ONE HUNDRED MINERALOGICAL QUESTIONS IMPACTING THE FUTURE OF THE EARTH, PLANETARY AND ENVIRONMENTAL SCIENCES

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AN HISTORICAL PERSPECTIVE

It is arguable that mineralogy is the oldest of all the practical sciences. The early manufacture of fire that could be called upon 'at will' depended, in part, upon the sparks produced on striking minerals such as pyrite. Although anthropologists cannot be certain of the first mineral-based fire strikers, the oldest commonly accepted evidence of fire production dates to *Homo erectus* populations 500,000 years ago. *Homo sapiens* were expert fire starters 40,000 to 50,000 years ago, during the Palaeolithic period. The importance of minerals and rocks for prehistoric human development is enshrined in our use of the terms *Stone Age*, *Bronze Age* and *Iron Age*. Stone tools were fashioned by our ancestors more than 30,000 years ago from hard, fine-grained rocks such as flint and naturally occurring glass such as obsidian. By 9000 BC, clays were being fired to make pottery, leading to other ceramic arts such as brick-making, and even glass-making by 3500 BC. By this time, copper was being extracted from its ores using primitive smelting techniques and used as the metal itself or alloyed with tin to make bronze. The people who found the copper sulfide ores were the first 'mineralogists' and, by 3000 BC, they had mastered the extraction of other metals (silver, lead, zinc, antimony) and their use in other alloys. The smelting methods developed to extract these metals from the minerals opened the way for development of the more demanding metallurgy needed to extract the most useful of all metals, iron. (The Roman writer Pliny described iron as "the most useful and most fatal instrument in the hand of man.") The importance of these ancient, mineral-based inventions cannot be overstated. They played a critical role in not only the productivity and range of hominids but perhaps in their very survival.

Some of the most influential naturalists of the late 18th century, including James Hutton, considered Georgius Agricola, the 16th century physician–natural historian who classified about 600 minerals, as the founder of modern mineralogy. It is no wonder that scientific historians often imply, if not argue, that the modern science of geology emerged from the field of mineralogy.

PRESENT AND FUTURE CHALLENGES

So, mineralogy has had a long and distinguished history as a science, but what of its future? The '100 questions' exercise aimed to identify 100 mineralogical questions that, if answered, would have the greatest impact on resolving current and future challenges in the Earth, planetary and environmental sciences. The exercise was launched in *Elements* in 2011 and promoted via a website (www.100-questions.org) and through the active participation of many national and international mineralogical societies. Submissions were accepted from across the community, and additional submissions were solicited by e-mail from authors and editors who have contributed research articles to *Elements* since its launch. This ensured that submissions were received from a cross section of the community (including mineralogists, petrologists and geochemists, broadly defined) working in current areas of research.

A total of 283 submissions was received. From these, the final list of 100 questions, which can be downloaded at www.elementsmagazine.org/supplements, was agreed upon and edited by the authors. Our aim was to have well-defined scientific questions of broad significance, ranging from the most fundamental to the most applied. While no such list can ever claim to be definitive, the results provide a fascinating snapshot of the mineralogical questions that scientists across a wide spectrum of the Earth sciences wish to address. It provides definitive proof, if such were needed, that mineralogy is as important now as ever, perhaps even more so given the challenges facing humanity in the 21st century.

Minerals in the Environment and as Resources

The great practical issues now facing humanity centre mostly on climate change, on the environmental impact of resource exploitation and on the search for adequate resources to support a global population expected to reach nine billion by 2050. These subject areas figure strongly in our list, in questions framed from the general to the specific. Some of the most pressing questions concern minerals in Earth's atmosphere, a relatively new field of research for mineralogists. They consist of broad questions about the role played by airborne mineral dusts in influencing global climate, about their radiative properties and about their interactions with other atmospheric constituents. Related questions concern the impact of mineral dusts on human health and of volcanic ash on the performance of jet engines. A more specific question is about which airborne minerals act most effectively as nuclei for the ice that forms ice clouds. Climate change issues are also central to worries about the stability of naturally occurring methane hydrates faced with a 'warming globe'. Attention is also drawn to aspects of climate change research where Earth scientists, including mineralogists, are uniquely able to contribute; these questions concern the geological record of past climates, whether in testing the reliability of climate proxies or in unravelling past climates through the study of cave deposits.

Consideration of Earth resources issues also brings up topics from the general to the specific, ranging from the assessment of the economics of exploitation of mineral resources on other planets and asteroids to the origins of carbonados, rare earth element deposits or secondary gold grains. Given the industrial importance of certain mineral groups, such as the zeolites, are there as yet unrecognized opportunities for modern industry to benefit from the mineral world? Resource exploitation also brings local and global problems, and the solutions are often mineralogical ones. The emissions of greenhouse gases such as carbon dioxide need to be controlled, and relevant questions have been raised about how to accelerate mineral carbonation and about the long-term fate of CO_2 injected into the subsurface. Closely related but much broader questions are concerned with the global carbon cycle, such as how the deep carbon cycle operates and by what mechanisms minerals stabilize organic carbon in soils. The nuclear industry is associated with problems that are well known, but critical questions remain about the reactions between minerals and nuclear wastes in deep disposal facilities or about the long-term fate of man-made actinides in the environment.

Many of the questions, although fundamental, have a bearing on the behaviour of contaminants in the near-surface environment of the Earth (the so-called 'critical zone') and the remediation of that contamination. Questions are raised concerning the atomic-scale mechanisms that control the mobility of trace elements, how organic matter affects

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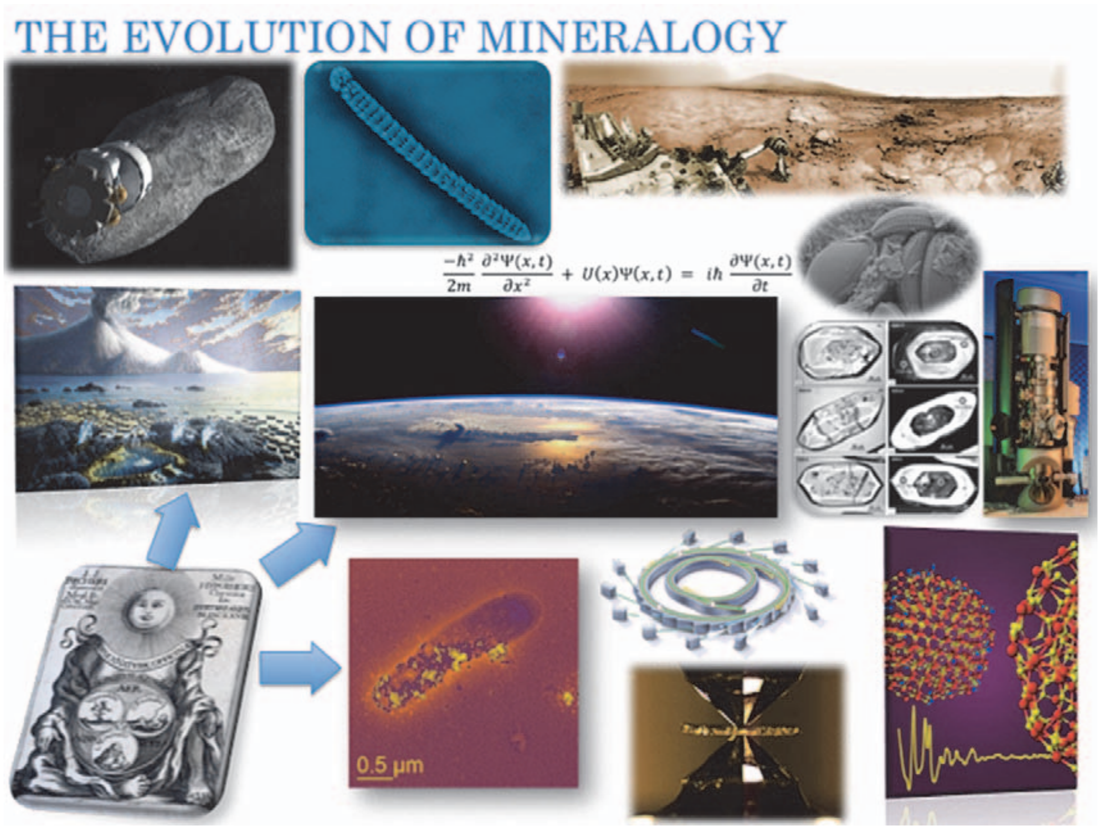
contaminant uptake on mineral surfaces, how minerals actually form in aqueous solution and how minerals interact with light to drive certain chemical reactions. Even more general questions are about how exploitation of mineral resources influences the biosphere and natural selection in the long term and about how we can control the mineral–fluid reactions governing processes of crucial importance to human 'sustainability'. The latter question relates to general issues concerned with remediation, which are addressed in more detail in questions about the use of nanoparticle minerals for decontaminating water, such as arsenic-contaminated water used for drinking and irrigation in parts of Southeast Asia. The origin of this arsenic is the topic of another question, and still another concerns the thermodynamic properties of the mineral phases carrying the arsenic.

Minerals Undergoing Change

Scientific research commonly begins with questions that are curiosity driven rather than having immediate practical applications, and, in an area as vital as mineralogy, there is no shortage of 'blue-skies thinking'. In metamorphic petrology, for example, topics raised range from global-scale Earth history – such as understanding the appearance of ultrahigh-pressure (UHP) metamorphism in the Neoproterozoic – to the micro-scale – for instance, understanding certain mechanisms of porosity generation. Other questions range from the general, as in asking about the rates of retrograde metamorphism, to the specific, as in how to better understand pressure estimates from UHP metamorphism in terms of lithospheric depths. An important research area identified in a number of submissions concerns the rates of processes, whether of metamorphic reactions or of processes at much lower temperature and pressure. Questions include the timescales of global silicate- and carbonate-mineral weathering, rates and mechanisms of replacement reactions below 300 °C, rates of reequilibration of minerals in a subducted lithospheric slab and how to relate laboratory measurements made on a timescale of minutes, hours, days or months to the geological timescale.

Minerals in Biological Systems

It is no surprise that several prominent biomineralization questions appear in the survey, and eight were put into the list of the final 100. Biomineralization involves more than 60 minerals in a vast array of varieties. This process is widespread in all six taxonomic kingdoms of the living world and began early on during the first great radiation of life marking the beginning of the Cambrian Period. Today, biominerals are found in organisms ranging from bacteria to humans. Several questions point in these broad directions, with one asking what are the "universal" characteristics of biomolecules that induce/inhibit the growth of biominerals suited for their various and vital roles in living things. Other questions are more directed but equally fascinating, such as those that address the extraordinary biological success of the hydroxyapatite–collagen association in bone. Other questions in this category are more unexpected, asking whether biological processes in the deep biosphere, including biomineralization, have anything to do with certain types of ore mineralization, or how complex organisms (such as vertebrates) are able to use magnetic biominerals to create navigational sensing mechanisms.



Minerals in the context of the Earth system, as viewed in 1668 by J. J. Becher in his masterpiece, *Physica subterranea* (lower left portion of the figure), and as viewed by today's mineralogists (the remainder of the figure). As an early chemical cosmogonist, Becher viewed the planet as composed of three primary components, air, water and earth, with earth divided into animal, vegetable and mineral (lower, central portion of his drawing).

Component images of this figure are reproduced courtesy of the following: Top row, left to right: DigitalSpace /Bruce Damer; Pupa U. P. A. Gilbert, Lee Kabalah-Amitai, Boaz Pokroy, University of Wisconsin-Madison – see also Kabalah-Amitai et al. (2013) Science 340: 454; NASA/JPL-Caltech/Ken Kremer/Marco Di Lorenzo

Second row, left to right: Time dependent Schrodinger equation for one dimension; Jim Schiffbauer, University of Missouri

Third row, left to right: Painting by Peter Sawyer, Smithsonian Institution; NASA Sun-Earth Day 2008, www.sunearthday.nasa.gov; Liu et al. (2004) Lithos 78: 411; NCFL FEI Titan, Virginia Tech

Fourth row, left to right: Becher (1668) *Physica subterranea*; Bose et al. (2009) GCA 73: 962; Australian Synchrotron; Steve Jacobsen, Northwestern University; Zhang et al., UC Berkeley, www.nsf.gov/od/lpa/news/03/pr0390.htm

Minerals and the Early Solar System

Questions targeting deep time and extraterrestrial minerals were well represented in this survey. There are specific questions about the formation of chondrules in chondritic meteorites and the dating/origin of highly refractory presolar grains, and there are fundamental questions about the building of planets, including minerals containing water or hydrogen/hydroxyl that would have been transported to the inner portions of our Solar System, especially the vicinity of Earth's orbit. Moreover, what additional mineralogical clues might support the giant impact theory for generating the Earth–Moon system or might reveal the nature and cause of the Late Heavy Bombardment between about 3.8 and 4.1 billion years ago? With future, more advanced exploration of Mercury, Mars and asteroids in mind, questions are asked about mineralogical evidence indicating conclusively the presence of extinct or extant extraterrestrial microbial life. Another question concerns the mineralogy of condensed (frozen) volatiles cold-trapped at the poles of the Moon and Mercury, and finally another is about the mineralogical role and availability of water on Mars. And if one had to choose the ultimate mineralogical question of all time, it would probably deal with the role that minerals played in the emergence of life on Earth, and as expected, this question was submitted to our survey.

Minerals at the Nanometre Scale

Nanomineralogy, within the much larger realm of nanogeocience, is one of the newest subfields in mineralogy and is also represented in this survey. Nanominerals and mineral nanoparticles, whatever their origin, seem to be ubiquitous, and for the most part they went unnoticed until recently. They were, in more ways than one, the 'invisible' part of the mineral kingdom. They were also completely misconstrued in the field of aqueous geochemistry when, for decades, anything that went through a 0.45-micron filter was considered 'dissolved'. The most fundamental part of this field, summarized in just one question in the list of 100, is how the chemical and mechanical properties of minerals vary as a function of their crystal size and shape in the nano-range of sizes (from one to a few tens of nanometers). This notion of property variation as a function of size provides the foundation of every subdiscipline under the now enormous and important field of nanoscience. Our survey shows that nanomineralogists are asking questions about the role that nanominerals and mineral nanoparticles play in (bio)geochemical processes at the local, regional and global scales; about how they affect life on Earth; and about the complex inventory and reactivity of perhaps the largest accumulation of nanominerals and mineral nanoparticles on the near-surface of the planet, that is, in the world's oceans. One question addresses perhaps the latest frontier in this rapidly growing field, namely the effort to understand the amount, distribution, and reactivity of poorly crystalline, inorganic nanomaterials in soils, sediments and surface waters.

Minerals from Crust to Core

Mineralogy continues to be central to the fields of petrology and volcanology. Questions of immediate concern to humans relate to the health impacts of volcanic ash and how these are controlled by the mineralogy of erupted material. Specifically, what conditions cause the formation of different polymorphs of silica in volcanic conduits, and what is their fate in the environment? Understanding what triggers volcanic eruptions in the past, present and future is a perennial theme, leading to questions about how to use minerals to record volatile components in magmatic systems and the role of mineral source composition in generating supereruptions and large igneous provinces. The desire to understand the dynamics and evolution of magma leads to the question of how to use liquid lines of descent to infer magma dynamics, with implications for the crustal evolution of liquid immiscibility in mafic magmas. The microstructural evolution of magma chambers is a particularly active area of current research, summarized by the question of whether layering in igneous rocks can be explained in terms of self-organization or whether it is more related to the processes of sorting and recrystallization of granular flows associated with periodic crystal-rich injections.

Palaeomagnetism is a powerful tool for studying the evolution, structure and dynamics of the Earth and other planets. As we strive to push the boundaries of what can be achieved using palaeomagnetism, an understanding of its mineral physics underpinnings becomes ever more important, and this is reflected in two questions that highlight the mineralogical challenges related to obtaining reliable palaeomagnetic data from ancient rocks on Earth and from extraterrestrial materials such as meteorites. Environmental magnetism is an emerging discipline that seeks to relate subtle variations in the concentration and grain size of magnetic minerals incorporated into sediment to variations in environmental and climatic factors. Although qualitative correlations between certain magnetic and environmental variables are well established, the question of what atomic and nanoscale mechanisms link the two – a central problem defining the nascent field of quantitative magnetoclimatology – remains open.

As seismologists reveal the complex, three-dimensional variations in seismic velocity, anisotropy and attenuation throughout the Earth's core and mantle, much is still to be learned about the underlying mineralogical processes that cause them. Not surprisingly, the greatest unknowns concern the most inaccessible parts of the planet. Fundamental questions regarding the crystal structure, chemical composition and grain size of iron–nickel alloy in the inner core remain highly contentious, and nearly ten years after the discovery of the perovskite to post-perovskite phase transition in $MgSiO_3$, questions still remain about whether this transformation can explain the anomalous seismic properties of the D'' layer at the base of the lower mantle. The list reveals a shift in focus away from traditional studies of equations of state towards a desire to understand how extrinsic factors and microstructural features (e.g. grain boundaries and phase interfaces) influence the seismic-frequency response of the mantle and core. A key question is how we can develop methods to determine whether variations in temperature or chemical composition (or both) are responsible for a given seismic signature. Several questions are about the geophysical ramifications of melts, fluids and volatiles, including their roles in the generation of ultralow-velocity zones, in controlling the frictional properties of subduction zone faults, and in determining the volatile budget of the mantle, and about how volatiles are incorporated into crystal structures of mantle minerals, as well as their influence on tectonic processes on Earth and other rocky planets. Computer simulations to predict the structure and properties of minerals at high pressure and temperature are as important as ever, raising the general question of how best to relate simulations at the atomic scale to geological processes at the planetary scale, and the more specific question of whether computer simulations are able to accurately predict the slip systems of minerals at high pressure and temperature. Finally, questions were asked regarding the nature of liquid metals and silicates at high pressure, an important factor during the formation of the Earth's core and for the present-day consequences of core–mantle interactions.

REFLECTION AND OUTLOOK

Over the last several decades, there has been widespread concern that mineralogy is a dying science. On retirement, traditional 'mineralogists' may have been replaced by people labelled environmental scientists, atmospheric scientists, oceanographers, and so on. In many university curricula, mineralogy courses have been reduced in number or eliminated. We believe that these changes have less to do with the science of mineralogy and more to do with breaking down barriers between subfields. Mineralogy always has been, and always will be, the foundation of all Earth and planetary sciences, as emphasized in the above, very brief, historical perspective. How we study minerals, and how that knowledge is applied, will change, as it must in any healthily evolving field of study. But, the one clear message to take from this survey is that mineralogy has a distinguished and remarkable past and a vibrant and even more dynamic future.

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