THE GOLDEN AGE OF MINERALOGY: REFLECTIONS BY IMA MEDALISTS

International Mineralogical Association

DOI: 10.2138/gselements.18.3.147

The International Mineralogical Association (IMA) was officially launched at its first general meeting in Madrid, in April of 1958. Electron-microprobe analysis had then just been developed by the French physicist Raimond Castaing, and the first microbeam analyses of geological samples (less than 1 µg in weight!) were about to be published by him in collaboration with the Swedish mineralogist Kurt Fredriksson. Within a decade, further experiments by Castaing and his students would pave the way for secondary-ion mass-spectrometry and electron energy loss spectroscopy, which enabled mineral analysis at the nanoscale. Significantly, these discoveries made in university labs also gave a powerful impetus to the development of a wide range of microbeam instruments. The emergence of synchrotron facilities in the 1970s and the harnessing of laser radiation for quantitative analysis, imaging, and spectroscopy in the 1980s opened new horizons for mineral scientists—particularly, in the areas of poorly crystallized and amorphous materials, phase transitions, extreme environments, and trace-element and isotope measurements—and stimulated interdisciplinary and cross-field research, which firmed up the position of our science in the study of rocks, the Earth's interior, geochemical processes, and the biosphere. Space exploration pushed the frontiers of this research first to our celestial companion and, in the past 15 years, to asteroids and comets. Last but not least, the rapid spread of computer networks and supercomputers in the 1990s to early 2000s helped revolutionize our understanding of minerals in the context of Earth's history and planetary evolution and ushered in the new era of mineral informatics.

Looking at this brief retrospect, one could argue that the last 60 years have been the Golden Age of Mineral Sciences. Indeed, in 1958, the 12 premier mineralogical journals cumulatively published fewer than 400 research papers in English, Russian, German, French, Italian, and Japanese. By comparison, ~600 articles were published in 2021 just on zircon, according to the Web of Science! Today, the Scimago Journal Rank lists 70 periodicals whose titles include the word "mineral," with their scope ranging from bone metabolism to ore processing, and their geography extending from Mexico to China. The number of known minerals has increased from some 1,150 "grandfathered" by the IMA in 1958 to an impressive 5,780 species currently listed on the website of the IMA Commission on New Minerals, Nomenclature and Classification. It truly must have been a tremendous experience working through this Golden Age of discoveries, breakthroughs, and innovation! Have we, as mineral scientists, now approached an intellectual plateau, and what does the future hold? Can our developmental milestones help the younger generation of researchers choose the right career path?

For the present *Perspectives*, we have asked the recipients of the IMA Medal of Excellence (www.ima-mineralogy.org/Medal.htm) to reflect on their personal "Golden Age" experience and share their thoughts on the past, present, and future of mineral sciences. This is the first in a series of two *Perspectives* columns organized by the IMA. Here we feature passages composed by Distinguished Professor Emeritus **Frank C. Hawthorne** (University of Manitoba, Canada) and Professor **Nikolay V. Sobolev** (V.S. Sobolev Institute of Geology and Mineralogy, Russia), the latter of whom sadly passed away earlier this year. This column thus marks some of Prof. Sobolev's final written contributions to the scientific community. The second part of this series will appear in *Elements*' December issue (vol. 18, no. 6), featuring passages written by **Rodney C. Ewing**, **Gordon E. Brown, Jr.**, both of Stanford University, USA, and **Robert M. Hazen** of Carnegie Institution for Science, USA. The IMA Medal was established in 2006 as a lifetime achievement award that recognizes the excellence and impact of one's contribution to knowledge, rather than the length of one's publication list.

Frank C. Hawthorne (IMA Medalist 2009; Distinguished Professor Emeritus, University of Manitoba, Canada)

Traditionally, mineralogy has involved the description of minerals via their properties, chemical composition, and occurrence. Minerals constitute a significant part of the Earth and rocky planets, and most Earth and planetary scientists work on some aspect of minerals and their response to changing conditions. As a result, the justification for doing mineralogy is almost always framed in terms of how useful it is to contiguous disciplines. Mineralogists are rarely funded to look at scientific questions that are fundamental to mineralogy itself. Why do minerals have the chemical formulae that they do? Why do minerals have their particular bond topologies? What are the atomic-scale reasons why minerals are stable over specific ranges of pH, Eh, temperature, pressure, and activities of their various constituents? What are the relations between bond topology and both the enthalpy and entropy of formation? What are the environmental controls on different crystal forms and habits? What mechanistic details control the sequence of crystallization and dissolution of minerals in specific environments? These questions have tended to be ignored in the past because they are intractable to standard theoretical methods and are seen as of no immediate practical use to other branches of science. Moreover, many mineralogists do not seem interested in such matters, perhaps because mineralogy lacks a rigorous way to consider such problems and standard theoretical methods cannot deal with the size, complexity, and disorder of most minerals: e.g., veblenite, $K_2\square_2Na(Fe^{2+}_5Fe^{3+}_4Mn_7\square)Nb_3Ti(Si_2O_7)_2(Si_8O_{22})_2O_6(OH)_{10}(H_2O)_3$ (Cámara et al. 2013).

There has been some recent work directed toward putting mineralogy on a more rigorous basis and attempting to address some of the questions mentioned above. Hawthorne (2015) has provided a bond-topological basis for mineralogy that can address many of these problems. Quantification of the structure hierarchy hypothesis (Hawthorne 2014) and the development of specific structure hierarchies—e.g., borates, sulfates, uranyl oxysalts, tellurium oxycompounds, and silicates—have led to a much greater understanding of the factors affecting the crystallization of hydroxy-hydrated oxysalts and crystallization sequences of such minerals. Mineral evolution (Hazen et al. 2008) focuses attention on large-scale spatial and temporal mineral parageneses from early stellar materials to surficial Earth and planetary environments. The complexity of an atomic arrangement (Krivovichev 2013) has given a quantitative measure of what was hitherto only a qualitative idea, and there is the possibility of relating complexity (Shannon entropy) to questions of mineral diversity (Christy 2018; Krivovichev et al. 2018).

Although the characterization of new minerals is a baseline activity in mineralogy, novel approaches to understanding the chemical compositions, structural arrangements, and behavior of minerals in the spatial, temporal, and thermodynamic diversity of Earth and planetary environments are critical if mineralogy is to advance beyond empirical scientific activity. Significant progress is dependent on younger mineralogists becoming involved in the recent advances mentioned above and developing new rigorous methods to further our understanding of minerals and their behavior at the most basic level.

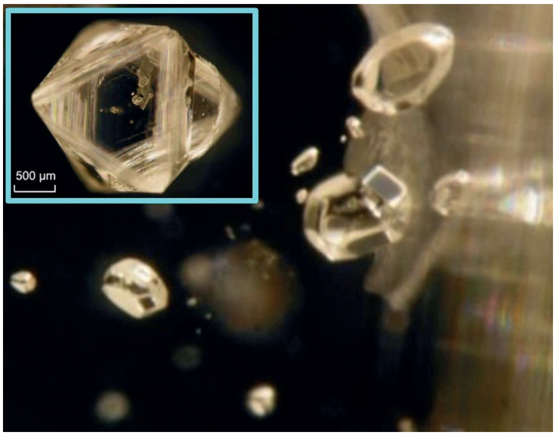
Nikolay V. Sobolev (IMA Medalist 2013; Professor, V.S. Sobolev Institute of Geology and Mineralogy, Novosibirsk, Russia)

Diamond is an exceptional member of the mineral kingdom. It is the hardest mineral with the simplest chemical composition of pure carbon, variable physical properties, and complicated formation conditions in the lithosphere at depths exceeding 120 km. In spite of its intensive study by mineralogists, gemologists, physicists, chemists, and material scientists, producing an enormous number of publications annually, there are many important unknowns that will need to be addressed with future diamond research.

Diamonds occur in rare mantle xenoliths, classified as peridotites and eclogites, some of which contain diamonds in proportions close to those of rock-forming minerals. Systematic studies of minerals coexisting with diamonds in such xenoliths, as well as of minerals and fluids encapsulated in diamond crystals, made it possible to develop a paragenetic classification similar to the one used for crustal igneous rocks. For example, the incorporation of Na in garnets and of K in clinopyroxenes associated with diamonds in peridotitic and eclogitic xenoliths was used to distinguish mantle diamond–pyrope facies from graphite–pyrope facies lacking such features (Sobolev 1977).

The composition of kimberlite indicator minerals was used for paragenetic classification purposes (e.g., garnets representing harzburgite-dunite, lherzolite, and wehrlite parageneses). Further paragenetic refinement is based on the composition of minerals that coexist with diamonds in mantle xenoliths and are present as inclusions in diamonds (FIG. 1), i.e., clinopyroxene-free harzburgite and/or dunite paragenesis of low-Ca, high-Cr pyrope garnets. These developments were of practical importance because the indicator mineral chemistry had widely been used in kimberlite exploration since 1969. Later on, these garnets indicating diamond potential were dubbed "G10". Indeed, the application of the newly developed "mineralogical mapping technique" has been highly successful in the exploration of the Yakutian kimberlite fields in Siberia (especially for the discovery of the Yubileynaya diamondiferous pipe) and has contributed significantly to the discovery of the Arkhangelsk kimberlite province in NW Russia. These examples illustrate the close ties between mineralogy, geology, and mineral deposit research.

Apart from encapsulated crystals, fluid inclusions are quite typical of some diamonds. The significance of hydrocarbons and CO_2 for diamond formation, first postulated 60 years ago (Sobolev 1960), has received much support in recent theoretical and experimental work simulating upper-mantle conditions. Many attempts have now been made to determine the composition of potential fluids, which required cutting-edge analytical equipment. For example, volatile components (including hydrocarbons) in garnet from diamondiferous metamorphic rocks in the Alps have been analyzed by Raman microspectroscopy (Frezzotti 2019). The predominance of higher hydrocarbons (pentane to hexadecane) and their derivatives at low levels of methane were determined by gas-chromatography mass-spectrometry for diamond-, garnet-, and olivine-hosted fluid inclusions in diamondiferous peridotites of the Udachnaya mine in Yakutia (Russia), suggesting that such hydrocarbons are major species in parental mantle fluids (Sobolev et al. 2019). In the first approximation, the diamond-forming medium will likely turn out to be an unusual ultrapotassic-carbonate-chloride-silicate-water-hydrocarbon fluid.



Diamond "spinel-type" twin from the Udachnaya pipe (Siberia) hosting olivine inclusions (MODIFIED FROM SOBOLEV ET AL. 2020).

Elevated K levels in clinopyroxenes, as well as the unusually high Mg content of some Mg–Ca garnets, were essential to the discovery of microdiamond inclusions in garnets and zircon from metamorphic rocks at Kokchetav, Kazakhstan (Sobolev and Shatsky 1990). Accessory zircon occurring in rocks affected by ultrahigh-pressure metamorphism (UHPM) is of particular significance as a perfect and unique container for minerals that are completely altered in the surrounding rock. The high-pressure silica polymorph coesite was found in zircon from white schists of Dora-Maira in the Western Alps, eclogite-hosted gneisses of Dabie Shan (China), and in coesite-diamond and coesite-diopside intergrowths trapped in zircon from the Kokchetav gneisses (Schertl and Sobolev 2013). This research, rooted in earlier work on diamond inclusions, greatly advanced our understanding of UHPM in crustal rocks.

This brief account of recent progress in diamond research is just one illustration of how careful and detailed mineralogical studies of one type of mineral deposit can change the way we think about such seemingly well-understood things as fluids and metamorphism. On a practical side, this academic work helps geologists identify new exploration targets and solid-state scientists design and test new useful materials.

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