology, petrography, and mineralogy.

During the golden age (1956–1975), the global search for new mineral deposits increased dramatically. Economic geologists were trained in the field, and teams of exploration geologists travelled all around the world. In the former USSR (Union of Soviet Socialist Republics), large geological expeditions discovered many of the largest ore fields in the world, such as those at Norilsk [the Ni–Cu–platinum-group element (PGE) deposit now in modern Russia, discovered in 1935] and Muruntau (the gold deposit now in modern Uzbekistan, discovered in 1958). In the anglosphere, mining companies hired field geologists educated at schools of mines and universities that offered BSc and MSc degrees. Training was usually completed during the first years of employment by joining an exploration or production team.

During the system age (1975–2005), hard commodity prices continuously decreased as a result of the discoveries of large ore deposits, low energy costs, and progress in mining engineering. Economic geologists were less and less in demand, and the cost of education became too expensive for universities. Job opportunities became scarce, most of the leading mining schools stopped teaching classes on mineral deposits and mining science and technology, focusing instead on oil and gas geology. Some schools even stopped teaching geology altogether and switched to the burgeoning new technologies and to computer sciences. Moreover, based on the plate tectonic paradigm, which had swept through geology during the late 1960s, geology was being transformed into a more integrated science, one where traditional hard-rock geology was now complemented by broader approaches, from geodynamics to climatology. Training in Earth sciences progressively favoured a more quantitative education that included a more-than-basic knowledge of physics, inorganic chemistry, biology, and thermodynamics (Montel and Martin 2014; Jébrak and Marcoux 2015). Field courses declined, largely due to costs, liabilities, and the perceived need to produce generalist ‘Earth scientists’, as opposed to ‘geologists’.

During the digital age (from 2005 onwards), computer capacity reached the point when quantitative and realistic 3-D and 4-D geological modelling became possible. Models that could integrate complex physical and chemical tools became available to non-specialists. This produced another shift in the education of applied (resource) geologists because, in theory, it has become possible to simulate both the genetic processes and the mining processes of any ore deposits.

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body. However, data entry and processing has progressively become a whole domain of activity unto itself, and this has contributed to further dilute the specifically geological training within a large diversity of sciences and techniques. Resource geology is now an umbrella subject under which one may find exploration geologists, geochemists, geophysicists, metallogeny specialists, geostatisticians, and quantitative modelers.

The 21st century will see humankind face major challenges that will strongly impact on mineral resources and the education of resource geologists. These challenges include resource quality, energy, international policy, and demography.

FACING NEW CHALLENGES

The increase in world population and individual consumption of resources is proving a challenge to the extractive industry. The first challenge is that, with increasing maturity of a given district (where the larger/richer outcropping orebodies often get found and developed first), geologists are faced with the dilemma of either having to explore for lower-grade/marginal deposits or having to search under progressively deeper cover to find good-quality deposits (Fig. 1) (Schodde 2014, 2017). The exploration of new geological environments, therefore, requires faster connections between research and applications in metallogeny.

The second challenge is one of energy transition. The impact of human-derived greenhouse gas emissions is now perceptible in large parts of the world. National and international strategies have to deal more and more with the effect of a warming climate on our civilization. These have impacts on the demand for more technological metals and on the ways that ore deposits are mined, all of which requires a shift away from fuel-intensive processes. Mining is a part of the life-cycle of geologic materials, a cycle that should also take into account recycling, energy consumption, and greenhouse gas emission budgets. Taking these factors into account will force geologists to get even more involved in the anthroposphere.

The third challenge is the increasing number of regulations relating to mining operations. In a heavily populated world, with a progressive decrease in the number of sparsely populated regions, geologists will need to deal with an increasing number of regulations, often demanded by local populations. Such regulations will come from every direction: professional geology associations, environmental codes for mining, multiple norms on social responsibility, non-governmental organizations, mining associations, geological surveys, United Nations agencies, and even banks and risk capital funds!

The fourth challenge is demographic. There will be an increase in competition for jobs as more and better educated geologists are trained in developing countries. The Indian School of Mines, in Dhaband, has, for example, more than 5,000 students. The China University of Geosciences counts more than 40,000 graduates, including Wen Jiao, the premier of China’s State Council. Because the training of economic geologists needs to be closely connected to that of an active mineral industry, students will shift from developed-world universities toward Asian and African countries where the local demand is booming and mining is undergoing a strong development.

THREE FUNDAMENTALS OF A RESOURCE GEOLOGISTS’ EDUCATION

1. Observation

Fieldwork is a fundamental component of any resource geology program. It integrates geological ideas and concepts and is the best way to educate the ‘eye’ of a future geologist. Field geology provides the images that really bring home an understanding of words such as ‘lustre’, ‘patina’, ‘twinning’, etc. Field training is especially important for resource geology because resource bodies are more and more hidden and difficult to detect in the field. It also develops many skills that are not directly related to geology: teamwork, time management, writing reports, managing safety, confronting ideas, solving problems in situ, making and testing hypotheses. This is good preparation for many types of job. In order to maximize its educational impact, fieldwork should be organized, taught, and evaluated as a global project that encompasses these non-geological aspects also, not only the outdoor work.

Field geology used to be taught with the simple tools of hammer, pen, notebook, lens, good legs, and good eyes. Nowadays, the “enhanced geologist v2.0” knows exactly...
where they are (by using the Global Positioning System), they measure chemical elements in the field (using a portable X-ray fluorescence spectrometer), they study unreachable outcrops (using drones), and they have a perfect memory in the form of a field computer and digital camera. All this brings with it new data and enhances the quality of the work without changing its fundamental nature: a universal exploration, because mining for 3-D an ore from dispersed discontinuous outcrops and integrating all observations into a coherent time-integrated geological model.

After the initial field exploration phase (mapping), the second step in a mining project is drilling. With an increasing number of deep targets, the number of drill holes is increasing all over the world. More efficient destructive drilling methods, using mini-coil drilling equipment which provide chips more so than cores, will require the exploration geologist to develop new diagnostic techniques and to acquire new abilities. Results of the drilling campaign can then be integrated into a 3-D model. In a project-oriented approach to education, fieldwork must be complemented by preparatory work, laboratory work on cores and chips, and the production of 3-D models of geological structures and ore bodies.

2. Imagination

In the extractive industry, geologists are sometimes considered as ‘poets’ with a fertile imagination. However, geological reasoning is actually a heuristic way of thinking, one that integrates, more or less conscientiously, all available data, including all the previous experiences of the geologist. A geologist is trained to build models from very little information.

Geology is an historical science, and this makes imagination a necessary ‘tool’ for a geologist and especially true for the resource geologist. The evolution of the Earth is a story, with a beginning and a succession of events, some of which will never happen again. Exceptional events, neither seen nor experimentally reproduced (or reproducible), are the norm. Disruptive thinking, however, has often come from other disciplines connected to the Earth sciences – see the geologically ground-breaking paper by geophysicist and meteorologist Alfred Wegener (1912) [continental drift] and the physicist Walter Alvarez (Alvarez et al. 1980) [meteorite impact hypothesis for the extinction of the dinosaurs]. Thinking ‘imaginatively’ is especially true for mineral exploration because many deposits were formed during the Archean and Proterozoic Eras, on a planet that was very different from today. Some of the largest metal deposits on Earth – such as the iron in the widespread Proterozoic banded iron formations or the Ni–Cu deposits associated with impact structures – resulted from unique events that shaped our planet. Therefore, the ability to imagine a world different from today’s is now recognized as a major quality for people in the industry.

3. Geologist as Physicist and as Physician

Compared to other sciences, geology requires some uncommon ways of thinking. This make geologists highly efficient in managing long, complex, multi-scale projects such as mining projects. A geologist is familiar with very long timescales and with large up- and down-scaling in time and space. Fractal geometry, one of the few multi-scaling ways of thinking, was adopted early by exploration geologists and ore-deposit geoscientists (Carson 1991; Johnston 1992; Jébrak 1997). As a naturalist, a geologist is also familiar with all sorts of images. New generations of geologists have grown up with imaginative worlds produced by Hollywood, video games, and more than a hundred years of science fiction novels. A geologist is also familiar with complex problems, which he tries not to oversimplify. Estimation and ordering of the importance of the parameters is usually more efficient than simplification. Compared to other scientists, geologists display an outstanding ability to think in three dimensions: they understand the distribution of ions in a crystal, the way pores are connected in sandstone or the interactions between faults and folds, all requiring the ability to generate 3-D mental images and to use the power of the mind to move inside them. A geologist can do this for large 3-D objects, like a mountain belt; and they can mentally reconstruct a 3-D model from several 2-D partial sections, such as geological maps, seismic profiles, or rock thin sections. This is a great advantage for working in a mine, or for reconstructing an ore body from a series of drilled cores.

Because of the increasing challenge of finding new deposits, one of the most important abilities for an exploration geologist is to detect and interpret small signals, at first not usually connected to the presence of a real ore deposit. This is at the very core of a geologist’s ability. Very often, geologists are called upon to solve problems and study geological objects when there are sparse or diverse clues, such as outcrops, chemical analysis, mineral compositions, satellite/drone images, quantitative aerial information, and geophysical data. From that starting point, he or she must reconstruct the studied object, provide a 3-D spatial organization of its components, and give its history. The way a geologist solves problems is actually similar to that of a medical doctor when establishing an early diagnosis.
makes conceivable the creation of virtual spaces (e.g. http://virtualoutcrop.com) which would allow students and teachers to study the best geological occurrences in the world within a classroom.

Data Mining

The mining industry, like many others, cannot avoid the general tendency of accumulating huge amounts of information: this is known as the ‘Big Data’ effect. For mineral exploration, the key to future discoveries are going to come from analysing large quantities of detailed geophysical, geochemical, and geological data. But how does one store all the raw data? How can one use the exploration data to make mining production more efficient? Exploring the possibilities of this new world will be the task of future professionals in the mining industry and in the oil and gas industry (Che et al. 2013).

Today’s students must be prepared for this revolution. They will require a solid basis in statistics and be able to ‘data mine’ mining data. Students will have to be educated in data acquisition, transformation, and interpretation techniques. They will also need to hone their critical senses and ask (and answer) questions such as the following: How should the quality of long-term measurements be ensured? Where should the sensors be placed? How to detect measurement artefact or drift? Is this a direct or indirect measurement?

A New Approach to Education

Educating young executives for the mining industry of the future is a true challenge. Geology will remain at the core of the training because mining is fundamentally about finding, digging, and extracting a mineral resource from a rock. However, a mine is not only a geological object: it also belongs to the engineering, economic, environmental, legal, and even the social world (Fig. 4). Any mine-related decision will likely have to deal with all these different aspects. These increasing challenges will require an evolution of our principles and techniques of training future geologists. Two major developments are in progress in
higher education: teaching procedures that are fully guided by learning outcomes and the total availability of information (Manduca 2007; Mogk 2007).

Learning Outcomes
Defining education schemes from learning outcomes requires a total re-thinking of teaching procedures. The teacher must help students construct their own knowledge bases, something that represents a dynamic shift from teaching to learning (Mogk 2007). Instead of simply describing the course that the teacher can offer, it identifies student needs, and precisely describes what students should be able to do at the end of the teaching process. The learning outcome should be describable by an active sentence, e.g. “A student is able to identify common opaque minerals using a reflected light microscope”, or “The student can write a report describing a complex outcrop in a synthetic and efficient way following the rules of scientific texts”. But this is not enough. The system of evaluating student performance should also be re-examined. For example, should there be two levels of evaluation (e.g. acquired or failed) or should there be more (e.g. above average – average – poor – fail)? Should some compromise be accepted: can a student’s weakness in mineralogy be compensated for by his/her excellence at solving differential equations? If not, where is the baseline for both? Courses also should be re-organized into coaches, advisors that will guide the student through his/her own learning process.

The principle of defining higher education programs from learning outcomes was adopted by the European Union in 2005 as part of their quality process in higher education (Standards and Guidelines for Quality Assurance in the European Higher Education Area 2015). However, the implementation of this program has been rather weak because such a major change from the traditional teaching methods seems to be uncomfortable for students but are even more so for teachers (Mauvette et al. 2003). A good learning-outcomes-defined program combines formal courses and scenarios given by practical activities, in a way very similar to what is called “problem-based learning” in educational scientific literature (Fretter and Lewis 2003; Mandora 2007). This method is particularly suitable for professional training. Learning outcomes can be connected to “skills” or “competencies” which describe professional skills and standards in the industry as established by professional associations (Liard 2016; Ordre des Géologues du Québec 2016).

The academic community is a conservative world. Changes in educational methods tend to take place rather slowly, and usually by new generations. However, professional training, which is directly connected to the industry, should be more open-minded. The mining industry could propose data sets to be worked on by students as a means of evaluating their ability for exploration targeting, and such a program could be based on the model of the Imperial Barrel Award Program of the American Association of Petroleum Geologists. Role-playing games could be used as practice in dealing with likely social or political issues that a mining operation might face.

Changing the Role of the Professor
The second major change is that knowledge is now widely and instantaneously available. During a class, a student can check what the teacher says. He or she may follow various online courses on whatever subject, sometimes in what may appear to be a more prestigious course than is being given by the teacher. The most visible part of this change is the development of multiple open online courses (MOOCs), and a student can now find an amazing number of courses on the web on any subject. Not everything is relevant, and some web sites may contain (big) mistakes. The new role of teachers is to create documents for MOOCs and to survey what exists on the internet, to advise students, and to teach them how to choose a good online course or media. The final stage of this evolution is that teachers may transform into coaches, advisors that will guide the student through his/her own learning process.

From the combination of the above two evolutions, a student’s final grade will be the results of the accumulation of certified skills, acquired by whatever means, in a much more individualized process than now. The role of the teacher will be to establish the list of skills, using industry itself for professional training, to make the certification procedure and to coach (or “mentor” as Mogk 2007 terms it) students in their learning process.

New Contents for a Mineral Resources Course
The basis for educating resource geologists has not changed for years. The core of any program is the definition of an ore deposit. Arndt et al. (2017) define an ore deposit as, “a mass of rock that contains a useful element, compound or mineral with a grade and total amount sufficiently high that the material can be mined economically”. Such a definition implies several things: an in-depth knowledge of Earth sciences in order to define the ore concentration; a knowledge of mining techniques to conceive the way to extract the deposit; and a knowledge of economics to demonstrate its profitability. However, the role of the resource geologist has changed with time. The legal aspects have always been present. Since the end of the 20th century, even the definition of an ore deposit has changed. It now becomes an economic mineable and socially acceptable mineral concentration. This opens the field of mineral resources to questions that could be posed by the human and social sciences: Is

![Schematic view of the skills necessary in a modern mining project. The project manager (central figure on diagram) must be an expert in at least one of the four main (inner) central fields, and be able to discuss matters with experts of the other (outer) 12 fields.](image-url)
the region and its population ready for mineral exploration and extraction? What are the environmental and social risks of mining developments? Moreover, the extractive industry is becoming more and more conceived as being a part of the metal cycle. These are complex challenges that open wide the topics that should be taught to future resource geologists (Fig. 4). Educating geologists for the mining industry should be much more than just training for ore geology. It should include all the aspects of the mining project, which should be considered as a single complex object viewable from various, yet somehow contradictory, points of view. Example of such programs can be found at Canada's Université du Québec on Abitibi-Témiscamingue (UQAT), or France’s Mines Paris Tech.

The examination of curricula of schools of mines or their equivalents shows that mining geology + mining engineering + mining economics is recognized as a coherent corpus of learning outcomes. This already very large educational domain will have to enlarge again to include the social aspects of mining. Every mine is now the concern of a large group of different people working as a team and involves more and more stakeholders. Education, therefore, also needs to become more comprehensive by viewing mining as a global technical and human project. The more the members of the team are able to understand each other, the more efficient will be the project. This must be translated back into foundational education schemes. Thus, a skill for a resource geologist might be, “to be able to discuss with an economist on the subject of the profitability of the mine”, and the reverse for the economist. But it is difficult to set up such a program. Nevertheless, data, models, and images could be shared in a very efficient way and constitute a basis for mutual understanding. A resource team will be organized and led by a coordinator. And who might such a coordinator be? A geologist would be a good candidate. After all, a mine is itself a geological object and geologists not only have a large scientific culture but they are familiar with complexity.

**WHAT OF THE FUTURE?**

It has been some 30 years since the opening of the first school of mines in Joachimstahl (now in modern Germany), and the education of resource geologists continues to be marked both by continuity and by disruptive changes.

Continuity is provided by the permanence of the core competency of the resource geologist: high quality of observations at any scale, and a capacity for controlled (scientifically constrained) imagination. A geologist will fundamentally remain a scenery novelist, an expert in great story telling. Universities and schools will produce basic geologists who have mastered core disciplines and develop them further with refined upper-level courses in disciplines such as petroleum geology or economic geology. The challenge will be moving toward technical, environmental and social concerns. Indirect methods will become more important, as exemplified by the rise in geochemistry and geophysics courses over the past 50 years, subjects that are presently involved in 30% of resource discoveries at the project scale (Schodde 2014). Conceptual thinking will drive these quantitative approaches. Our challenges will be to build bridges and enhance dialogue between different disciplines and to balance necessary core specialties against the need to be familiar, at least in part, with a wide variety of subjects, from mineralogy to social issues. This requires better connections between universities and engineering and business schools.

Disruptive changes will come from innovations in mining, including new mineral discoveries, new environments, new technologies, and new fields of interest. The next generations of students will develop new capacities of learning through social media, simulation, and data mining. New jobs will arise, ranging from the ‘nano-mineralogist’ to the geologist who is specially trained in social and economic aspects. We will, therefore, need visionary professors, intrepid administrators and a supportive mineral industry.

**ACKNOWLEDGMENTS**

This paper is based on two invited conferences given in June 2015 at the Collège de France in Paris. We warmly thank Georges Calas for these invitations. We also thank R.C. Schodde, J.J. Royer and C. Stewart for providing the pictures used in this article, and B. Wood, J. Rosso and P. Roycroft for careful editing.

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The 17th DMG short course on solid-state nuclear magnetic resonance (NMR) spectroscopy was held 17–20 May 2017 at the Institute of Geology, Mineralogy and Geophysics of the Ruhr University Bochum (Germany). Spectroscopic NMR investigations can be a valuable tool in mineralogy and material sciences. This was perfectly demonstrated by Dr. Michael Fechtelkord to 12 students who came from different parts of Germany. The students were introduced to the secrets of ¹H spin-lattice relaxation, magnetic dipolar interactions, the magic-angle spinning (MAS) method, 2-D multi-pulse techniques, cross-polarization MAS (CPMAS), double rotation (DOR), multiple quantum MAS (MQMAS), and satellite transition spectroscopy (SATRAS).

DMG SECTION MEETING: GEOCHEMISTRY AND PETROLOGY/PETROPHYSICS

This year’s joint meeting of the DMG sections Petrology/Petrophysics and Geochemistry was held 23–24 June 2017 at the Institute for Geological Sciences at Freie Universität Berlin (Germany). In attendance were 75 junior and senior participants, representing 16 different institutions. The local organizers, Ralf Milke and Timm John (Chairman of the Petrology/Petrophysics section), as well as Ronny Schönberg (Chairman of the Geochemistry section), provided a warm welcome and opened the first scientific session. Nine talks and more than 20 posters were on offer by post-docs and graduate and undergraduate students. The traditional evening barbecue was held in a relaxed atmosphere, which allowed for meeting old and new friends and for lively scientific discussions.

The second day of the program had 14 talks, including Ralf Milke’s highly impressive presentation, “How Blind People Can Discriminate Between Minerals”. Ralf Milke regularly offers guided tours for visually impaired people, showing them the Freie Universität’s mineral collection. After a second poster session, the meeting concluded with the award for best talk going to Tobias Grützner (University of Münster, Germany) for his presentation, “Fluorine in the Earth’s Mantle Transition Zone – Experimental Results”. The best poster was awarded to Paul Fugmann (University of Jena, Germany) for his presentation, “Petrography, Geochemistry and Age of the Lomati River Complex, Central Barberton Greenstone Belt, South Africa”.

Some participants decided to continue their stay and participate in the Lange Nacht der Wissenschaften [Long Night of the Sciences], where 70 scientific institutions in Berlin open their doors to the public.

The diverse range of topics presented at the 2017 meeting of the DMG’s Petrology/Petrophysics and Geochemistry sections allowed participants to look ‘outside the box’ and ‘inside’ to other interesting petrology and geochemistry topics. Thanks go to the organizers for a great meeting! Watch dmg-home.org for next year’s Sektionstreffen in Göttingen 2018.

Jennifer Günther, Anastasia Zemlitskaya (Mainz)

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We are looking forward to seeing you in Bonn in late summer 2018!

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THE PRESIDENT’S CORNER

In this issue, I would like to mention one of the most significant and important functions of the Clay Minerals Society (CMS): the CMS Source Clays Repository, which is currently located at Purdue University (Indiana, USA) (http://www.clays.org/sourceclays_history.html). In their preface to the Clays and Clay Minerals 2001 special issue entitled “Baseline Studies of The Clay Minerals Society Source Clays”, Costanzo and Guggenheim (2001) state, “The Source Clays Program of The Clay Minerals Society was initiated in 1972 to distribute a set of reference clays, so that distributed clays could be identical for all recipients. Because most clays do not consist of a single phase, the immediate objective was not to produce a pure product consisting of one clay mineral, but to provide a uniform product. These materials were collected and processed carefully, and sufficient amounts were collected so that material was available for researchers for many years.”

A quick Google Scholar search of ‘Source Clays’ revealed the various analytical reports of the Baseline Studies, including diffraction, spectroscopic, thermal, elemental and surface area data, which were cited 1,937 times in other papers. The real number is probably much larger. Indeed, the Source Clays SWy, SAz, STx, KGa-1 and KGa-2 are household names to many researchers. A quick Web of Science search showed 128 citations for KGa, 257 for SWy, and 120 for SAz Source Clays (http://www.clays.org/sourceclays_source_and_special.html).

The repository is important to the CMS and the clay science research community. The Society’s Source Clays Repository offers two types of materials: the source clays themselves, and what are referred to as ‘special clays’. As stated on the CMS website, the special clays are rare but of great theoretical interest. In 2016, a total of 1,035 units of clay were sold. Of these, 455 units were of source clays, and 573 units of special clays. In 2016, the repository started selling Reynolds Cup units of were sold in 2016 (http://www.clays.org/Reynolds.html). Unfortunately, an infinite supply of all the source clays was not obtained. Thus, currently, some source clays have been exhausted and others are in very short supply. The society has a standing committee for its source clays which is actively working on replenishing the clays. Thus, the Clay Minerals Society continues to serve the larger clay-sceence community in providing reference and education materials, and reference clay minerals for a wide range of applications.

Douglas K. McCarty (mccardog@gmail.com),
President, The Clay Minerals Society

REFERENCE

CMS MEMBERSHIP RENEWAL

Don’t forget to renew your membership for 2018!

IN MEMORIAM

Robert J. Pruett (1963 to 2017)

The Clay Minerals Society (CMS) sadly lost one of its highly esteemed members, Dr. Robert “Bob” James Pruett. He passed away 25 July 2017 in Millersville (Georgia, USA). Bob received his BS degree at the University of Wisconsin (USA), and his MS and PhD degrees at Indiana University (USA), where he studied under the pioneering clay scientist Professor Haydn H. Murray.

Bob was a member of five professional societies, but CMS was special to him as evidenced by his contributions. He served on many of its committees and on the CMS Council. At the time of his death, he was President-elect. He was also very active in the Society for Mining, Metallurgy, and Exploration (SME).

Bob had worked for IMERYS Oilfield Solutions as Technical Director since March 2013. Prior to that, he had worked for IMERYS’ Pigments for Paper and Packaging Group. He served as the Minerals Technology Director for their pilot plant, analytical lab, microbiology lab, and process development department (Sandersville, Georgia). Bob joined the Georgia Kaolin Company (GK) research department in 1990 and relocated from New Jersey to Georgia in 1991 when ECC International (ECCI) acquired GK. Bob became leader of the Minerals Technology Department in 1996 and continued in that role after IMERYS purchased ECCI in 1999.

Bob was an internationally recognized and innovative expert in many industrial mineral processes: he conceived the development of hyperplaty clay products and their scaling up through commercial production. Bob played a key role in developing his company’s hydrous product portfolio, which relied on the ability to measure shape factors for kaolin products and process streams, a field where Bob was also an internationally recognized expert. All of his professional and scientific achievements could not overshadow his humble, kind, and generous character, to which all who knew and worked with him have testified.

Clay science has lost a great scientist, society member, friend, and colleague, who will be fondly remembered for many years.

Douglas K. McCarty, President 2017–2018
The Clay Minerals Society

The 55th Annual Meeting of the Clay Minerals Society will be held 11–14 June 2018 at the University of Illinois, Urbana-Champaign (USA). The theme of the meeting is New Visions in Clay Science. The meeting will include thematic sessions on a variety of relevant topics and a workshop on medicinal applications of clay minerals. Visit www.conferences.illinois.edu/cms for more details.

Dr. Yuji Arai, Organizing Committee Chair
SFMC GENERAL ASSEMBLY REPORT

The SFMC’s annual general assembly was held 16 June 2017 at the National Museum of Natural History in Paris (France). At the assembly, Marc Blanchard, SFMC Secretary, summarised the activity of the society during the year 2016. The SFMC supported several scientific meetings, among them the 2nd European Mineralogical Conference, the 4th Serpentine Days meeting, the meeting of the French Association of Crystallography, the 38th Meeting of the International Cement Microscopy Association, and the 5th School of Crystallography (Synchrotron SOLEIL). At the SFMC 2017 general assembly, Marc also spoke of the two winners of the 2016 Haüy–Lacroix Award, and the society’s contributions to the European Journal of Mineralogy and Elements. Christian Chopin, SFMC Treasurer, presented the 2016 budget, which was approved. Following this, the assembly discussed the possible creation of a prestigious SFMC prize for researchers in the field of mineralogy and crystallography.

Before closing the SFMC’s general assembly, Bertrand Devouard, SFMC President, announced that the 2017 Haüy–Lacroix Award will go to Alexandra Goryaeva (MATEIS, INSA-Lyon, France) for her PhD modeling work of the post-perovskite phase deformation, and to William Rapin (Paul Sabatier University, Toulouse, France) who studied the hydration of Mars surface by analyzing data collected by the Curiosity rover.

Members of the SFMC had a most pleasant end to the 2017 assembly by visiting the new setting of the mineral collection of the Sorbonne University, accompanied by the curator, Jean-Claude Boulliard.

FAME-UHD: A NEW BEAMLINE AT ESRF

A New National and International Research Instrument for Investigating the Chemical State and Structure of Highly Diluted Elements

How do cerium oxide nanoparticles link to cells? What is the partitioning of germanium as a function of ore-deposit conditions of formation? In which chemical state are the rare-earth elements in meteorites? These are some of the questions that can be addressed with a new collaborating research beamline: FAME-UHD (French Absorption spectroscopy beamline in Material and Environmental sciences at Ultra-High Dilution), which is based at the European Synchrotron Radiation Facility (ESRF) in Grenoble (France).

The FAME-UHD facility has been open to researchers (French and international) since January 2017 and is designed to provide new characterisation possibilities. It is now possible, for example, to determine the chemical state and the structure of diluted elements using X-ray absorption spectroscopy both on FAME and FAME-UHD, the latter being dedicated to analysis with high-energy resolution. These two instruments are complementary, both in terms of accessible concentration range as well as in terms of available in situ sample environments. Both give the possibility to probe elements at concentrations lower than a few ppm (parts per million) in natural or synthetic samples. The considerable gain in performance has been obtained thanks to the installation of state-of-the-art optical elements, as well as a crystal analyser spectrometer which is a very selective X-ray fluorescence detector.

Scientists coming to FAME or FAME-UHD not only want to demonstrate the presence of particular chemical elements but also want to determine their speciation, i.e. their oxidation/reduction state and how the elements bind to neighbouring molecules. Lowering detection limits down to the ppm level at FAME-UHD enables the characterisation of trace elements in natural samples (e.g. in soils, in hydrothermal fluids, or in the investigation of pollutant effects on bio-environments). The FAME-UHD beamline also opens up research on fields such as ecotoxicology, in which the ability to access very low chemical concentrations (and determine chemical speciation) means that proof-of-principle studies can be tested against reality.

Staff affiliations: Institut Néel (UPR 2940 CNRS, Grenoble) and OSUG (UMS 832 CNRS / UGA, Grenoble).

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Website: http://www.esrf.fr/home/UsersAndScience/Experiments/CRG/bm16.html
IAGC AWARDS

We are pleased to announce the International Association of GeoChemistry’s awards for 2017. Congratulations to all the recipients, and thank you for your service to the IAGC and the geochemical community! We are now accepting award nominations for 2018 through 31 December 2017. Eligible awards for 2018 include the Vernadsky Medal, the Harmon Distinguished Service Award, the Kharaka Award, IAGC Fellow, and the Certificate of Recognition. To nominate a deserving colleague, go to www.iagc-society.org/awards.html.

Harmon Distinguished Service Award

Richard B. Wanty of the US Geological Survey in Denver (Colorado). Rich served as IAGC Vice President for 2011 and 2012, was President in 2013 and 2014, and has just finished his term as Past President. Under his leadership, the IAGC revitalized the Urban Geochemistry Working Group and added the Environmental Geochemistry Working Group and BIOGEMON group to the list of IAGC-supported meetings. In addition, Rich fostered more interaction between the IAGC and other organizations, such as the Geochemical Society. Rich continues to be an international leader in the Applied Isotope Geochemistry (AIG) Working Group where he has been a major scientific contributor. This year, he is leading the Applied Isotope Geochemistry 12 (AIG-12) meeting in Copper Mountain (Colorado, USA). Rich always brings great energy and a positive attitude to all he does; he was a thoughtful and collegial leader, setting an example for all who follow. Rich is truly deserving of the Harmon Distinguished Service Award for 2017.

IAGC Fellows

John J. Gurney, Emeritus Professor of Geochemistry in the Department of Geological Sciences at the University of Cape Town (UCT) (South Africa), has made significant contributions to the field of geochemistry over the course of a 50+ year professional career. In 1968, Prof. Gurney received his PhD from UCT, which was funded by a post-doctoral fellowship at the Smithsonian Institution (Washington DC, USA) from 1970 to 1971. As an academic staff member at UCT from 1972 to 2004, John investigated the upper mantle beneath the South African craton and addressed the origin of kimberlites by establishing and leading the Kimberlite Research Group. John has authored 273 peer-reviewed research publications, a body of work that has defined our current understanding of kimberlites and established the way in which diamond exploration is presently conducted. John was granted a Personal Chair in Geochemistry in 1984 and is a Lifetime Fellow of the Royal Society of South Africa. Other awards John has received are as follows: the IAGC Certificate of Recognition for a career of upper mantle and diamond research and its practical application in 2007; Distinguished Lecturer of the Society of Economic Geologists in 2008; Society of Economic Geologists Silver Medal for contributions to mineral exploration in 2005; Professional Management Review Golden Arrow Award for the “Most-Admired Individual in Geology Education in South Africa” in 1999; Draper Memorial Medal (the highest award of the Geological Society of South Africa) in 1995; International Lecturer Award of the Society of Economic Geologists in 1992; Alex L. du Toit Memorial Lecturer Award of the Geological Society of South Africa in 1989.

A chemist by training, John’s first research appointment was in 1963 as an analyst in Prof. Louis H. Arhens research team in the newly formed Geochemistry Department at UCT. Trace-element studies on mantle xenoliths led to a PhD and a post-doctoral fellowship at the Smithsonian Museum (Washington DC, USA). Returning to UCT in 1972, he was appointed head of the newly created Kimberlite Research Group (KRG), a position he held until his retirement in 2004. During this period, the KRG was a leader of mantle research and published in scientific journals. The UCT also hosted two very successful kimberlite conferences with John’s input, visiting scientists being attracted to participate in joint research projects. Since his official retirement, while continuing his mantle research, John has established Mineral Services Ltd, a company that consults for the diamond exploration industry.

Kharaka Award

Parthasrathi Chakraborty is from India and received his PhD from Carleton University (Canada) in 2007. Partha has an impressive scientific resumé. He has worked on trace metals, including mercury, and has developed expertise in the geochemistry of both the water column and sediments. He has 46 publications and these have been highly cited: his h-index is 16, according to Google Scholar, and he has received a total of 538 citations. His most-cited papers address important and interesting aspects of the environmental chemistry of metals. The most highly cited paper is his 2012 work on lead and cadmium speciation in sediments. Other papers dealing with metal binding and speciation are also highly cited, including his paper on cadmium–humic interactions. Other highly cited papers deal with metals in effluents and in sediments. Partha is currently published at a high rate, averaging six papers per year!

Partha is well-recognized for his knowledge, being a member of two Scientific Committee on Oceanic Research (SCOR) working groups, and having received the Krishnan Award from the Geological Society of India, as well as other awards. He supervises graduate students and his students have gone on to have successful careers. The IAGC is happy to bestow the Kharaka Award to Parthasarathi Chakraborty in recognition of his accomplishments, and we wish him well in all his future endeavors in geochemistry.

Ryu-Ping (Yo) Chin has been a faculty member at the Ohio State University (USA) since 1991. He is an environmental and organic geochemist. He has made important and seminal contributions to the investigation of both naturally occurring and xenobiotic organic matter, its characterization, and its behavior in aquatic systems. He has coauthored 95 refereed publications on the topics of naturally occurring dissolved organic matter, of trace-metal–organic matter interactions, and of the effects of photo-oxidation and redox changes on anthropogenically introduced pesticides, herbicides, fire-retardants, and related compounds. Besides the quantity of his work, the quality of his work is also very high. He currently has a h-index of 36 (ISI Web of Science), with citations approaching 6,000. He has published in some of the best environmental geochemistry journals in the world, with 30 publications alone in the American Chemical Society (ACS) journal Environmental Science and Technology. He currently serves on ES&T’s Science Advisory Board. He has been honored by ACS with an Excellence in Reviewing Award, with a Certificate of Appreciation for Service, and has won numerous Certificate of Merit for Oral Presentation awards. He recently stepped down as a member in the U.S. National Research Council’s Water Science and Technology Board, and he has been a member of the Committee on Future Options of the Nations Subsurface Remediation Effect.

Yo Chin has been a contributing member of IAGC’s Urban Geochemistry Working Group, contributed one of the four papers to the special issue of Elements: Science of the Anthropocene that was devoted to this topic, was a coauthor on the working group’s recent review paper in Applied Geochemistry (Chambers et al. 2016), and has contributed another paper to a special issue of Applied Geochemistry on urban geochemistry. In addition to his scholarly and service contributions, he has also been an outstanding classroom teacher and student mentor. Eleven of his graduate students over the past 13 years have won prestigious fellowships; many of them are now faculty members themselves or are prominent researchers in government laboratories. In his over 20 years at Ohio State, Dr. Chin has developed a distinguished record of research, scholarship, service and teaching, one that is worthy of consideration for Fellowship of the IAGC. He is an international leader in the field of aquatic organic geochemistry.

Yu-Ping (Yo) Chin has been a faculty member at the Ohio State University (USA) since 1991. He is an environmental and organic geochemist. He has made important and seminal contributions to the investigation of both naturally occurring and xenobiotic organic matter, its characterization, and its behavior in aquatic systems. He has coauthored 95 refereed publications on the topics of naturally occurring dissolved organic matter, of trace-metal–organic matter interactions, and of the effects of photo-oxidation and redox changes on anthropogenically introduced pesticides, herbicides, fire-retardants, and related compounds. Besides the quantity of his work, the quality of his work is also very high. He currently has a h-index of 36 (ISI Web of Science), with citations approaching 6,000. He has published in some of the best environmental geochemistry journals in the world, with 30 publications alone in the American Chemical Society (ACS) journal Environmental Science and Technology. He currently serves on ES&T’s Science Advisory Board. He has been honored by ACS with an Excellence in Reviewing Award, with a Certificate of Appreciation for Service, and has won numerous Certificate of Merit for Oral Presentation awards. He recently stepped down as a member in the U.S. National Research Council’s Water Science and Technology Board, and he has been a member of the Committee on Future Options of the Nations Subsurface Remediation Effect.

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FROM THE PRESIDENT

My first From the President in Elements (Feb. 2016) highlighted my path into service for the Association of Applied Geochemists (AAG) and the collaborative benefits that I had gained from being a student member. The AAG has a smaller, collegiate-feel for applied geochemistry, and we are keener than ever to build our student member numbers. Student membership is only $10 and includes our journal, Geochemistry: Exploration, Environment, Analysis (GEEA), our newsletter Explore and a number of student-focused awards and programs, including one for analytical support. At $10 it is exceptional value.

As part of my commitment to increasing our younger membership, the AAG offers valuable student funding and support services. These include the following:

1. Analytical support (in-kind)
2. Conference travel funding
3. Conference presentation and publication awards
4. Abstract fee funding

The analytical support program enables some research samples to be analysed at our participating laboratory partners (Actlabs, ALS, Bureau Veritas Minerals Acme, Bureau Veritas Minerals Ultratrace, Intertek Genalysis, LabWest). These analyses are done at either no cost or a significantly reduced cost to the student. The AAG facilitates deserving students getting the needed analyses done, and our committee also assists in getting this research published in our journal GEEA or the Explore newsletter at a later time.

Conference travel funding is offered to support student attendance primarily at our International Applied Geochemistry Symposia (IAGS). The next IAGS is in Vancouver (Canada) in June 2018 as part of the Resources for Future Generations conference (RFG2018 http://rfg2018.org/): we hope to support a number of students for their conference fees and, potentially, some travel/accommodation costs (to a set value). The AAG will also offer improved student paper and poster prizes at the upcoming IAGS in Vancouver, thanks in part to our sponsors, SGS Minerals.

Finally, the AAG expects to reimburse students for all abstract fees incurred by submitting to RFG2018 if the student is presenting in an IAGS-affiliated session. All details are available on our website or will be updated shortly as the RFG2018 program develops. See https://www.appliedgeochemists.org/

It is worth your time as a student to join the AAG and get involved. I hope to meet many more students presenting their research at our upcoming meetings and developing the necessary collaborations for a strong future career in applied geochemistry.

Ryan Noble
AAG President

UPDATE ON INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIA (IAGS) 2018

The AAG has partnered with the Resources for Future Generations 2018 (RFG2018) conference, which is to be held 16–21 June 2018 in Vancouver (British Columbia, Canada), to hold the IAGS2018 symposium as an integral component of the RFG18 conference. The 4-day conference will cover a wide variety of topics on energy, minerals, water and the Earth and is expected to attract in excess of 5,000 attendees to Vancouver. This will provide the AAG with the opportunity to showcase, through specific AAG sessions, the advancements and applications of geochemistry in the spheres of exploration and environment.

Eleven AAG-specific applied geochemistry sessions will be chaired by AAG members. Details of the sessions are provided below. The call for abstracts opened on 1 August 2017 and will close on 15 January 2018. Submissions of abstracts to the AAG sessions, as well as registration, short course and field trip selection, will be handled through the RFG2018 website at http://rfg2018.org. The abstract submission process will allow the selection of the specific sessions for submissions. Members of the AAG are encouraged to submit abstracts to the appropriate AAG sessions. Registration at the conference will also allow AAG members full access to the complete RFG2018 technical sessions.

A series of short courses and field trips are also being organized by the AAG for inclusion in RFG2018.

For further information, visit RFG2018.org or contact Dr. Peter Winterburn at pwinterburn@eoas.ubc.ca

AAG Sessions at RFG2018

MIN24 “Stable and Radiogenic Isotope Systems: Applications in Exploration and the Environment.” Modern analytical technology has substantially reduced the cost of isotopic analysis to the level of routine analysis. In addition, new systems have become commercially viable and the knowledge base and understanding of a range of isotope systems is now well documented. This session will demystify the application of isotopes in exploration and the environment through case studies that will demonstrate the value and the added benefits of integrating isotope studies with other information in exploration decision-making processes.

MIN25 “Exploration Case Studies – Out of the Box Concepts, Methodologies and Practices.” Case studies of mineral exploration, both positive and negative, will be highlighted, with an emphasis on the application of geochemistry. Particular emphasis will be given to case studies that employed out-of-the-box concepts, models or methodologies that demonstrated new advances in mineral exploration, discovery, risk abatement and cost reduction.

MIN26 “Big-Data: Integration, Management and Regional-Scale Surveys.” Exploration companies, geological surveys and mining companies typically own gigabytes to terabytes of geochemical information with associated attributes, much of which is poorly examined beyond simple numerical treatments for limited components.

MIN27 “Footprints of Giant Orebodies.” Over the last five years, across the globe, there have been several major research initiatives by organizations [e.g. Canada Mining Innovation Council (CMIC) and AMIRA...
International Ltd.] directed at developing fully integrated geological, mineralogical, chemical and geophysical footprints of large orebodies beyond visible alteration to so-called cryptic effects. This session is intended to draw together key papers highlighting integrated models and their application to exploration.

**M1N28** “Micro- to Macro-Biogeochemistry: Exploration, Processing, Remediation and the Environment.” Biological systems play an increasingly significant role in mineral exploration, mineral processing and site remediation and such systems can exploit the natural interactions and processes between geological materials and biological processes. This session will review recent progress and new innovations in the use of natural processes in resource development.

**M1N29** “Exploration Undercover – Techniques, Technology and Strategy.” Demands for mineral resources continue to affect society: there are high metal prices, skill shortages, governmental policy changes, and billions of dollars in resource investment. The discovery of new mineral resources requires increasing risk, increasing costs, and increasingly effective exploration techniques. Exploration activity itself is increasingly focused in difficult localities, such as those that lack outcrop, are covered by transported surficial materials or are deeper in the crust. As a result, the demand to develop new and improved geochemical exploration techniques and strategies is higher than ever. This session will include papers that review state-of-the-art progress, new concepts, technologies, case histories and exploration strategic paths aimed at discovery.

**M1N30** “Mineral Exploration in Extreme Environments.” Exploration geochemistry in hyper-arid, tundra, tropical, high altitude, sub-oceanic and extra-planetary environments requires special techniques and technologies. This session will be devoted to research, development and case histories of mineral exploration in these diverse, significantly more important, yet very problematic environments. The emphasis will be on applied geochemistry.

**M1N48** “Hydrocarbons in the Exploration for Metalliferous and Non-Metalliferous Deposits.” Hydrocarbons have shown considerable potential as an exploration tool for the discovery of mineral deposits. However, the technique is not without controversy. Through case studies and recent technological advances, this session will present recent results on the application of hydrocarbons in mineral exploration.

**M1N55** “Analytical Technology in the Search for Minerals: Space to the Lab to the Field.” A session devoted to recent, experimental and proposed developments in technologies that could be applicable to the discovery of new mineral deposits and environmental studies. The emphasis will be on chemical, mineralogical, isotopic and spectral analytical techniques, including remote sensing, laboratory analysis and field analysis.

**M1N57** “Geometallurgy: Exploration–Evaluation–Exploitation–Environment.” This session will examine the role of geometallurgy and geochemistry through the complete birth–cradle–grave cycle of an orebody, documenting how geometallurgy can effectively reduce risk and cost at an early stage of exploration through evaluation and mining, and through to the impact of geometallurgy on waste disposal and mine closure. The session will comprise a keynote plus selected case studies of the application of geometallurgy, in particular novel or unconventional applications to natural resources.

**WA14** “Hydrogeochemistry: Environment and Exploration.” A session devoted to the application of water geochemistry as both a tool to search for water resources and mineral resources, in addition to exploring the geochemistry of contaminated waters and their mitigation and remediation. The session will cover research and development of new techniques and technologies in addition to case histories of hydrogeochemistry in exploration and remediation.

**WA17** “ARD in Mining and Civil Construction.” Acid rock drainage (ARD) and metal leaching (ML) are potential hazards that should be assessed at an early stage when planning major excavations for resource development or civil construction. Potential acid-generating materials can be predicted based on static and kinetic testing. This information forms an essential component of ecological risk assessments that also incorporate information on pathways and receptors that could be affected by ARD/ML. Such risk assessments should be incorporated at an early stage into the engineering design of excavated material placement areas in order to minimize environmental impacts.

**AAG Short Courses and Field Trips at RFG2018**

The AAG has proposed 8 short courses operated by renowned AAG members covering both theoretical and practical aspects of exploration and environmental geochemistry. These comprise:

- Analytical Quality Control: Data Integrity for the Advancement of Science (L. Bloom)
- Exploration Geochemistry: From fundamentals to the field (P. Winterburn)
- Regolith in deeply weathered terrains (R. Anand)
- Integration of Exploration Geochemical and Mineralogical Data (D. Arne)
- Advanced Concepts in Evaluating and Interpreting Geochemical Data (E. Grunsky)
- Mineral Chemistry – Application to Mineral Exploration (C. Ihlenfeld)
- Lithogeochemistry: Theory and application from project generation to operation (I. Dalrymple)
- Exploration Geochemistry: Field analysis and characterisation (B. Lemiere)

Excursions organized through the AAG include:

- Yerington Porphyry Lithogeochemistry field trip in Nevada (USA) with D. Tosdal and J Dilles
- Lithogeochemistry and Alteration at the Highland Valley Porphyry Complex in British Columbia (Canada) with K. Bryne
- Visits to the ultra-modern analytical facilities at ALS Vancouver - Geochemistry and Bureau Veritas in Vancouver (British Columbia, Canada)
2018 ANNUAL METSOC MEETING: YOUR INVITATION TO MOSCOW

You are cordially invited to attend the 81st Annual Meeting of the Meteoritical Society, which will take place 22–27 July 2018 in Moscow (Russia). The meeting is jointly organized by the V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry of Russian Academy of Sciences, the Vernadsky Geological State Museum, the Ural Federal University and the Kazan Federal University (all in Russia). Most foreign citizens require a visa to enter the Russian Federation. We strongly recommend applying for a tourist visa. An AIM TOURISM visa includes: exhibition visit and participation in conferences and other events. Travel arrangements, including visa support, accommodation, transportation, and guided tours will be provided by the "Reisebüro WELT" Company. Please follow the link for TRAVEL ARRANGEMENT on our website (http://metsoc81-moscow.ru).

Oral sessions will take place in the conference halls of the Academy of Science Presidium building (“Golden Brain”); plenary sessions, invited lectures, the Barringer lecture, and the award ceremony will take place in the largest hall, which seats 1,000 participants. The Golden Brain building will also house the poster sessions.

Conference registration begins at 4:00 p.m. on Sunday, 22 July 2018 at the Vernadsky State Geological Museum in the historical center of Moscow, right across from Red Square and the Kremlin. At 5:30 p.m. on Sunday, a welcome party will be held in the museum. On Wednesday afternoon of the meeting, several excursions will be offered that explore Moscow (such as a city tour, a boat trip along the Moscow River, or a Red Square and Kremlin guided tour). The conference banquet will be held in the comfortable Korston Hotel banquet hall at 6:00 p.m.

A number of pre- and post-conference tours are being prepared: a 3-day trip to Saint-Petersburg, including a visit to the Russian Geological Institute (VSEGEI) which has a special exhibition dedicated to the Popigai impact structure; a 2-day tour to Yaroslavl, including a visit to the public museum of Russia’s deep-drilling projects and a visit to the deep-core repository which stores krens from the famous 5 km deep drill core of the Puchezh–Katunki impact crater and the super-deep Kola borehole; a 4-day trip to Ekaterinburg to visit the boundary between Europe and Asia, the underground museum of gold mining (with its crocodile room), and the fall site of the Chelyabinsk meteorite; and a 3-day trip to the famous ancient city of Kazan, including a tour to the Karla impact crater.

We have reserved rooms in multiple hotels, offering a range of price categories and distances from the “Golden Brain” building. And because only one of the hotels is within walking distance of the Academy of Sciences Presidium building, we will offer a 7-day travel pass to all participants of the conference.

Moscow is the capital of Russia: its political, economic, cultural and scientific center. It was founded eight centuries ago by Prince Yuri Dolgoruky. Historians have accepted the year of 1147 as the start of Moscow’s history. Though Peter the Great moved the capital to St. Petersburg in 1712, Moscow remained the heart of Russia. Now, Moscow is one of the largest cities in Europe. Moscow has three international airports (Sheremetyevo, Domodedovo and Vnukovo); its express trains, buses and taxis allow one to reach the city center within one hour; and its famous subway system and renovated public transportation operate from 6:00 a.m. to 1:00 a.m. We look forward to welcoming you to Moscow.

Marina Ivanova, e-mail: metsoc2018@gmail.com

2017 ANNUAL MEETING STUDENT TRAVEL AWARDS

On behalf of the Meteoritical Society, we would like to thank the organizations whose generous sponsorships provided student travel grants, postdoc travel grants, and travel grants for scientists from countries with limited financial resources. These sponsoring organizations, and the recipients of the travel awards, are listed below.

This year, 63 travel grants were given to students and researchers who attended the annual meeting of the society in Berlin (Germany). Travel grants were generously sponsored by the Barringer Crater Company, the Planetary Studies Foundation, NASA Emerging Worlds, Elsevier, the Meteoritical Society’s Endowment and Travel for International Members Funds, and the International Mineral Collectors Association (the Brian Mason Award).

The Barringer Crater Company
Morgan A. Cox, Curtin University (Australia)
Samuel Ebert, Westfälische Wilhelms University (Münster, Germany)
Runlian Pang, Nanjing University/Friedrich Schiller University (China)
Marcus Patzek, Westfälische Wilhelms University (Münster, Germany)
Soumya Ray, Arizona State University (USA)
Jan Render, Westfälische Wilhelms University (Münster, Germany)
Poorna Srinivasan, University of New Mexico (USA)
Martin D. Suttle, Imperial College, London (UK)
Zachary Torrano, Arizona State University (USA)
Takash Yoshizaki, Tohoku University (Japan)
Daniela Weimer, ETH Zürich (Germany)
Patrizia Will, ETH-Zürich (Germany)
Weifan Xing, Chinese Academy of Sciences/China University of Geosciences (China)
Bidong Zhang, University of Western Ontario (Canada)
Mingming Zhang, Chinese Academy of Sciences (China)

Planetary Studies Foundation
Daniel R. Dunlap, Arizona State University (USA)
Paul W. Scholar, Case Western Research University (USA)

NASA Emerging Worlds
John N. Biglolski, CUNY Graduate Center/American Museum of Natural History (USA)
Michael Bojazi, Clemson University (USA)
Caroline Caplan, University of Hawaii (USA)
Samuel D. Crossley, University of Maryland (USA)
Leticia P. De Marchi, Auburn University (USA)
Crystalynda Fudge, Arizona State University (USA)
Jennika Greer, University of Chicago (USA)
Brendan A. Haas, Washington University (USA)
Rachel Rahib, University of Nevada, Las Vegas (USA)
Sarah Roberts, University of Tennessee (USA)
Seryl Ann Singerling, University of New Mexico (USA)
Krysten L. Villalon, University of Chicago (USA)

Elsevier
Queenie H. S. Chan, The Open University, UK
Nan Liu, Carnegie Institute, USA

The Meteoritical Society Endowment Fund
Luke Daly, University of Glasgow (UK)
Pierre Haenecour, University of Arizona (USA)
Nicole Lanning, Smithsonian Institution (USA)
My Riebe, Carnegie Institution of Washington (USA)
Reto Trappitsch, Lawrence Livermore National Laboratory (USA)
The Meteoritical Society’s Travel for International Members (TIM) Fund
Houda El Keri, Hassan II University (Morocco)
Fazia Kassab, University of Science and Technology Houari Boumédiène (Algeria)
Taha Shisheh, Hassan II University (Morocco)

International Collectors Association – Brian Mason Award
In 1997, Joel Schiff, the first editor of the popular Meteorite magazine, created a travel award in honor of Brian Mason, who was born in New Zealand and spent the majority of his career as a curator at the Smithsonian Institution (Washington DC, USA). The award is given to a student attending the annual meeting of the society who submits an abstract that clearly explains exciting results of particular interest to readers of Meteorite magazine. The recipient is required to write a popular account of their 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 Santa Fe meeting awarded Levke Kööp and Emilie Dunham the Brian Mason Award. Levke Kööp is a postdoctoral fellow at the University of Chicago (USA). His abstract was entitled, “Calcium and Titanium Isotope Systematics in Refractory Inclusions from CM, CO, and CR Chondrites” and the authors were L. Kööp, A. Davis, A. Krot, K. Nagashima, and S. Simon. Emilie Dunham is a graduate student at Arizona State University (USA). Her abstract was entitled, “The Range of Initial $^{10}$Be/$^{9}$Be Ratios in the Early Solar System: A Re-assessment based on Analyses of New CAIs and Melilite Composition Glass Standards” and the authors were E. Dunham, M. Wadhwa, and M.-C. Liu.

CALL FOR AWARD NOMINATIONS
Please nominate a colleague for one of the society’s awards. Nominations should be sent to Secretary Mike Weisberg (metsocsec@gmail.com) by 15 January 2017 (31 January 2017 for the Service Award and 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 at the society website or e-mail the secretary.

The society gives a number 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. 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.

Element
Mineralogical Society of Poland

IN MEMORIAL
Stanisław Hałas – passionate person, teacher, scientist, inventor, and experimenter
Professor Stanisław Hałas, a full professor and world-renowned researcher in isotope geochemistry at the University of Maria Curie-Skłodowska (UMCS) in Lublin (Poland) passed away 3 May 2017. He was 72 years old.

Professor Hałas received his MSc degree in physics in 1968 from UMCS. Following his degree, he joined the Institute of Physics at UMCS where he remained for the rest of his career. He obtained the title of professor in 1992 and was, for many years, the chair of the Department of Mass Spectrometry in the Institute of Physics UMCS. Stan was a distinguished scientist in the fields of mass spectrometry and isotope geochemistry and geochronology, and he was a pioneer in developing new measurement and analytical techniques. Stan was, above all, a creator: he was a novel inventor and could seemingly make something from almost nothing. His authorship or coauthorship of 24 patents is not surprising. Stan Hałas was also the author of hundreds of scientific papers and was one of the most cited Polish scientists in his discipline.

Stan was highly committed to teaching thousands of students and to the careful training of his graduate students and postdoctoral associates. He supervised six PhD students and introduced many Polish scientists to isotope geochemistry during the 50-year lifespan of his hospitable laboratory. He collaborated with others, working in laboratories in Calgary (Canada), Heidelberg (Germany), East Kilbride (Scotland) and Potsdam (Germany). Professor Hałas was distinguished by numerous decorations and awards, both Polish and international, and he was either a president or a member of numerous Polish and foreign scientific societies.

Stan was a physicist by education, but his intensive and extensive activities in isotope studies of rocks and minerals left his mark on Polish mineralogy, petrology and geochemistry. Stan will be remembered as the best physicist among geologists, and the best geologist among physicists. Even after he retired, Stan actively participated in research and was always full of new ideas and trying to initiate new projects.

Professor Halas was active not only professionally. Among his other interests included observing the sky, giving public demonstrations of physics, car touring, swimming and gardening. He is survived by his wife, six children, and six grandchildren. He will be very much missed by his colleagues, friends, family and all who knew him.

Ziggy Sawłowicz
THE CANADIAN MINERALOGIST

The Canadian Mineralogist is Alive and Well

We are happy to report that, thanks to the exceptional efforts of our editorial team – Managing Editor Mackenzie Parker and Editorial Assistants Jordan Roberts and Donald J. (DJ) Lake – our journal is now back on schedule and we are looking forward to implementing new initiatives. If you would like to find out more, and you are planning to attend the next Geological Society of America (GSA) meeting, you are invited to join us for The Canadian Mineralogist Contributor Event at the Sheraton Seattle Hotel on 24 October 2017. Come and meet the editorial team and share some mineral-themed martinis and appetizers!

Our average submission-to-publication time has fallen to under four months. So ... send us your manuscripts, especially if you want them published quickly.

Sincerely yours,
Lee A. Groat
Editor, The Canadian Mineralogist

UBC Research, Published in the July Issue of
The Canadian Mineralogist, Unearths Canadian
Sapphires Fit For A Queen

New research from mineralogists at the University of British Columbia (Canada) could make it easier to find high-quality Canadian sapphires, the same sparkling blue gems that adorn the Sapphire Jubilee Snowflake Brooch that was presented to Queen Elizabeth II.

Philippe Belley and colleagues outline their findings in the July issue of The Canadian Mineralogist (2017, v55, pp 669-699). They report on the unique recipe of pressure and temperature events from Earth's history that were required to form sapphires in Nunavut Territory (Canada). The researchers compared this information to regional data to pinpoint the most promising areas for sapphire exploration. Those areas are expected to occur near a thrust fault that separates the Lake Harbour Group and Narsajuaq terranes. A terrane is a fault-bounded area or region with a distinctive stratigraphy, structure, and geological history.

The so-called Beluga sapphires were discovered near Kimmirut, Baffin Island (Nunavut, Canada) by brothers Nowdluk and Seemeega Aqpik in 2002. The location is Canada’s only known deposit of sapphires. The gems form the basis of the ceremonial brooch given to the Queen in July 2017 by Canada’s Governor General David Johnston.

According to Lee Groat, a UBC researcher involved in the study, “This has enabled us to identify the areas of greatest potential for Kimmirut-type sapphire deposits in southern Baffin Island, which will facilitate gemstone exploration in this part of the Arctic”. “But it’s also a deposit model that can be applied to exploration worldwide.” Read the full article at https://science.ubc.ca/news/ubc-research-unearths-canadian-sapphires-fit-queen

Upcoming Issue – Call For Papers

A thematic issue of The Canadian Mineralogist in honour of Milan Novak will follow PEG2017 – 8th International Symposium on Granitic Pegmatites (in Norway) and the Tourmaline 2017 International Symposium held in Prague (Czech Republic).

Submission deadline for this thematic issue is 1 December 2017 for publication in May 2018.

Now Available
Minerals with a French Connection
Special Publication 13 of The Canadian Mineralogist

Systematic mineralogy has as its main goal a survey of crystalline species, the basic building blocks of all natural assemblages. As a nascent area of investigation under the initial guidance of such visionaries as Romé de l’Isle (1736–1790) and René-Just Haüy (1743–1822), mineralogy consisted essentially of the systematic approach. Since then, the field has evolved and developed in multiple directions. Nevertheless, systematic mineralogy remains a solid core, enriched each year by discoveries of a hundred or so new species. This book illustrates this systematic approach in the context of mineral species with a French connection. François Fontan (1942–2007), research scientist (CNRS) at Université Paul Sabatier in Toulouse (France), undertook the project; Robert Martin, Emeritus Professor of Geology at McGill University, Montreal (Canada), brought it to fruition. The profiles and discoveries of past and contemporary contributors to the vitality of mineralogy in France are highlighted, as is the geological context of the type localities.

Order online at www.mineralogicalassociation.ca

Yves Moëlo
Institut des Matériaux Jean Rouxel (Nantes)
MAC AWARDS – CALL FOR NOMINATIONS

Peacock Medal
The Peacock Medal is awarded to a scientist who has made outstanding contributions to the mineralogical sciences in Canada. There is no restriction regarding nationality or residency. The medal recognizes the breadth and universality of the awardee’s contributions to mineralogy, applied mineralogy, petrology, crystallography, geochemistry, or the study of mineral deposits.

Young Scientist Award
This award is given to a young scientist who has made a significant international research contribution during the early part of their developing scientific career. The scientist will have received his/her PhD not more than 15 years before the award. He or she must be a Canadian working anywhere in the world or a scientist of any nationality working in Canada. The research areas include mineralogy, crystallography, petrology, geochemistry, mineral deposits, or related fields of study.

Leonard G. Berry Medal
The Leonard G. Berry Medal is awarded annually for distinguished service to the association. The award recognizes significant service in one or more areas, including leadership and long-term service in an elected or an appointed office. The medal is named after Leonard G. Berry (1914–1982), a founding member of MAC, editor for 25 years of The Canadian Mineralogist, and its predecessor, and the first winner of MAC’s Past-Presidents’ (now Peacock) Medal.

Nominations for the 2018 medals and award are to be submitted to Ron C. Peterson (Department of Geological Sciences and Geological Engineering, Queen’s University, 99 University Avenue, Kingston ON K7L 3N6, CANADA). E-mail: peterson@queensu.ca.

Please submit your nominations by 31 December 2017. Check our website, www.mineralogicalassociation.ca, for additional details.

STUDENT TRAVEL/RESEARCH GRANTS
The Mineralogical Association of Canada awards travel and research grants to assist honors undergraduate and graduate students in the mineral sciences to:

- Present their research at a conference
- Visit a facility, laboratory, or field area to gather data for their research
- Pay for analyses that cannot be acquired at their university or for equipment needed for an independent research project.

The maximum grant value is CDN$1,200 per student. Grants will fund up to 50% of costs incurred for registration, travel, and subsistence, and up to 100% of other research costs (e.g. equipment, analyses).

Quotations and receipts may be requested for any equipment purchased.

For more information, see www.mineralogicalassociation.ca.

Deadline to apply: 15 January 2018

UPCOMING CIM–GAC–MAC JOINT MEETING

Resources for Future Generations
Vancouver, British Columbia, Canada 16–21 June 2018

The countdown for the Resources for Future Generations symposium in 2018 (RFG2018) is on. There are over 200 proposed sessions that have come in from around the globe.

The rapid growth of developing economies and the fundamental needs of many disadvantaged people across the globe are resulting in an increased demand for many resources and changes in the delivery of existing ones. The need for focused environmental priorities and new technologies will add additional requirements and constraints.

Under the auspices of International Union of Geological Sciences (IUGS) and supported by the Canadian Federation of Earth Sciences, the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), the Geological Association of Canada (GAC) and the Mineralogical Association of Canada (MAC) are partnering to bring industry, academia and governments together to tackle this growing issue.

Anchored in six themes – “Energy”, “Minerals”, “Water”, “The Earth”, “Education & Knowledge”, “Communities & Resources” – RFG2018 will showcase advances in Earth sciences, education, and innovation that can change the course of history.

Abstracts can be submitted up until 15 January 2018. Early-bird registration opened on 1 September 2017 and will end on 15 April 2018. Mineralogical Association of Canada, Geological Association of Canada, and Canadian Institute of Mining, Mineralogy, and Petrology members in good standing receive registration discounts!

Submit your proposal or register at: rfg2018.org

UNDERGRADUATE AWARDS 2016–2017
MAC undergraduate student awards are given annually to undergraduate students (2nd year of study or higher) at a recognized Canadian university or institute of higher education for excellence in one of the specialties supported by the Mineralogical Association of Canada (mineralogy, crystallography, geochemistry, petrology, and mineral deposits). Congratulations to the following students who received this award in 2016–2017.

Zoe E. Chapman-Humphreys, University of Victoria
Amy Cleaver, Lakehead University
Alison Cottrell, University of Regina
Rachel Culver, Queen’s University
Jacqueline Dubreuil, UBC Okanagan
Grace Emily Enns, University of Windsor
Christopher Grondin, Université Laval
Anna Katarina Haataja, University of Calgary
Byunghun Ko, University of New Brunswick
Stephanie Anne Kobylinski, University of Waterloo
Adam C. LaRiviere, University of Alberta
Derek Leung, Laurentian University
Nathan M. McCullough, Acadia University
Linda Pan, McGill University
Todd Robinson, Brock University
Colin G. Ross, St. Francis Xavier University
Karim Simard, Université du Québec Chicoutimi
Jolee K Stewart, University of Western Ontario
So how did MSA get started? Edward H. Kraus, Professor of Mineralogy at the University of Michigan (USA) and the MSA’s "founder", first sent letters of inquiry to 51 likely members in North America to see if they would join or support a mineral society. He received 29 favorable replies and, in combination with a number of commitments made by people in-person, had a total of 40 interested people. With this, Kraus circulated a draft of bylaws and asked for comments. After the many comments had been received and the necessary changes made to the bylaws, he arranged an in-person organizational meeting whereat MSA was founded on 30 December 1919. Clearly, Kraus and his colleagues saw the need for an organization to facilitate formal and informal communication and networking within the mineralogical community.

Publishing is one way a society can fulfill its mission to a membership: it provides information to the society and an outlet for that membership. The American Mineralogist, the publication most identified with MSA, was actually started in 1916 by interested mineralogists and collectors from Philadelphia (The Philadelphia Mineralogical Society) and New York (the New York Mineralogical Club), and elsewhere, to make up for the loss of The Collector journal in 1909. Management of the American Mineralogist was taken over by MSA in 1920, fulfilling the commitment for formal communication by the nascent society. That tradition continued as one of the MSA's strongest suits, adding the Reviews in Mineralogy volumes in 1974, Elements in 2005 (replacing the newsletter The Lattice and a collaboration with other societies, of course), along with several monographs and special papers since 1962.

As the annual meeting of the Geological Society of America was the locale for the action to form MSA, it continues to be the convenient occasion for business meetings and sessions sponsored by the society. The MSA moved to sponsor sessions and activities at other society meetings, such as those by the American Geophysical Union (AGU) and the Goldschmidt Conferences. However, sponsoring its own meeting has not been favored for a variety of reasons, including costs that might compromise the more substantive publishing endeavors. The issue of a society meeting continues to be a concern for some members, and I would be interested to learn strong opinions on the subject. As has been announced, MSA will have a celebratory and reflective centennial meeting in the summer of 2019, where we hope the future of our science and the MSA itself will be one topic for discussion.

The MSA has expanded its role into education via workshops, short courses, and a textbook; and there is outreach via the lecture program, Minerals 4 Kids, booths at various meetings, and the list server MSA-talk. The MSA is, thus, fulfilling the activities that a professional society should perform. Nevertheless, MSA Council continues to look for ways to serve the membership better, as was presented in my last letter. We count on the membership for support of the society, to dedicate time on committees and activities, and for dues and contributions to keep it financially healthy and able to address the membership's needs. Thus, as a society, I believe MSA fulfills its mission successfully but can always look for ways to improve, even at the ripe age of 98.

This is my fourth and final letter in Elements as MSA President. It has been an honor and privilege to serve MSA and ponder what to communicate in these missives. Please look forward to the next letter from Michael Brown, the incoming (or rising) president in the next issue.

George Harlow
2017 MSA President

Why Create a Society like MSA?

As the annual meeting of the Geological Society of America was the locale for the action to form MSA, it continues to be the convenient occasion for business meetings and sessions sponsored by the society. The MSA moved to sponsor sessions and activities at other society meetings, such as those by the American Geophysical Union (AGU) and the Goldschmidt Conferences. However, sponsoring its own meeting has not been favored for a variety of reasons, including costs that might compromise the more substantive publishing endeavors. The issue of a society meeting continues to be a concern for some members, and I would be interested to learn strong opinions on the subject. As has been announced, MSA will have a celebratory and reflective centennial meeting in the summer of 2019, where we hope the future of our science and the MSA itself will be one topic for discussion.

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The February 2017 (v13n1) issue of *Elements* reproduced a typeset flyer calling for the organization of a Mineralogical Society of America. It was sent by Edward H. Kraus, a faculty member at the University of Michigan, to 51 mineralogists in the USA and Canada. The mimeographed letter reproduced here was sent by Dean Kraus in October 1917 as a follow-up, saying the formation of the organization would be put on hold because of “very unsettled conditions at present”. The “very unsettled conditions” were a result of the April 1917 entry of the United States into the First World War, a war that had been ongoing since July 1914. Plans to organize the society were restarted within a few months from the 11 November 1918 armistice and signing of the peace treaty in June 1919. The MSA was formed Tuesday, 20 December 1919, at the Copley Square Hotel, Boston (Massachusetts) during the meeting of the Geological Society of America.

**MSA CENTENNIAL HISTORY**

**AWARD NOMINATIONS**

**Nominations Sought for 2019 Awards**

Nominations must be received by 1 June 2018

The **Roebling Medal** (2019) is MSA’s highest award and is given for eminence as represented by outstanding published original research in mineralogy.

The **Dana Medal** (2019) recognizes continued outstanding scientific contributions through original research in the mineralogical sciences by an individual in the middle of their career.

The **Mineralogical Society of America Award** (2019) is given for outstanding published contribution(s) prior to 35th birthday or within 7 years of the PhD.

The **Distinguished Public Service Medal** (2019) is presented to an individual who has provided outstanding contributions to public policy and awareness about mineralogical topics through science.

**Society Fellowship** is the recognition of a member’s significant scientific contributions. Nomination is undertaken by one member, with two members acting as cosponsors. Form required, contact committee chair or MSA home page.

Submission requirements and procedures are on MSA’s home page: [http://www.minsocam.org/](http://www.minsocam.org/)

**NEW PUBLICATION**

**Care and Documentation of Mineral Collections**

Jean F. DeMouthe


This work is an attempt to provide information and guidance on all aspects of caring for and documenting mineral collections. It is aimed at professionals and amateurs alike and is dedicated to everyone who shares a love of minerals and those who care for and about collections. Chapters include: “Collection Organization”, “Documentation”, “Ancillary Collections”, “Preventive Conservation”, “Collection Organization”, “Storage”, “Hazards, Safety, and Risks”, “Administrative Policies”, “Private Collections”, and “Bibliography and Resources”. Description and ordering online at [www.minsocam.org](http://www.minsocam.org) or contact Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1110 USA phone: +1 (703) 652-9950 fax: +1 (703) 652-9951 e-mail: business@minsocam.org. Cost is $45 ($33.75 members MSA, GS, CMS).

**RESEARCH GRANTS**

The Mineralogical Society of America 2018 Grants for

**RESEARCH IN CRYSTALLOGRAPHY**

from the Edward H. Kraus Crystallographic Research Fund with contributions from MSA membership and friends

**STUDENT RESEARCH IN MINERALOGY AND PETROLOGY**

from an endowment created by MSA members

Selection is based on the qualifications of the applicant; the quality, innovativeness, and scientific significance of the proposed research; and the likelihood of success of the project. There will be up to three US$5,000 grants, with the restriction that the money be used in support of research. Application instructions and online submission are available on the MSA website, [http://www.minsocam.org](http://www.minsocam.org). Completed applications must be submitted by 1 March 2018.
THE EMU 2017 SCHOOL ON MINERAL FIBRES

The 2017 EMU (European Mineralogical Union) school entitled Mineral Fibres: Crystal Chemistry, Chemical–Physical Properties, Biological Interaction and Toxicity was held 19–23 June 2017 at the Chemistry and Earth Sciences Department UNIMORE in Modena (Italy). The school had been designed with a strong multidisciplinary slant, aimed at fully understanding both the nature and the biochemical activity of mineral fibres. The following topics were covered: crystal structure and crystallography, occurrence of mineral fibres and naturally occurring asbestos; experimental methods for the investigation of mineral fibres: optical microscopy, X-ray diffraction, electron microscopy, vibrational spectroscopy, iron spectroscopy and synchrotron radiation–based techniques; surface and bio-chemical properties of mineral fibres; in vitro and in vivo tests to assess cyto/genotoxicity and carcinogenicity of mineral fibres; epidemiological studies of asbestos-related diseases; genetic factors, mutations and toxicity of mineral fibres.

Attending the school were 80 participants and 15 lecturers. These came from many countries – Argentina, Australia, Canada, Croatia, France, Hungary, Italy, Norway, Slovakia, Slovenia, Spain, Switzerland, USA – and from backgrounds that spanned the university, public and private sectors. Many ‘local’ Italian lecturers (G. Andreozzi, P. Ballirano, E. Belluso, F. Belpoggi, G. Della Ventura, L. Fazio, A. Gualtieri, A. Pacella, A. Pugnaloni, O. Sala, F. Turci and R. Vigliaturo) plus eminent international figures in the field of mineral fibres shared their knowledge and expertise. For example, Dr. Don Halterman (Occupational Safety and Health Administration, Salt Lake City, Utah, USA) explained the physical characteristics of mineral fibres. Dr. David Bernstein (toxicology consultant based in Geneva, Switzerland) gave a picture of the bio-chemical processes occurring after the inhalation of mineral fibres. Profs. Michele Carbone and Haining Yang (both from the University of Hawaii, USA) presented the results of their research (published in Nature) on BAP1 and MM cells. Dr. Bruce Case (McGill University, Canada) gave his lecture in remote mode. In addition, there were practical sessions in optical and electron microscopy and a field trip to a quarry containing asbestos in Borgotaro (Parma). Completing the programme was a visit to the Istituto Ramazzini (Bologna).

The school was sponsored by the International Union of Crystallography (IUCr), the European Mineralogical Union (EMU), the Italian Society of Mineralogy and Petrology (SIMP) and private sponsors.

The accompanying EMU Notes in Mineralogy book, Mineral Fibres: Crystal Chemistry, Chemical–Physical Properties, Biological Interaction and Toxicity (edited by A.F. Gualtieri), was released in time and gifted to all the attendees.

The short course received very positive feedback from the attendees. The lectures, photos and all the news that was related to the event are available at the web site http://emu2017.unimore.it/.

EMU NOTES IN MINERALOGY

Two new volumes have been published in the EMU Notes in Mineralogy series.

Volume 17 – Redox-Reactive Minerals: Properties, Reactions and Applications in Natural Systems and Clean Technologies

Minerals are naturally occurring inorganic solids that make up the solid part of most solar terrestrial planets. Redox-active elements such as iron, manganese, titanium and sulfur in these minerals allow them to engage in a wide range of electron-transfer reactions, including those mediated by biota or processes involved in palaeo-weathering and biogeochemical cycling. The importance of redox-reactive minerals in many natural and industrial processes has been demonstrated by a plethora of scientific publications and industrial applications in recent decades. In this book, the influence of redox-reactive minerals on key biogeochemical processes and the opportunities for their application in environmental technologies are outlined and illustrated in 14 comprehensive chapters. The book will be a key reference for Earth science students, geologists, geochemists and engineers and other researchers and practitioners in this rapidly growing interdisciplinary field.

The book is available from the Mineralogical Society online bookshop: www.minersoc.org (click on bookshop) at a price of £55 (institutions) and £40 for individuals (+ shipping). Copies are also available from the Mineralogical Society of America and from Amazon.

Volume 18 – Mineral Fibres: Crystal Chemistry, Chemical-Physical Properties, Biological Interaction and Toxicity

Asbestos is probably one of the most studied substances ever. Asbestos is synonymous with argument and controversy: it is magic but feared, essential but dreaded, a strategic natural raw material but a source of concern and hazard, it is banned but still used safely, and so the list goes on. Asbestos-related diseases are certainly of significant concern in terms of occupational and public health. Asbestos World Health Organisation officials estimate that 125,000,000 people worldwide are exposed annually to asbestos in occupational settings, and >100,000 people die annually of diseases associated with asbestos exposure. Use of asbestos has been banned in most developed countries, but chrysotile asbestos is still used in many developing countries. This book presents the state-of-the-art in the vast multidisciplinary research field of asbestos and of mineral fibres in general. The protagonists of the book are the mineral fibres with their immense complexity and poorly understood biochemical interactions. The approach of the chemist/mineralogist/crystallographer puts the fibre in focus, whereas the approach of the biochemist/toxicologist/doctor assumes the perspective of the organism interacting with the fibre. The perspectives of both the ‘invader’ and the ‘invaded’ must be considered together to establish a conclusive model to explain the toxicity of mineral fibres. In fact, this sharing of different perspectives and working in a multidisciplinary way is the key to understanding the mechanism of asbestos-induced carcinogenesis. With this in mind, the state-of-the-art in the field of mineral fibres is illustrated and discussed in this volume, with a multidisciplinary approach taking into account all the different scientific strands (biology, chemistry, epidemiology, mineralogy, physics, toxicology etc.). The different views have been considered in an attempt to assemble the pieces of the jigsaw and to present the reader with an up-to-date and complete picture.

The book is available from the Mineralogical Society online bookshop: www.minersoc.org (click on bookshop) at a price of £55 (institutions) and £40 for individuals (+ shipping). Copies are also available from the Mineralogical Society of America and from Amazon.
AN ALPINE EXCURSION – ELERI CLARKE

My fieldwork took place 3–7 July 2017 in the mountains around Zermatt (Switzerland). The purpose was to collect serpentinite samples for my PhD and gain a wider contextual knowledge of the Alps. My PhD, so far, has focused on pre-collected samples gained from collaborations with other researchers. Although this was highly beneficial, it meant that I had never seen my rocks in the field, which limited my contextual comprehension. On this trip, not only was I able to collect nine more samples for my project, I also explored the deep roots of the Alpine orogeny.

Here, I was shown a range of mantle-related rocks, from ‘pristine’ peridotitic mantle (with centimetre-sized orthopyroxene!) through to fully serpentinitized mantle and dehydrated serpentinite. These rocks were associated with Bundnerschiefers (oceanic floor sediments), eclogites, a hearty greenschist overprint and eclogite facies ocean floor pillow basalts.

This was also a brilliant opportunity to meet and talk with geologists from the University of Lausanne and benefit from their extensive Alpine knowledge and experience (and good sense of humour!). Ultimately, this trip will be critical to the success of my PhD and I am grateful to all of those who helped make it happen.

2017 SCHLUMBERGER AWARD
The Mineralogical Society–Schlumberger Award will be presented to Professor Margaret “Maggie” Cusack later in 2017.

STRATEGY MEETING FOR THE SPECIAL INTEREST GROUPS

The society has eight special interest groups (SIGs) and they were called to a meeting hosted by the President of the MSGBI, Hilary Downes, in late September 2017 to discuss future strategies in terms of meetings and publications. Further detail will be published in future issues of Elements but in the meantime, the society would welcome comments and suggestions about the SIG meetings and society meetings.

DISTINGUISHED LECTURERS 2017/18

Dr Helen Williams (University of Cambridge) and Dr Dan Smith (University of Leicester) will be the society’s Distinguished Lecturers for 2017/2018. If your department was not lucky enough to secure a lecture for this year, please visit the website at http://www.minersoc.org/distinguished-lectures-17-18.html to check if one of the selected venues is nearby. All venues welcome visitors from other departments. Do think about applying for a visit by a Distinguished Lecturer next year. The deadline is usually 1st September.

- Lecture B: “Wet Magmas and Copper Fertility”
- Lecture C: “Tracing Fluid Transfer Across Subduction Zones Using Iron and Zinc Stable Isotopes”
- Lecture D: “The Iron Isotope Composition of the Earth’s Lower Mantle: Implications for Mantle Mineralogy and Differentiation Processes”

MINERALOGICAL SOCIETY NEW BOOK TITLE

The EMU–MinSoc Notes in Mineralogy series has yet another new arrival to report, bringing to four the number published in 2017.

Volume 19—Mineralogical Crystallography

At the dawn of structural crystallography, Walther Friedrich, Paul Knipping and Max von Laue carried out the first experiments and developed the theory of X-ray diffraction. From the early days, when even the simplest inorganic structures filled an entire PhD study, structural crystallography evolved at its own pace and found new partners in chemistry, physics, materials science, biology and other fields of the physical sciences. Both morphological and structural crystallography, however, have remained as important instruments in the mineralogist’s toolbox. Efforts to enhance the existing instrumentation, to improve our understanding of the theory of diffraction, to study nanoparticulate or poorly ordered materials, and to master large, complex structures continue in all fields of physical sciences. Mineralogists can, thus, use the fruits of this labour and include them in its own toolbox.

Mineralogical Crystallography is edited by Jakub Plašil, Juraj Majzlan and Sergey Krivovichev, and includes the following five chapters:

- “Structure description, interpretation and classification in structural mineralogy” S.V. Krivovichev
- “Methods of crystallography: powder X-ray diffraction” A. Altomare, C. Cuocci, G.D. Gatta, A. Moliterni and R. Rizzi
- “Electron crystallography” L. Palatinius, M. Gemini and M. Klementova
- “Environmental mineralogical applications of total scattering and pair distribution function analysis” F.M. Michel
- “Aperiodic mineral structures” L. Bindi and G. Chapuis

MEMBERSHIP

The Mineralogical Society continues its policy of giving one year’s free membership to students. We have set a limit of 150 free student memberships per year and these are allocated on a first come–first served basis. If you have not previously benefited from free membership of the society, then join now at www.minersoc.org. Just click on “Join”.

Note that all members are now able to access both of our journals and Elements as part of the membership fee. Log in at www.minersoc.org and you will be presented with a link to the full text online. If your library offers access to Mineralogical Magazine or Clay Minerals through GeoScienceWorld, please access the content through the library as this usage generates income for the society.

BURSARIES

Below is an excerpt from the report of one of the student bursary winners for this year. You can see all of the reports at http://www.minersoc.org/bursary-report.html. In 2017, between the society centrally and the Special Interest Groups, we distributed >£10,000 in grants. The deadline for the next round of awards will be 13 January 2018. Read the criteria carefully and apply in good time. A healthy proportion of applicants receive funding up to £500.
The Japan Association of Mineralogical Sciences (JAMS) is proud to announce the recipients of the 2017 society awards. The Japan Association of Mineralogical Sciences Award is conferred each year to a maximum of two scientists for their exceptional contributions to the mineralogical and related sciences. The Manjiro Watanabe Award, named in honour of Professor Manjiro Watanabe, a famous Japanese mineralogist, and founded by his bequest, is awarded every year to a scientist who has significantly contributed to the mineralogical and related sciences over his or her long career.

**Japan Association of Mineralogical Sciences Award: Hiroaki Ohfuji**

Hiroaki Ohfuji of the Geodynamics Research Center at Ehime University (Japan) is a mineralogist who uses electron microscopy to help understand the crystallization and self-organization mechanism of minerals at the nanometre- and micrometre scales. His first research project was the study of the structure and formation process of frambooidal pyrite, a raspberry-like aggregate of pyrite microcrystals, under the supervision of Prof. Junki Akai (at Niigata University) and Prof. David Rickard (at Cardiff University, UK). Through detailed scanning electron microscopy and electron backscatter diffraction analysis, he revealed the 3-D packing structure of the microcrystals in frambooidal pyrite and discovered their unique “icosahedral packing.” After he started his career at Ehime University, he expanded his interest to the study of the crystallization and texturing processes that occur during chemical reactions and phase transitions of various synthetic minerals/materials. One of his major achievements is the elucidation of the texturing mechanism of ultrahard nano-polycrystalline diamond (NPD), which is synthesized by direct conversion of graphite under high pressure and high temperature. This led to the microtexture control of NPD to further strengthen its hardness and mechanical properties and to create new varieties, such as layered NPD. Furthermore, he has recently identified a natural counterpart of NPD in the diamonds produced by the large meteoritic impact in the Popigai crater (Russia). He is currently working on the origin of mantle diamonds, including polycrystalline varieties such as ballas and carbonado, and on volatile recycling in subduction zones.

**Japan Association of Mineralogical Sciences Award: Tatsuhiko Kawamoto**

Tatsuhiko Kawamoto of the Institute for Geothermal Sciences at Kyoto University (Japan) studies the behaviour of hydrous magmas and aqueous fluids. He started his research as a petrology student supervised by Shohei Banno and Yoshiyuki Tatsumi at Kyoto University. He described every phenocryst in a single thin section in an attempt to explain enigmatic plagioclase morphologies. He began conducting high-pressure and high-temperature (HPHT) experiments as a postdoc at the Ikuo Kushiro’s lab at the University of Tokyo, where he conducted partial-melting experiments of hydrous mantle peridotite with Kei Hirose and duplicated andesite–dacite–rhyolite magmas by crystal fractionation of a hydrous arc basalt. He then joined the Depths of the Earth led by John Holloway of Arizona State University (USA), and became the first Japanese person to learn how to use the multi-anvil-type HPHT apparatus in the United States. He proposed a choke point for subducting hydrous minerals, a hydrous mantle transition, and a method by which to generate komatiite and kimberlite magmas. He then went on to learn the Bassett-type diamond anvil cell from Hélène Bureau, Nikolay Zotov, and Hans Kepler at the Bayerisches Geoinstitut (Germany), after which he moved back to Kyoto University. With Kenji Mibe, Masami Kanzaki, Shigeki Ono, and Kyoko Matsukage, he identified the critical end-points between various magmas and aqueous fluids by using X-ray radiography, and suggested new hypothesis for subduction zone magmatism. He has found seawater-like saline fluid inclusions in mantle xenoliths beneath Mount Pinatubo (Philippines) and other volcanoes, proposing the importance of being salty in subduction zone fluids.

**Manjiro Watanabe 2017 Award: Kichiro Koto**

Kichiro Koto was appointed to an academic position at the Institute of Scientific and Industrial Research, Osaka University (Japan), in 1963 when he was still a graduate student at the University of Tokyo (Japan). He received a doctor of science degree in 1969 from the University of Tokyo with his thesis, “Description, Stability, and Crystal Structure of Anilite Cu₅S₄, a New Mineral.” He then focused on mineral crystallography using X-ray diffraction and X-ray absorption fine-structure (XAFS) spectroscopy. He studied the crystal structures, phase relations, and transition mechanisms of natural and synthetic silicates and oxides. He also studied iron and copper sulfides (e.g. pyrrhotite, digenite, and bornite) and successfully analyzed incommensurate superstructures with nonstoichiometric composition. From 1977 to 1979, he worked with Prof. H. Schulz at the Max-Planck-Institut für Festkörperforschung (Stuttgart, Germany) as a “guest-scientist.” During this time, he studied the superionic conductors of silver iodide and lead fluoride. The crystallographic investigation of ion motion, based on precise electron density distributions in situ, and especially at high temperatures, provided important information on the diffusion path and mechanism of ions in solids. He also studied the various superionic conductors of spinel-, fluoride- and perovskite-type structures. And he studied physically important substances, such as ferroelectric compounds, with colleagues from other scientific fields. From 1984 to 1985, he oversaw the project “Microstructures and Thermal-Pressure Hysteresis of Minerals.” He continued his crystallographic studies on minerals and superionic conductors after moving to Tokushima University in 1988.
RENEW YOUR MEMBERSHIP FOR 2018
Geochemical Society (GS) members can renew quickly and securely on the GS website www.geochemsoc.org. Renew by 31 December 2017 to save $5 off the regular dues and enjoy uninterrupted access to *Elements*, *Geochemical News*, and registration discounts to Goldschmidt2018 in Boston (Massachusetts, USA) and other conferences. Members also have access to the online member directory (available by signing into your profile on the website). You can also choose a two-year membership option to save time and money. If you prefer to renew by mail, please visit the website to download a form to send with your payment.

<table>
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<tr>
<th>2018 Dues Rates</th>
<th>Early (by 31 December 2017)</th>
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<tr>
<td>Professional</td>
<td>$30</td>
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<td>Senior</td>
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<td>Student</td>
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The society also offers a Life Member option that eliminates the need to renew every year. The current life membership rate is 70 minus your current age times US$35, with a minimum rate of $175. Contact the business office at gsoffice@geochemsoc.org for more information on upgrading your membership to this convenient option.

KEEP YOUR PROFILE CURRENT
Have you recently moved or changed your email address? Keeping your GS member profile current allows us to send *Elements* and *Geochemical News* to the right place every time. Updating your contact information is easy: just visit www.geochemsoc.org/contact and click the link to access your online member profile. You can also email the business office with updates or corrections at any time.

Geochemical Society Business Office
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USA

GS CAREER CENTER
The Geochemical Career Center features job opportunities from employers all around the world. If you are looking for a teaching, research, or postdoctoral position, be sure to add the Career Center to the websites you follow. If you are an employer seeking excellent candidates, it’s a great way to advertise your position to members of the society. Visit www.geochemsoc.org/career-center to get started.

GOLDSCHMIDT2018 CALL FOR SESSIONS
The science committee and theme chairs for Goldschmidt2018 have identified 15 broad themes for the conference, and the entire geochemistry community is now invited to submit suggestions for sessions. The call for sessions will close on 1 November 2017; this is your chance to ensure that your favorite subject will be covered during the conference. Details on how to submit a session proposal can be found at goldschmidt.info/2018.

FIND US THIS FALL AT GSA AND AGU
The Geochemical Society will be at the Geological Society of America (GSA) Annual Meeting in October 2017 and the American Geophysical Union (AGU) Fall Meeting in December 2017. Find us in the exhibit hall to renew or update your membership, learn about our programs, or just to say “Hello”. Thanks to partnerships with GSA and AGU, Geochemical Society members can take advantage of the discounted member registration rates for both conferences.
SIX QUESTIONS TO ROB RAISWELL

Rob Raiswell gained his research degrees from the University of Liverpool (UK), and his first academic position was as a Lecturer in Sedimentary Geochemistry at the University of East Anglia (UK). In 1983, he moved to the Department of Earth Sciences at the University of Leeds (UK) and remained there until retirement. The Earth sciences department became the School of Earth and Environment, and he is now an Emeritus Professor in the school. Rob believes he has been very fortunate to have held a variety of visiting positions in some of the best schools in the USA – Yale University, Georgia Institute of Technology, and the University of California, Riverside – and has been elected a Fellow of the European Association of Geochemistry and of the Geochemical Society. He still retains research interests in the geochemistry of glacial systems and the polar iron cycles.

Rob Raiswell co-authored with Don Canfield the first issue of Geochemical Perspectives, ‘The Iron Biogeochemical Cycle Past and Present’, and he is regularly involved with creating the EAG cartoons ‘Black & White’.

1. What or who inspired you to become a geochemist?
I became a geochemist mostly through a series of lucky accidents. I had an undistinguished academic start, only acquiring an ordinary degree in chemistry at the University of Liverpool at the second attempt. Fortunately, I was able to persuade the Geology Department to allow me to do a research MSc (and later a PhD), largely thanks to Mike Atherton who was a metamorphic geochemist in the department. Mike was farsighted enough to see the potential of low-temperature geochemistry and was prepared to take a risk on me as a graduate student.

2. How do you think the field has changed since you were a student?
There has been a huge expansion in low-temperature geochemistry, whereas igneous and metamorphic geochemistry were dominant when I started research. Now there seems to be an ever-expanding group of talented low-temperature geochemists. However, competition has also hugely increased and this has resulted in individuals to become more focused. Consequently, our different science communities are becoming introspective and reluctant to search outside existing paradigms. The corresponding growth in literature also makes it difficult to read widely, which also discourages cross-disciplinary exchanges. The best geologist is the one who has seen the most rocks ... and this is also true for geochemistry!

3. Which career choices were the most important?
I was fortunate to start my academic career in the School of Environmental Sciences at the University of East Anglia, where my chemistry degree plus geochemistry research background was in keeping with their emphasis on inter-disciplinarity. The university also supported my study leave with Bob Berner at Yale University [USA], which brought me into contact with a fabulous group of PhD geochemists that included Don Canfield, Tim Lyons and Bernie Boudreau. I had seen Bob Berner’s early papers and thought his 1964 *Geochemica et Cosmochimica Acta* paper on modelling porewater sulfate [v. 28, pp 1497-1503] was an exciting use of kinetics in sediment diagenesis.

4. What has been your greatest obstacle?
Having to continually remind too many chemists and geochemists about the fundamental role of mineralogy in Earth surface systems.

5. What inspires or motivates you?
I enjoy working on large-scale geochemical problems. The textbooks by Garrels and Mackenzie on *The Evolution of Sedimentary Rocks* and Garrels, Mackenzie and Hunt on *Chemical Cycles and the Global Environment* were my inspiration for this approach.

6. What qualities do you look for in a potential PhD student?
Enthusiasm, way ahead of exceptional academic qualifications. Willingness to learn new skills, problem-solving ability and persistence. Research is more about perspiration than inspiration!

**EAG MEMBERSHIP: TO ENJOY A FULL YEAR OF BENEFITS, JOIN OR RENEW NOW**

The EAG has developed a comprehensive set of membership benefits at a very affordable price, suiting early career scientists or more advanced ones, anywhere in the world.

- Member registration rates to Goldschmidt conferences
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- Print and online issues of *Elements*
- Reduced subscription rates to *Chemical Geology* and *Geofluids*
- Sponsorship of students attending workshops and conferences in Europe
- Ambassador Program, supporting early career scientists based in Europe to attend conferences outside of Europe
- Sponsorship of member-led workshops and conferences
- **Member rates for print publications** of the Mineralogical Society of Great Britain and Ireland (MSGBI), the Italian Geological Society (SGI), the Italian Society of Mineralogy and Petrology (SIMP), and the French Quaternary Association (AFEQ)
- **Member rates to publish** open-access articles in *Mineralogical Magazine* and *Clay Minerals*
- **Member rates to attend events** organised by the MSGBI, the International Association of GeoChemistry (IACG), the International Society for Environmental Biogeochemistry (ISEB), the Society for Geology Applied to Mineral Deposits (SGA), and the European Association of Geoscientists & Engineers (EAGE)
- Receipt of monthly newsletters
- Access to networking through the EAG blog, social media, information about jobs, conferences, geochemistry related news and other activities of interests to geochemists

**Membership Rates**

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<tr>
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<td>Student 3 years</td>
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<td>25 Euros</td>
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<tr>
<td>Professional 5 years</td>
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Did you know that **institutional membership** is also possible? Check www.eag.eu.com/membership for more information or contact our business office.
Focus on EAG Partnerships

With the aim of strengthening geochemistry internationally, the EAG has partnered with many learned societies. These include international, national, or specific discipline-focused societies. Such partnerships increase visibility and allow a sharing of information with different audiences; they also benefit members of both the EAG and the partner society at the individual level.

For example, partnership with the MSGBI allows EAG members to purchase print publications of MSGBI at the reduced member rate. The same applies to print publications of SGI, SIMP, and the AFEQ. Members of the EAG are also able to attend events organised by MSGBI, ISEB, IAGC, SGA or EAGE at the reduced member rate. And as noted above, members of the EAG can benefit from the MSGBI member rate to publish open-access articles in the journals Mineralogical Magazine and Clay Minerals.

These partnerships also allow members of all the partner societies listed below to benefit from the reduced member rate when registering at Goldschmidt conferences in Europe.

You can find all the details of each partnership agreement online at www.eag.eu.com/about/partnerships. And of course, if you have any questions, please don’t hesitate to contact us.

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GEOCHEMICAL PERSPECTIVES LETTERS IS MOVING TO ONLINE FORMAT ONLY

As announced in the preface of our last published issue of Geochemical Perspectives Letters (GPL), we will now move to an electronic format only. This move was planned at the inception of the journal and allows us to readily expand the number of manuscripts published and the speed at which we can publish without incurring additional fees. We hope this will make GPL a yet more attractive place for our community to share its latest research so please submit your next high impact manuscript to GPL.

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Letters

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GOLDSCHMIDT2017: BREAKING RECORDS!

The 27th Goldschmidt Conference of the European Association of Geochemistry (EAG) and the Geochemical Society (GS) took place 13–18 August in Paris (France) and, while preparations for Goldschmidt2018 in Boston (Massachusetts, USA) are already under way, we’d like to share with you some highlights, and a few statistics, from the recent Paris conference.

Goldschmidt2017 certainly broke several records, including the highest number of attendees (4,630) and abstracts (4,264). The conference’s success is the product of the hundreds of volunteers who served on the various committees (Science, Organising and Local) and who acted as theme chairs, convenors, mentors, and bloggers. We warmly thank all contributors for their time and commitment, and we would like to say a special “Thank you” to our fantastic team of student helpers.

The dedication and leadership of three people, however, stand out: Antje Boetius (Principal Convenor and Chair of the Organising & Science Committees), Bernard Marty (EAG President), and Marc Chaussidon (Chair of the Local Organising Committee).

Goldschmidt2017 Statistics

<table>
<thead>
<tr>
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<td>Posters</td>
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Participants came from 85 countries, some as far as New Zealand!
The 20 most represented countries were:

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<td>Israel</td>
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</tr>
<tr>
<td>Norway</td>
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EARLY CAREER SCIENTISTS PROGRAM AND SUPPORT

We thank Adina Paytan for her efforts in setting up an extensive program aimed at Goldschmidt2017’s junior delegates.

This year, the program included:
- Nine lunchtime workshops, which were attended by 371 students
- ‘Meet the Plenary’ event, which allowed groups of students to share lunch with the plenary speaker of the day
- The Mentor Program, which comprised 168 mentors and 214 mentees

New for 2017 were the Pop-up Talks presented by passionate young researchers. This initiative was developed by junior scientists Steffi Lutz, Kimberley Bitterwolf and Alexandra Holland. To find out more, please read the blog post ‘Love Triangles and Spies – Geochemistry in 3 Minutes’, by Claire Cousins.

The Goldschmidt Conference has a strong tradition of supporting the attendance of delegates from countries with low-income economies, and, in 2017, the Grant Program enabled 58 junior scientists to attend. We thank the Geochemical Society and publisher Elsevier for their financial support to this program. Another 27 grants were awarded to US-based students thanks to generous contributions from the National Science Foundation (USA) and NASA.

MEDALLISTS AND PLENARY LECTURES

Recognition of scientific excellence is at the heart of EAG and GS values, and this is perfectly illustrated by the 14 awards presented at this year’s conference—another record! We congratulate all the medallists. The full list of medallists is available at https://goldschmidt.info/2017/medals-View. Interviews with some of the medallists can be found on the EAG Blog page for Goldschmidt2017 (http://blog.eag.eu.com/category/goldschmidt2017/).

This year’s Goldschmidt also marked the launch of a new award, the Robert Berner Lecture, created by students and friends of the late Professor Robert Berner (1935–2015) of Yale University (USA) to commemorate his intellectual legacy in geochemistry. The inaugural Robert Berner Lecture was awarded to Joshua West (University of Southern California, USA).

Goldschmidt is always keen to find outstanding plenary speakers: people able to bring new perspectives to a large audience. This year’s speakers, and their lectures, included:
- Matthieu Gounelle, “From Prodigies to Meteorites (1492–1803)”
- Paul Falkowski, “How Corals Make Rocks”
- Hélène Langevin-Joliot, “Pierre and Marie Curie and Radioactivity”
- Laurie Reisberg, “Highly Siderophile Elements: A Window into the Earth’s Mantle”
- Shuhei Ono, “Clumped Isotopologue ($^{13}$CH$_3$D) Fingerprinting of Methane Sources”
PRESS COVERAGE

Substantial efforts were put into communicating our science to the general public and, through the teamwork of Press Officer Tom Parkhill and EAG Councillors Vinciane Debaille, Siggi Gislason, Emily Pope and Dominik Weiss, Goldschmidt2017 received extensive international press coverage. Articles appeared in, for example, the Times, Agence France Presse, the Washington Post, El País, El Mundo, the Guardian, Science, the Australian, BBC News and were broadcast on German State Radio.

Here are some highlights:
- BBC News – “Radioactive ‘pooh sticks’ trace carbon’s ocean journey”
- The Washington Post – “The first animals evolved during the absolute worst time on Earth”
- Science – “Record-shattering 2.7-million-year-old ice core reveals start of the ice ages”
- Sky News Australia – “Mars rover to focus on alien life”
- National Geographic, Spain – “Roma se convirtió en una superpotencia gracias a la plata ibérica”

GOLDSCHMIDT WILD ORBIT CINEMA

A science video competition was a first at Goldschmidt2017, and we’d like to thank Adrienne MacArtney for this wonderful initiative. More than 90 submissions were received and, after a first round of selections, 15 of the best short science films were screened throughout the conference. An average of 60 delegates attended the daily lunchtime screening, and special workshops and discussions on how to make a science movie were also organised. The 15 movies selected can be watched at http://wildorbitfilms.com/finalists2017/finalists2017.html. Two external judges chose the three best movies: Biology Meets Subduction (by the Deep Carbon Observatory), Atoms to Volcanoes (by Terry Thomas) and Paleodul (by Gonzalo Moreno). Congratulations to the winners!

WORKSHOPS AND FIELD TRIPS

Goldschmidt2017 broke yet another record with 14 pre-conference workshops, which were attended by 361 scientists. These workshops covered an array of subjects, from geochemical modelling, to understanding noble gases, to the environmental geochemistry of boron, and many more.

Another 84 delegates participated in the four pre- and post-conference field trips, mixing science with the discovery of local treasures (local wine, delicious food and beautiful landscapes!).

We take this opportunity to thank all of the workshop and field trip organisers.

SOCIALS

As per Goldschmidt tradition, a full and diverse social program was offered to attendees. Attendees were able to discover Versailles at night and with fireworks, to walk through the Marie Curie Latin Quarter, to enjoy the traditional ice-breaker, to dance at the Goldschmidt Rocks party, to dine on the River Seine while discovering the wonders of Paris, and to enjoy special museum tours of the Louvre or the Musée d’Orsay. A total of 1,543 social tickets were sold this year, probably another record!

SPONSORS AND EXHIBITORS

The success of the Goldschmidt Conference is also possible thanks to the support of our sponsors. We are particularly grateful to our Platinum sponsor Thermo Fisher Scientific, our Palladium sponsor Agilent Technologies, and our Gold sponsor Oxymore. And we were most excited to welcome 40 exhibitors, all of whom are thanked for sharing their expertise with the delegates.

SOCIAL MEDIA, BLOG, PHOTOS AND VIDEOS

A team of seven intrepid bloggers was assembled to blog the conference. We thank Deirdre Clark, Martin Mangler, Sami Mikhail, Claire Cousins, Clare Stead, Tadhg Dornan and Foteini Drakou for sharing their experiences in their 17 blog posts. This year, Bernard Marty (EAG President), Eiji Ohtani (EAG Urey Award), Julie Prytulak (EAG Houtermans Award), Francis McCubbin (GS Clarke Award), Shuhei Ono (EAG-GS Paul Gast Lecturer) and Li Zhang (Shen-su Award) were interviewed by Sami Mikhail. These fascinating interviews can be found on the EAG Blog (see http://blog.eag.eu.com/).

Goldschmidt2017 was also active on social media, posting 1,234 tweets. Finally, another record was possibly broken with the number of conference photos taken: 1,039 in all! The photos are all available online and, as always, videos of the plenary talks can be viewed at https://www.youtube.com/user/goldschmidtconf.

Our final thanks go to the conference’s organizer, White Iron Conferences, and to all the delegates of Goldschmidt2017 who made it such a memorable event. The European Association of Geochemistry and the Geochemical Society look forward to welcoming you to next year’s fantastic 28th V.M. Goldschmidt Conference, which will be held 12–17 August 2018 in Boston (USA).
SEARCH (AND DISCOVERY) OF NEW IMPACT CRATERS ON EARTH

Ludovic Ferrière

When looking at other terrestrial planetary bodies of the Solar System, such as our Moon, Mars, Mercury or the asteroids, it is obvious that impact craters are the dominant geological features to be seen on their surfaces. On Earth, however, impact craters are not so obvious and, in most cases, they are hard to spot. Our planet is geologically active. Its surface is constantly altered by plate tectonics and erosion and is largely covered by oceans and (densely) vegetated areas, making the identification of impact craters difficult. In addition, on Earth, an impact crater cannot be recognized, like on other planetary bodies, based only on its morphological characteristics because circular features can be formed by a variety of completely different geological processes (e.g. volcanism, salt diapirism, etc.). A requirement for the confirmation of an impact structure on Earth is the finding and characterization of diagnostic indicators for shock metamorphism, such as shatter cones (Fig. 1), planar deformation features in minerals (Fig. 2), high-pressure mineral glasses, high-pressure mineral phases, and/or anomalies in platinum-group elements (e.g. iridium) or isotopic anomalies (e.g. osmium) in specific geological settings [for further information see French and Koeberl (2010) and Ferrière and Osinski (2012)]. Rarely do projectile fragments survive an impact event. Thus, finding meteorite fragments spatially associated with a crater is restricted to small and relatively young impacts.

When in the field, the only distinctive shock-deformation features that can be seen with the naked eye (meso- to macroscale features) are shatter cones. These are distinctive curved to curvilinear fractures decorated with divergent striations radiating from the apex of a conical feature or from a narrow apical area (Figs. 1 and 3). Partial to complete shatter cones can occasionally be observed in coarse-grained rocks, such as granites or conglomerates, but they are best developed in fine-grained rocks. Care should be taken to properly characterize field samples. People often report they have found shatter cones when what they have actually found are ventifacts, slickensides, or other features that may look like shatter cones. Nice examples of shatter cones and further information on how to identify them can be found in Ferrière and Osinski (2012) and Baratoux and Reimold (2016). Other odd looking rocks, in particular brecciated rocks (which are not diagnostic), should be collected and then investigated under the microscope. Finding shocked minerals – the equivalent of DNA or blood at a crime scene – would indicate that the samples were affected by an impact (note that the absence of shocked minerals doesn’t allow a conclusion to the contrary!). The microscopic part of the work can be long and tedious due to, in some cases, a ratio of one shocked grain to hundreds or thousands of unshocked grains. Shocked grains will show planar microstructures that formed upon shock compression, if the involved pressure was strong enough (i.e. several GPa). Planar microstructures are mainly of two types: (1) planar fractures, which are planar, parallel, thin open fissures; (2) planar deformation features, which are narrow, individual planes of amorphous material comprising straight, parallel sets spaced 2–10 µm apart that generally occur as multiple sets per grain (Figs. 2 and 3). Both types of microstructures are crystallographically controlled. The finding and proper characterization of these microstructures can be used to confirm an impact origin knowing that they are, in nature, uniquely formed by shock metamorphism [i.e. in the case of planar fractures, they are diagnostic indicators only when occurring in multiple sets; see French and Koeberl (2010) for further information]. Shocked quartz grains are typically used to identify impact craters [see French and Koeberl (2010) and Ferrière and Osinski (2012) and references therein], but other shocked minerals, such as zircon and other accessory minerals have been increasingly used in the last few years [see Cavosie et al. (2010) and Timms et al. (2017) and references therein] and appear to be very promising, in particular for old eroded...
impact structures. As for shatter cones, special care should be taken in the identification and characterization of planar fractures and planar deformation features because some features commonly found in quartz (and also in other minerals) – tectonic deformation lamellae, irregular fractures, or trails of fluid inclusions (or cleavages for a number of minerals) – may superficially look like shock microstructures.

In addition to planar fractures and planar deformation features, some high-pressure glasses (e.g. diaplectic quartz glass, maskelynite, etc.) and high-pressure phases (e.g. coesite, stishovite, reidite, etc.) are also diagnostic. However, their use should be done with extreme care as some of those are also products of endogenic processes (i.e. not exclusively formed by impact metamorphism). It is vital to know the geological context of the specimens.

New impact structures are discovered/confirmed (almost) each year. As of today, about 190 impact structures have been unambiguously identified on Earth, based on the finding of diagnostic indicators for shock metamorphism. Finding a new impact structure is something very exciting, but what is even more interesting is the number of new questions that arise: When did it form (i.e. how old it is), How big was the impact (in the case of eroded structures this “basic question” is not so trivial), and, What local or regional effects did it have?

Impact structures (and their associated phenomena) offer unique opportunities to help answer fundamental questions on the impact cratering processes. Many impact structures have not yet been discovered/confirmed and a number of the confirmed ones have not been studied in detail. In some cases, the only publication available is a conference abstract that reports the discovery. There are many impact structures just waiting to be discovered/confirmed and investigated. Let’s start the hunt!

REFERENCES
NEW CALEDONIA: LAND OF NICKEL

France Bailly1

New Caledonia (strictly Nouvelle Calédonie) is the most distant French overseas territory. Located in the southwest Pacific Ocean, this small archipelago (18,575 km²) is about 1,200 km from the east coast of Australia and 1,600 km northwest of New Zealand. The name was given by the famous English navigator and explorer James Cook, who published the first map of New Caledonia in 1774. Caledonia was the Roman name for Scotland, and it is said that the coasts of New Caledonia reminded Cook of Scotland, of which his father was a native.

More than a third of the main island, Grande Terre, is formed of peridotite mountains, fragments of an immense ophiolitic sheet that was obducted onto the New Caledonian microcontinent during the Eocene. Rapid weathering, with a tropical climate, has covered this ultrabasic bedrock with a thick mantle of laterite, which has concentrated metals, particularly nickel, in its lower layers. New Caledonia presents the third largest nickel deposit in the world and, according to recent estimates, has more than 25% of the world’s nickel resources and about 40% of the world’s oxidized nickel ores.

New Caledonia’s history coincides with that of nickel. In 1864, a new nickel ore, composed of garnierite (Fig. 1), a green serpentine-group mineral, \((\text{Ni,Mg})_3\text{Si}_2\text{O}_5(\text{OH})_4\), was discovered in New Caledonia by a young geologist named Jules Garnier (1839–1904). Mining developed very rapidly after 1873. Nickel, cobalt, iron, and also gold, copper, coal and jade were exploited at several sites. Settlers and adventurers set out to search for ‘green gold’. The stories of the mining pioneers are exciting, punctuated by famous names like John Higginson, André Ballande, Lucien Bernheim, Henri Lafluer, and Georges Montagnat, strong personalities and families, mixing mining fortunes and political commitments. As a result of this effervescence, migratory movements generated by the mining industry were largely responsible for the ethnic diversity of the Caledonian population, along with the indigenous people, the Melanesian Kanak communities. The production and processing of nickel continued through successive periods of boom and crisis and is now a central issue in the decolonization process (which started in 1988) being negotiated by France in New Caledonia. Nowadays, the mining areas, spread over the whole of Grande Terre, comprise about 250,000 hectares of scattered concessions shared by French or international mining companies and a few medium-scale local firms.

In a mountainous environment with intense climatic events (Fig. 3), the damages caused by the old open-pit mines (before 1970’s) are significant (Fig. 2). Other effects of the mining industry for New Caledonia are the excessive polarisation of the economy and changes in the traditional way of life of the indigenous Kanak communities. For a long time, the nickel industry was of no benefit to them. The gradual entry of the Kanak into the political and economic arena took place gradually after the Second World War. Progressively, political emancipation and a willingness to share resources led to the involvement of the Kanak people in mining activities.

1 National Centre for Technological Research, New Caledonia
E-mail: france.bailly@cnrt.nc
Increasing environmental awareness has paved the way for a new regulatory framework. Stakes are considerable, as nature and biodiversity are fabulous in New Caledonia. The terrestrial flora and fauna present unusual rates of endemism, particularly on ultrabasic soils. New Caledonia is ranked as one of the world’s hotspots for its exceptional and highly threatened biodiversity, and several parts of the New Caledonian reef and lagoon have been classified as UNESCO World Heritage sites since 2008. Steps are now being taken to restore mining sites by introducing endemic plants (Fig. 4).

If the recent developments and the implementation of large-scale metallurgical projects have positively and lastingly changed the country’s economy, it remains for policy-makers to preserve it for future generations by promoting more sustainable development. To face the challenges of a ‘better way of mining’, mining sector stakeholders created a dedicated resource agency devoted to applied research and technology development in New Caledonia’s mining industry. This public-interest group, the National Centre for Technological Research (CNRT), acts as an operational support facility for fundamental and applied research on New Caledonia’s mining sector, something that is vital to the whole industry.

Since its inception in 2007, CNRT has funded some 50 multidisciplinary research projects. Research has focused on three identified areas (technology, natural environment and societal issues) to fill on-going gaps in fundamental knowledge, offer and adapt new technology that is relevant to the industry, develop methodology aids, manage knowledge transfer and upgrade practices on the ground. These actions by the CNRT have effectively added value to New Caledonian research, while keeping it permanently in touch with industry. The fact that CNRT takes up social challenges, funds innovative projects and caters for its membership’s concerns, makes it more than a research-funding facility. While it does endeavour to develop fundamental and applied research projects, it also strives to provide technical and economic solutions and foster knowledge-transfer between mining companies and other businesses and professionals in the industry.

New Caledonia has become something of a ‘laboratory’ for studying the complex interactions between mining and society, now an essential component for consideration in its economic development.
### DINGWELL SELECTED INTO LEOPOLDINA

Prof. Donald Bruce Dingwell, Director of the Department of Earth and Environmental Sciences of the LMU Munich has been elected to membership in the Leopoldina, Germany’s national academy of sciences. Dingwell has played a major role in the development of experimental Earth sciences in general and experimental volcanology in particular. He is already a member of 3 other academies. Founded in Schweinfurt in 1652, the Leopoldina is the world’s oldest continuously existing academy for medicine and the natural sciences. The academy elects distinguished academics and scientists to become members. Currently, the Leopoldina has approximately 1,500 members in over 30 countries.

### DEMOUCHY RECEIVES EMU RESEARCH EXCELLENCE MEDAL

The 2016 EMU Research Excellence Medal has been awarded to Sylvie Demouchy of CNRS, Geosciences Montpellier (France) for her scientific leadership in experimental geochemistry and mineral physics, her scientific breadth, and her extensive service to the academic community. She completed her PhD at the Bayerisches Geoinstitut (Germany), focusing on hydrogen incorporation mechanisms in olivine and its high-pressure polymorph wadsleyite. She subsequently went on to post-doctoral positions at the Lunar and Planetary Institute, Houston, and the University of Minnesota (USA), where she has broadened her scientific portfolio by becoming a rock squeezer. In 2007, she moved to the CNRS in Montpellier, where she is currently a tenure researcher in the Mantle-Interfaces research group, leading their high-pressure laboratory and enjoying experimental mineralogy with the young researchers. She is co-author of over 36 major publications in top international journals, making significant breakthroughs in the understanding of hydrogen mobility in upper mantle minerals, and the viscoplasticity of olivine-rich rocks, using both experimental techniques and natural mantle rock specimens. She has consistently demonstrated that rheological laws established at high-temperature cannot be extrapolated to lithospheric conditions, and has elegantly demonstrated that hydrolytic weakening of olivine is probably only a minor effect in the uppermost mantle. In addition to her research achievements, Sylvie has been involved in several European research programs during her career, as a student on the European Union’s Training and Mobility of Researcher’s HydroSpec programme (TMR HydroSpec), a young researcher on the EU’s Marie Curie project International Reintegration Grand’s Physics of the Earth’s Mantle (IRG PoEM), to a PhD supervisor for the European Union’s Horizon 2020 action Innovative Training Network for Complex Rheologies in Earth dynamics and Industrial Processes (ITN CREEP), and trained a large number of research students and young scientists.

Dr. Demouchy presented her award talk at the Goldschmidt conference in Paris (France) in August 2017 during session 7e, “Diffusion, deformation and transport processes in geomaterials”. Her presentation focused on the distribution of hydrogen in the rocks of the uppermost mantle and its consequences on Earth’s dynamic.

### IMA 2016 MINERAL OF THE YEAR

The International Mineralogical Association is pleased to announce that the Mineral of the Year award for 2016 goes to merelaninite, Mo₄Pb₄VSb₅S₇.

This mineral was discovered in collector specimens from the Merelani region in northeastern Tanzania, and investigated by John A. Jaszczak (Michigan Technological University, Houghton, USA), Michael S. Rumsey (Natural History Museum, London, UK), Luca Bindi (Università di Firenze, Florence, Italy), Stephen A. Hackney (Michigan Technological University), Michael A. Wise (National Museum of Natural History, Washington DC, USA), Chris J. Stanley (Natural History Museum, London), and John Spratt (Natural History Museum, London).

Merelaninite, whose unusual whisker-like crystals were initially mistaken for molybdenite, is actually a new member of the cylindrite group (Jaszczak et al. 2016). The new species is remarkable not only for its morphology, which is reminiscent of slender microscopic “scrolls”, and its structure, which is composed of alternating pseudo-tetragonal (PbS-type) and pseudo-hexagonal (MoS₂-type) layers, but also for the fact that it comes from the famous mining area that has produced the gemstone tanzanite (vanadium-bearing blue zoisite) for 50 years. Other unusual minerals found in association with merelaninite are well-crystallized wurtzite and alabandite, which represent just one evolutionary stage in the complex metamorphic history of the Merelani deposits. We would like to congratulate John Jaszczak, Mike Rumsey, and their co-authors on this award and encourage all readers to learn more about merelaninite from the open-access article in Minerals (www.mdpi.com/2075-163X/6/4/115).

The close runner-ups were the Pb–Cu–Te oxysalt andychristyite (Kampf et al. 2016a), and the mineral vanarsite, which contains As–V polyanions (Kampf et al. 2016b).

### REFERENCES

Jaszczak JA and 6 coauthors (2016) Merelaninite, Mo₄Pb₄VSb₅S₇, a new molybdenum-essential member of the cylindrite group, from the Merelani tanzanite deposit, Lelatema Mountains, Manyara Region, Tanzania. Minerals 6:115


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JOB POSTING
Simon Fraser University 368

FACULTY OF SCIENCE
Department of Earth Sciences
TASC1 7415
8888 University Drive
Burnaby, BC, Canada V5A 1S6
www.sfu.ca/earth-sciences.html

Assistant Professorship in Natural Hazards

The Department of Earth Sciences at Simon Fraser University invites applications for a tenure track Assistant Professorship in Natural Hazards commencing as early as September 2018. A PhD is required, and post-doctoral research, teaching or industry experience is desirable. Qualiﬁed candidates will be considered for a Tier 2 Canada Research Chair (see below). The research activities of the successful candidate will complement the existing natural hazards research interests within the Department, while contributing to the expertise of the Department as a whole. Candidates with expertise in remote sensing, risk assessment and mitigation, ﬁeld-based observation and/or laboratory-based studies examining natural hazards, in particular, geological hazards, are encouraged to apply.

The successful candidate will develop a strong, externally funded research program, and supervise both Master’s and doctoral students. Teaching responsibilities will include undergraduate and graduate level courses, to support the environmental geoscience curriculum, for example, by teaching courses in Quaternary geology or environmental geoscience. The successful candidate is expected to eventually take on a leadership role in the Centre for Natural Hazards Research.

For additional information about this position, see http://www.sfu.ca/earth-sciences/

All qualiﬁed candidates are encouraged to apply; however, Canadian Citizens and Permanent Residents will be given priority. Simon Fraser University is committed to employment equity and encourages applications from all qualiﬁed women and men, including visible minorities, Aboriginal peoples, persons with disabilities, and LGBTQ persons. The University acknowledges the potential impact of career interruptions on a candidate’s record of research productivity, and encourages qualiﬁed candidates to explain any impact career interruptions may have had on their record of research achievements.

Applicants are requested to submit a curriculum vitae, a statement of research and teaching interests, and the names, addresses, phone numbers, and email addresses of three referees. Electronic applications are preferred. Review of applications will begin November 1, 2017.

CRC Tier 2 Chairs
• Tier 2 chairs are intended for exceptional emerging scholars (i.e., candidates must have been an active researcher in their ﬁeld for fewer than 10 years at the time of nomination).
• Applicants who are more than 10 years from having earned their highest degree (and where career breaks exist, such as maternity, parental or extended sick leave, clinical training, etc.) may have their eligibility for a Tier 2 chair assessed through the program’s Tier 2 Justiﬁcation process. Please contact the research grants ofﬁce for more information.

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