

Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology

August 2006
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Early Earth

The Origin of the Earth

Impact Processes on the Early Earth

Earth's Earliest Atmosphere

Antiquity of the Oceans and Continents

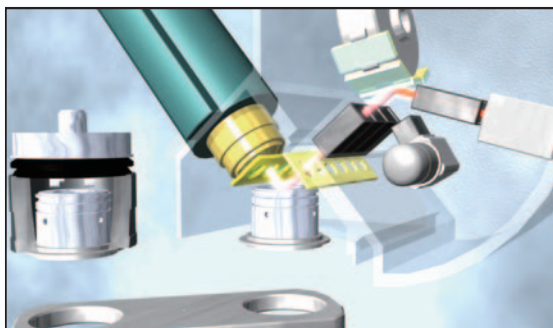
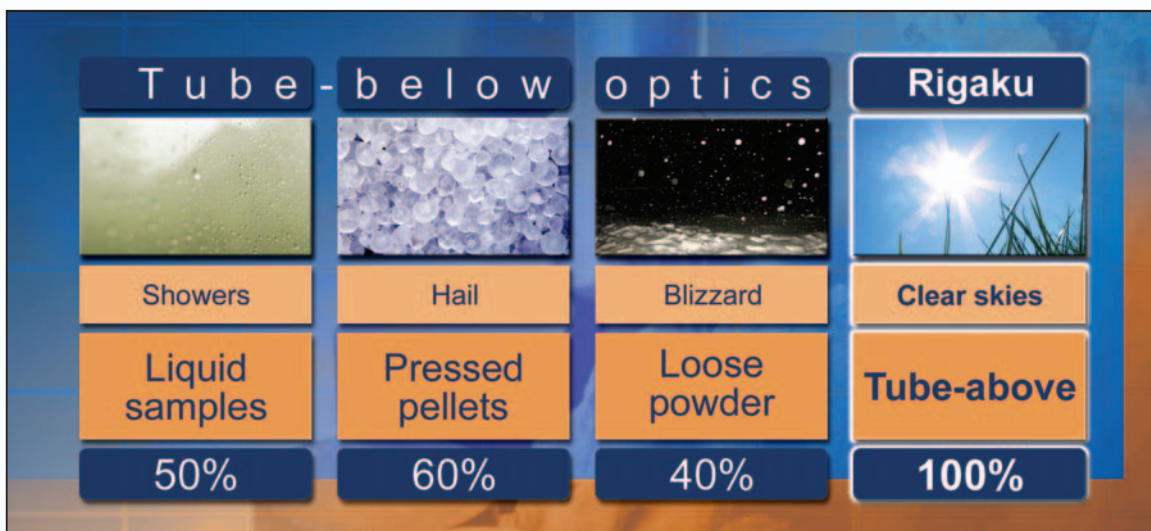
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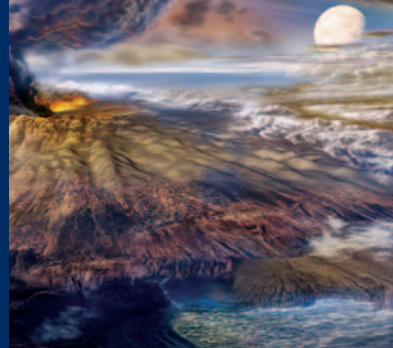
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Elements

An International Magazine of Mineralogy, Geochemistry, and Petrology



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ABOUT THE COVER:
Artist's view of the cool early Earth as it may have appeared at 4.2 Ga. Meteorite impacts were still relatively common on Earth and Moon. The Moon was in closer orbit, and its dark maria had not yet appeared. On Earth, volcanism and other magmatic processes were starting to form granitic rocks and proto-continental crust. Liquid water covered much of Earth, locally altering rocks, and the stage was set for emergence of life.
From Valley JW (2005) A cool early Earth? *Scientific American* October 2005: 40-47, IMAGE COURTESY OF DON DIXON



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The Mineralogical Society of America is composed of individuals interested in mineralogy, crystallography, petrology, and geochemistry. Founded in 1919, the Society promotes, through education and research, the understanding and application of mineralogy by industry, universities, government, and the public. Membership benefits include special subscription rates for *American Mineralogist* as well as other journals, 25% discount on *Reviews in Mineralogy and Geochemistry* series and *Monographs*, *Elements*, reduced registration fees for MSA meetings and short courses, and participation in a society that supports the many facets of mineralogy. For additional information, contact the MSA business office.

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The Société Française de Minéralogie et de Cristallographie, the French mineralogy and crystallography society, was founded

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The International Mineralogical Association, the European Mineralogical Union and the International Association for the Study of Clays are affiliated societies of *Elements*. The affiliated status is reserved for those organizations that serve as an "umbrella" for other groups in the fields of mineralogy, geochemistry and petrology, but that do not themselves have a membership base.



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Vestiges and Prospects



The creation of the Earth – ‘The Creation’ – is a pre-occupation of all the world’s great religions, and Christianity, Islam and Judaism share a common creation story with

its roots in prehistory. The evidence-based, scientific view of the formation of our tiny speck in the cosmos, the theme of this issue of *Elements*, is altogether younger, having evolved over little more than two centuries. It seems a good moment to reflect on the fundamental differences between science and faith, and on the modesty, underlying simplicity and unifying power of the scientific approach.

Central to the scientific view is the understanding that the Earth is enormously old – the concept of ‘deep time’. This was first put on a sound footing by a Scottish farmer whose Edinburgh home was about two miles from my office. James Hutton’s 1788 paper ‘*Theory of the Earth*’ ends with one of the best-known sentences in the history of geology: ‘The result, therefore, of our present enquiry is, that we find no vestige of a beginning, – no prospect of an end’. Hutton’s detractors, ignoring the key word ‘find’, accused him of atheism, because otherwise his sentence seems to imply that there was no creation event, just an unending steady-state. In fact Hutton retained his faith and thought that his observations provided an argument for ‘wisdom and benevolence’ in Nature. This issue of *Elements* is about the vestiges of the Earth’s origins that modern work has unearthed; ‘vestiges’ is still a hauntingly appropriate word.

Hutton first communicated his ideas in the form of an extended abstract, read to the Royal Society of Edinburgh by his friend Joseph Black (he of specific and latent heat, and discoverer of carbon dioxide) in 1785. Hutton’s first two paragraphs are beautiful and encapsulate to perfection the way in which many Earth scientists continue to work to this day:

‘The purpose of this Dissertation is to form some estimate with regard to the time the globe of this Earth has existed, as a world maintaining plants and animals; to reason with respect to the changes which the earth has undergone; and to see how far an end or termination to this system of things may be perceived, from the consideration of that which has already come to pass.

As it is not in human record, but in natural history, that we are to look for the means of ascertaining what has already been, it is here proposed to examine the appearances of the earth, in order to be informed of operations which have been transacted in time past. It is thus that, from principles of natural philosophy, we may arrive at some knowledge of order and system in the oeconomy of this

globe, and may form a rational opinion with regard to the course of nature, or to events which are in time to happen.’

Hutton’s concern with the end of the world seems strange to us now, but we must view his work in the context of his time. Archbishop Ussher had in 1658 published his oft-quoted estimate, based on arcane interpretation of middle-eastern calendars and holy writings, that Earth was created on October 23rd, 4004 BC. Ussher’s estimate was included in the English Bible, and was accepted as Scripture. In this context Hutton’s second paragraph represents a great leap from a view based on faith to one based on evidence and reason, in other words, on science. Hutton deduced that the Earth must be much older than 6000 years because he saw great thicknesses of sedimentary rocks resting on older, harder rocks that had been tilted, producing unconformities, a thrilling glimpse of ‘ancient worlds’. High mountains were eroded over long periods to provide new sedimentary rocks. His inability to quantify the rates of these processes led him to write, in one of the final paragraphs of his abstract ‘that, with respect to human observation, this world has neither a beginning nor an end’.

Hutton has here put his finger on one of the defining characteristics of the scientific method. If we cannot solve a particular aspect of a problem, we say so, and leave it to future generations to make the key observations. This editorial will be read by scientists of many faiths and by humanists like myself, but we will all agree on the essence of science: the endless questioning of received wisdom; the utter honesty, so that we state not just the precision and accuracy of our measurements but point to both the strengths and weaknesses of our arguments; we draw attention to things we do not understand and have an attitude of mind that admits to uncertainty; if we have to, we say, publicly, ‘I was wrong’. And, above all, we appreciate that all scientific theories begin as myths and gain the status of theory only when they have withstood repeated attempts at falsification.

Science has grown from these simple principles through the free-thinking of pioneers like Hutton, who maintained his faith but discarded the literal interpretation of the written word. In the face of overwhelming evidence that the scientific method works for the good of mankind, religious fundamentalists of many faiths appear unable to embrace the simplicity and honesty of science. Some of these extremists hold high office in countries around the world. Inter-faith warfare is one of the central causes of avoidable horrors in the modern world. As scientists we should take every opportunity to set out the universal principles that give science its power.

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BEHIND THE SCENES AT *ELEMENTS*: HOW WE DEVELOP THEMATIC ISSUES

What goes on behind the scenes to produce an issue of *Elements*? Should anyone besides the editors care? Even if you have never considered being a guest editor of an issue of *Elements*, or even if you are not the least bit curious about how all this works, we encourage you to read on. The first thing to remember is that *Elements* belongs to each one of us as individual scientists. Without this simple yet powerful principle, this magazine would simply not work. *Elements* does not belong to principal editors or societies or to the disciplines that they represent. As important as these societies are, and the disciplines represented therein, it is absolutely vital that *Elements* transcend them. What drives *Elements* is the continuous and unending scientific creativity of each and every one of us. Science is what scientists do, and the goal of *Elements* is to represent, indeed to project, what we do as mineralogists, geochemists, and petrologists, for each other and for the rest of the world. With this in mind, the process of creating an issue of *Elements* becomes abundantly clear. We (the three principal editors and the managing editor) are happy to receive proposals for thematic issues at any time. One simply needs to go to www.elementsmagazine.org and click on "Forms" to get instructions on how to submit a proposal. Once submitted by a potential guest editor, the editors will consider the proposal and often ask for revisions if the proposal has potential. We will also ask for the author list to be firmed up. If the proposal is eventually accepted, it will be slotted in the *Elements* production schedule such that ample time is allowed for proper development of the issue and a balance of subject diversity in the annual line-up is maintained. If the accepted proposal is particularly timely for whatever reason, this can also be

taken into account in the scheduling. The next critical step is for the guest editor, the principal editor assigned to be in charge of that issue, and the managing editor to have an extended conference call, during which the processes of producing the issue are reviewed in detail. Authors are contacted, the writing begins and finishes, and the reviewing, revising, and final production proceeds under the watchful eyes of several of us over the ensuing months. The final result will be another issue that represents all of us well. We could produce nothing less.

Editorial Meeting

The editors met in Baltimore, USA, on May 26, 2006. The main items on our agenda were choosing the incoming principal editor for 2007 and completing the line-up of thematic content for 2007. We are now in the enviable position of receiving more proposals than we can accommodate. This will ensure the vitality and the relevance of *Elements*. We are now booking issues for 2008 and welcome proposals. Some people have expressed concern that we might run out of topics. We look blankly because we see exactly the opposite happening.

2007 Principal Editor

Susan Stipp of the University of Copenhagen, Denmark, has just accepted our invitation to replace Mike Hochella as principal editor for a three-year term, from 2007 through 2009. We are delighted that Susan will join the *Elements* team. An article about Susan and her background will appear in the first issue of 2007.

Welcome to AIPEA

We welcome the International Association for the Study of Clays (Association internationale pour l'étude des argiles) as an affiliated society, thus joining the International Mineralogical Association and the European Mineralogical Union. President David Bish introduced AIPEA in the last issue (page 188). The affiliated status is reserved for umbrella organizations. In this

case, AIPEA members are the clay societies of the world. We look forward to reading their news.

New Features

"Publications Forum" was quietly introduced in volume 1, issue 4, with two articles on open access. Since then, we have published on GeoScienceWorld and on copyright issues. Other articles in preparation will deal with impact factors, the Fog index, references, etc. If there is a topic you would like us to discuss, please send us an e-mail.

In this issue, we give a voice to students by launching a "Students Page," and we hope it will become a regular feature of *Elements*. Graduate and undergraduate students: if you want to raise issues of concern or share an important experience, the space is yours. This page will also be the ideal place to advertise grant and scholarship application deadlines.

Elements is Yours

Elements is your magazine. Let us know what else you would like to read in it. We welcome letters to the editors concerning the editorials or any other topic you think would interest the mineralogy-geochemistry-petrology community. We welcome contributions to "Parting Shots," in which we publish spectacular or interesting photographs. And we rely on members to bring to our attention "People in the News."

Thanks

We thank John Valley, guest editor, and the five authors who contributed papers to this issue; the society news editors of the participating societies; the other contributors to this issue: Alain Baronnet, Dan Kyle, Crystal Mann, Kaspar Mossman, and Anthony J. Naldrett.

Mike Hochella, Ian Parsons, Bruce Watson, and Pierrette Tremblay

Cont'd from page 195

Footnote to Editorial

I was surprised to learn, while researching for this editorial, that slightly before Ussher, in 1644, Dr. John Lightfoot, Vice-Chancellor of the University of Cambridge, had deduced, by exhaustive study of the Scriptures, that 'heaven and earth, centre and circumference, were created all together, in the same instant, and clouds full of water,' and that 'this work took place and man was created by the Trinity on October 23, 4004 BC, at nine o'clock in the morning.' A remarkable convergence, and what enviable precision! The 9 am is often wrongly ascribed to Ussher.

Ian Parsons

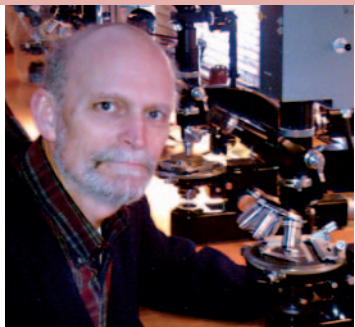
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EDITOR'S NOTE: Dan Kile contacted us over a year ago with an offer to write an article on the importance of optical microscopy as an analytical technique. In light of the extensive discussion of the topic on the MSA listserv recently, Dan's thoughts seem very timely.

Polarized Light Microscopy in Geoscience Education: Relevant or Obsolete?



For more than 100 years, optical mineralogy has been a staple of the geosciences curriculum. In the past, it was the *only* means of identification for certain minerals, and a high level of proficiency was required. At present, however, most universities have reduced the optical mineralogy component of the program, either by eliminating it entirely, or by integrating it with other courses. Consequently,

microscopy instruction has evolved towards "cookbook" styles of teaching, and many students can graduate with a geosciences degree without ever having used a polarized light microscope (PLM).

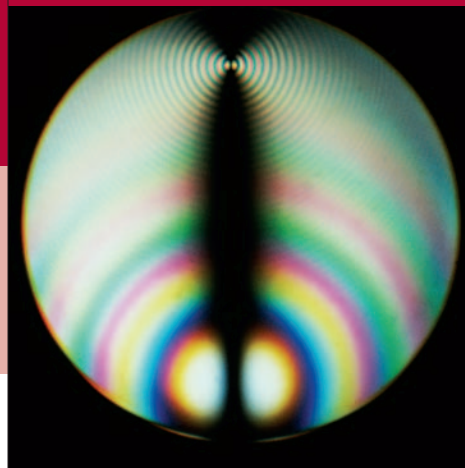
The reasons for this decline are varied. First, X-ray diffraction (XRD), scanning electron microscopy (SEM), and electron microprobe methods have largely supplanted (not replaced!) optical methods. This trend parallels an increasing reliance on computers to provide ready answers for a given set of analytical data. A number of factors have conspired to create this situation. In the case of XRD, for example, a technician can be trained to prepare samples, operate the instrument, and generate a list of mineral phases present in about an hour. In contrast, well-grounded training in optical mineralogy takes a substantial investment of time and considerable practice. Second, and perhaps most importantly, an evolving curriculum (whereby new course requirements such as remote sensing, geophysics, aqueous geochemistry, and fluid flow have been added to accommodate a changing science) mandates that something has to give in the degree program. Third and less obvious is the diminished likelihood of competing successfully for NSF funding for studies based on a methodology deemed by some to be anachronistic.

As a result, the capability for PLM work in both collegiate and industrial sectors is drastically reduced. With each retirement of a classically trained crystallographer or petrologist, the knowledge base of mineral optics declines. One wonders if we will reach a point of no return, with no one able to pass on skills long since forgotten. Because teachers have a propensity to teach as they have been taught, new faculty will be less likely to incorporate optical methods into a curriculum amidst the press of other demands. Moreover, in a self-fulfilling prophecy, decreased demand for PLM equipment is leading to a decline in the commercial availability of optical apparatus and teaching aids.

I would argue that despite the introduction of microbeam and XRD technology, polarized light microscopy remains a versatile, efficient, and necessary technique for the identification of crystalline materials, not only in the geological sciences, but also in materials sciences, forensics, pharmaceuticals, environmental sciences, archeology, and chemistry.

Why is PLM still a critical component of an undergraduate science degree?

- PLM provides a range of sample information that is not equaled by other methods of analysis. Pleochroism, birefringence, dispersion, crystal textures, intergrowths, polymorphic phases, and dispersion are among the characteristics that are best assessed by PLM.



An unusual interference figure of a twinned diopside crystal, from an oriented section made in ca. 1900 by the firm Steeg and Reuter. Such preparations, used to illustrate properties of retardation and birefringence as related to isochromes, were commonly used in earlier years and are now seldom seen.

- Given the great expense of a \$200,000 X-ray diffractometer compared to a \$10,000 polarizing light microscope, it is apparent that a PLM is far more cost effective. Moreover, most graduates out in the working world will find that there is no microprobe down the corridor, and contracting analytical work for XRD and microbeam analysis can be both expensive and time consuming. Conversely, training in PLM will permit graduates to expeditiously and economically answer many real-world problems.
- Training in microscopy hones the often-overlooked yet important skills of careful observation, data recording, and three-dimensional visualization; combined with careful reasoning it engenders critical abilities in cognitive learning that few other disciplines can provide. Computer analysis cannot replace human observation and judgment.
- Few other subjects offer the integration of so many fields of science as does optical mineralogy, e.g. physics, chemistry, mineralogy, and geology.

One must ask what will be the consequences if PLM and mineral optics are shortchanged in the curriculum? The use of immersion methods, universal stage, and rotating compensators are becoming lost arts, and the level of understanding of mineralogically important topics, such as dispersion and its relation to crystal symmetry, is declining each year. Immersion preparations can be especially important. For example, they allow extraction of far more information from a given sample than can be seen in a standard thin section, and they afford, by virtue of thicker grains, a much better visualization, and hence understanding, of optical properties as related to crystallographic orientation. Yet few colleges offer this instruction, largely because such knowledge has not been passed on to the present generation of instructors. The universal stage provides unique capabilities not replicated by any other instrument, but the ability to use it will soon fade with the gradual disappearance of the equipment and the knowledge of its operation.

With the elimination of a full-semester course in optical mineralogy at most institutions, many approaches have integrated optics with classes in mineralogy, petrology, or instrumental analysis. Is this trend in the best interests of the students and the science? In my opinion, an abbreviated format does not permit introduction of important concepts such as the indicatrix, conoscopy, relief, anomalous interference colors, dispersion, or immersion methods. Moreover, simple cookbook methods (e.g. identifying a mineral in thin section as quartz because "it looks like quartz") are mostly inadequate; without a firm understanding of the fundamentals, mistakes are inevitable. Competency can only be attained from a thorough course of instruction; short courses, video instruction, and on-line classes, while serving an important purpose, are no substitute for rigorous hands-on training in the presence of an instructor. After all, how comfortable would one be flying in a 747 piloted by an individual whose training was limited to reading an owner's manual and practice on a flight simulator?

Cont'd on page 198

Meet the Authors



Alex N. Halliday was recently appointed to the Chair of Geochemistry at the University of Oxford where he moved from ETH Zurich. In the past he has engaged in a broad range of isotope geochemistry

research, in particular in silicic magmatism, crustal fluid flow, lower crustal processes and mantle geochemistry. More recently however his interests have broadened to the origin and early differentiation of the terrestrial planets and large-scale surface processes such as ocean circulation. An underlying research theme has been the development and use of new isotopic methods. He is involved in a wide range of scientific organizations.



Christian Koeberl is a professor of geo- and cosmochemistry at the Department of Geological Sciences, University of Vienna, Austria. He studied chemistry and astronomy at the Technical University

of Vienna and the universities of Vienna and Graz, where he finished his PhD in 1983 in cosmochemistry. In the 1980s and 1990s he was a visiting scientist at the Lunar and Planetary Institute, Houston, and at the Carnegie Institution of Washington. For the past 20 years the study of impact craters and processes has been one of his main research

interests. He has published about 280 peer-reviewed papers and written or edited nine books.



Allen Nutman's interest in early Archean geology has spanned three decades, starting with his late 1970s PhD work (at the University of Exeter, UK) on rocks of Archean age in West Greenland. Since the late

1980s he has been based primarily at the Australian National University, where he works at the SHRIMP facility in the Research School of Earth Sciences. He has worked extensively on the early Archean rocks of West Greenland and Western Australia, and has also undertaken research on similarly old rocks from Labrador and China. His approach is to integrate field observations, mapping and geochemistry with zircon geochronology.



J. William Schopf is director of the Center for the Study of Evolution and the Origin of Life and member of the Department of Earth and Space Sciences at the University of California–Los Angeles. He

received his undergraduate training in geology at Oberlin College and his PhD degree in biology from Harvard University. Author or editor of three prize-winning volumes on the

early history of life, his prime research interest, Professor Schopf is a member of the National Academy of Sciences, the American Philosophical Society, and the American Academy of Arts and Sciences. Recipient of numerous medals and awards, he has twice been awarded a Guggenheim Fellowship.



John W. Valley, Charles R. Van Hise Professor of Geology at the University of Wisconsin–Madison, received his AB from Dartmouth College and PhD from the University of Michigan (1980). He main-

tains a mass spectrometer lab for stable isotope geochemistry and in 2005 installed a CAMECA IMS-1280 ion microprobe for in situ analysis of ultrasmall samples. His interests in the early Earth and in the thermal and fluid history of mountain belts span 30 years. Currently, he is president of the Mineralogical Society of America.



Kevin Zahnle is research scientist at NASA's Ames Research Center located in California's Silicon Valley. He attended McGill University and the University of Michigan. Then he moved to California. He has studied

atmospheric chemistry, atmospheric escape processes, and asteroid and comet impacts on planets and satellites. Zahnle has contributed film reviews to *Nature* and has appeared on TV as Godzilla in NHK's "Miracle Planet II."

WATCH FOR OUR NEXT ISSUE

Glasses and Melts: Linking Geochemistry and Materials Science

GUEST EDITORS: Grant S. Henderson (University of Toronto), Georges Calas (IMPMC and Université de Paris 6 et 7), and Jonathan F. Stebbins (Stanford University)

Geological interest in studying melts stems from early recognition that melts play a fundamental role in determining the physical and chemical behaviour of magmas. However, due to the inherent difficulties associated with working at high temperatures, much of the geological research over the last 30 years has used quenched melts or glasses as proxies for melts themselves. The assumption that the structure of the glass resembles that of the melt has been found to be good, at least at the temperature where the melt transforms to a glass. We will review how glass research has contributed to our understanding of melt structure and the behaviour of magmas. Emphasis is placed on elucidating the links between our knowledge of the atomic structure of melts and the macroscopic behaviour of magmas such as rheology, diffusion, trace element partitioning and redox behaviour.



The structure of silicate glasses and melts

Grant S. Henderson, Georges Calas,
Jonathan F. Stebbins

Geochemical aspects of melts: Volatiles and redox behaviour

Harald Behrens (University of Hannover)

Transport properties of magmas: Diffusion and rheology

Donald B. Dingwell (University of Munich)

Dynamics of magmatic systems

Bruce D. Marsh (Johns Hopkins University)

Geological glasses as Earth and industrial materials

Laurence Galois (Institut de minéralogie
et de physique des milieux condensés
and Université de Paris 6 et 7)

Cont'd from page 197

Cutting back the role of optical mineralogy in the geosciences curriculum needs to be carefully reconsidered—especially by those departments contemplating elimination of the program altogether. Given the present state of affairs, however, it is unlikely that optical mineralogy will be reinstated to a full semester course of instruction. The best alternative is to integrate it as much as possible with the entire range of mineralogy, petrology, and analytical courses, rather than simply relegating optical work to a few lectures and laboratory sessions. This approach might be the best means of conveying the versatility of this powerful technique to future generations of geoscientists.

Daniel Kile
Scientist Emeritus,
U.S. Geological Survey

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Early Earth

John W. Valley¹

The earliest Earth was a strange inhospitable world, yet transitions to a more familiar planet occurred within the first billion years. In spite of sparse preservation of an ambiguous rock record, recent studies refine the nature and timing of key events. This issue reviews current knowledge of the age of the Earth, massive early meteorite impacts, the early atmosphere and hydrosphere, the rock record, and the first life.

KEYWORDS: Hadean, early Earth, geochronology, meteorites, atmosphere, oceans, zircon, life

The surface of the Earth was cruelly inhospitable at the time of its birth about 4.5 billion years ago. Red-hot oceans of magma, massive meteorite strikes, and a dense atmosphere elicit the name “Hadean” for this earliest time period (Fig. 1). Clearly such extreme conditions had to subside before continents, oceans, and life could survive on Earth (see cover). So when did the Hadean end? Evidence from rocks has been used to place this boundary at 3.8 Ga (billion years before present), the age of the oldest known water-laid sediments. The fossil record of life begins even later at 3.5 Ga, although low carbon isotope ratios ($^{13}\text{C}/^{12}\text{C}$) in carbonaceous matter from Isua, Greenland, suggest that life got its start before 3.8 Ga. Recently, isolated detrital zircons as old as 4.4 Ga from localities in Western Australia have provided evidence that the Hadean was shorter than previously thought. While extreme opinions exist on both sides, a moderate position is that small continent-like land masses existed by 4.4 Ga and oceans hospitable to life existed at 4.2 Ga (Fig. 2). In this interpretation, the Hadean was over by 4.2 Ga and possibly earlier. Life may have emerged quickly in the post-Hadean oceans—there is no direct evidence. If life did exist before 3.8 Ga, it was subjected to intense meteorite bombardment and possibly extinction.

The age of the Earth has been debated for centuries. Accurate estimates based on the radioactive decay of uranium to lead were first made with improved mass spectrometers following the Second World War. In the second article of this issue, “The Origin of the Earth—What’s New?,” Alex Halliday describes the precise chronology of events that has been established from the many isotope systems now available for determining the age of rocks. A traditional type of geochronometer uses parent–daughter isotope pairs with long half-lives for radioactive decay (i.e. $^{238}\text{U}\rightarrow^{206}\text{Pb}$, half-life of 4468 million years, Myr); this method has established the geological time scale in years before the present. A more recently exploited technique uses isotope pairs with short

half-lives (i.e. $^{26}\text{Al}\rightarrow^{26}\text{Mg}$, half-life of 0.73 Myr), in which the parent isotope is now extinct; ages are measured relative to the formation of the solar system. Thus, we can count forward or backward. This situation leads to the irony that the occurrence of some events is well established during the first 50 million years, but the next 500 Myr period from which no known rocks have been preserved (some-

times called the geological “Dark Ages”) is poorly understood, and the following 4000 Myr of Earth history are increasingly well documented. No single date can be assigned for the formation of the Earth, which accreted over a period of time from swirling dust, rocks, and planetesimals (~1 km diameter bodies) in the solar nebula. However, the age of the solar system is known with extreme precision from studies of meteorites to be 4.567 Ga. The Earth grew rapidly after this start, and calculations show that it attained most of its mass within 10 million years. Other events within the first 50 Myr include the gravitational settling of iron to form the metal core of the Earth and the



FIGURE 1 Artist’s view of the Hadean Earth from the 1952 cover of *Life* magazine and numerous subsequent textbooks. While such energetic conditions prevailed during the first 50 million years after the Earth formed, recent studies suggest that a more clement climate and a cool early Earth became the norm within 200–300 Myr (see cover illustration).

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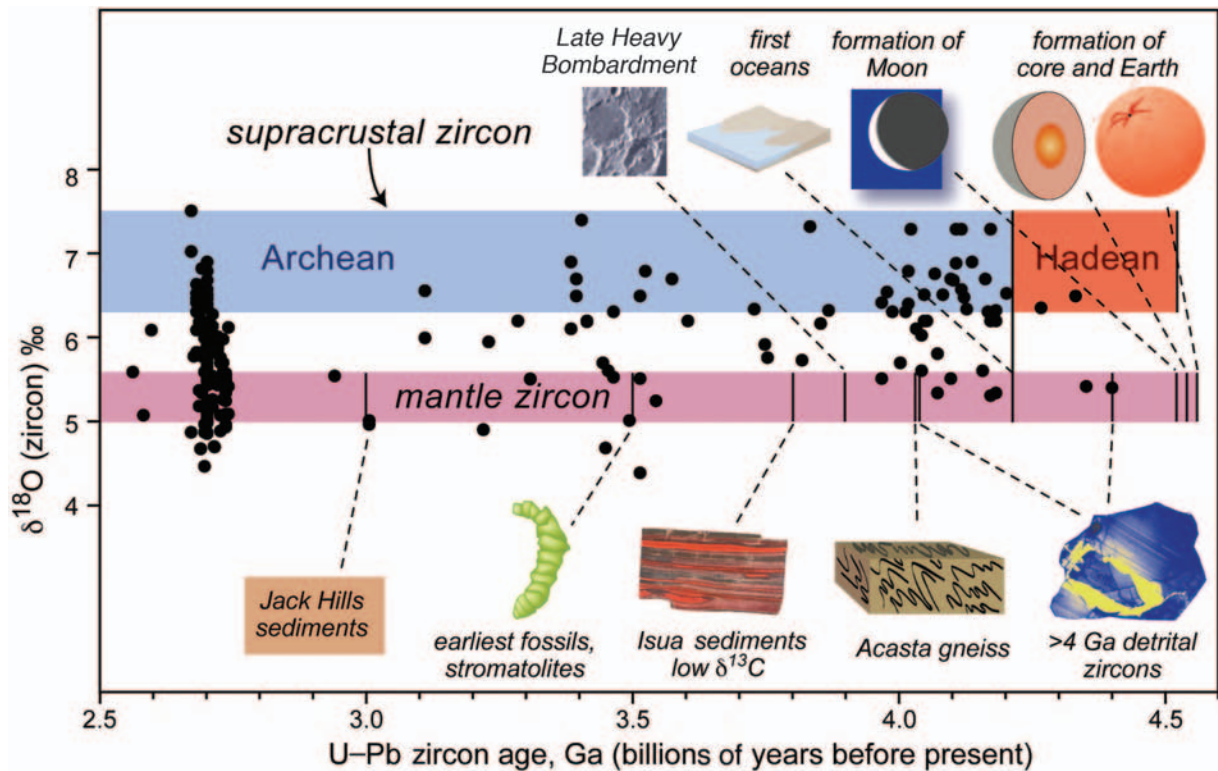


FIGURE 2 Timeline for the first billion years of Earth history. Key events are shown along with oxygen isotope ratios ($\delta^{18}\text{O}$) of zircons from igneous rocks and their U-Pb age. Primitive rocks in equilibrium with the Earth's mantle have average $\delta^{18}\text{O}$ of 5.3‰ (Valley et al. 2005). Higher "supracrustal" values (6.5 to 7.5) result from processes that require liquid water on the surface of the Earth. Thus, the end of the Hadean was at or before 4.2 Ga.

formation of the Moon when a planet struck the Earth—a terrestrial impact so violent that both bodies melted and partly vaporized.

The Earth continues to grow today, with 10^6 – 10^7 kg of meteorites added each year, including thousands that are fist-size or larger. This is a trace contribution to the mass of the Earth and largely goes unnoticed. In "Impact Processes on the Early Earth," Christian Koeberl portrays a far more violent early history of meteorite impacts and cratering. During accretion, the mass flux of material added to the Earth was extreme, but it dropped five to ten orders of magnitude during the first 100 Myr and has continued to decline ever since, except during a resurgence called the Late Heavy Bombardment at ~3.85 Ga. While no evidence of impacts during the first billion years is preserved on Earth, largely due to tectonic reworking, nearly 200 younger impacts are known, the oldest being the Vredefort Dome (2023 Ma) in South Africa. Only the ancient surfaces of the Moon and Mars have provided evidence of the earlier ravages.

The early atmosphere was thick, hot, and poisonous. Carbonic "greenhouse" gases prevailed, and before 2.3 Ga, levels of oxygen were too low to sustain aerobic life. In "Earth's Earliest Atmosphere," Kevin Zahnle traces the evolution from a Hadean atmosphere to more clement conditions that could nourish life. Early on, not only were the oceans vaporized by energetic impacts, so was the silicate surface of the Earth, followed by magmatic "rain" and "hailstones" of rock! However, the faint young Sun was 30% weaker than today, and cooling of Earth's surface was surprisingly rapid. Calculations suggest that post-Hadean temperatures subsided enough to precipitate steam as ocean water and, depending on poorly known levels of atmospheric insulation, to freeze water. Zahnle argues that the cool early Earth was actually a snowball with pools of water localized around geothermal vents or at impact sites. These changing conditions could have spurred the emergence of life.

Rocks at least 2.5 billion years old are found on every continent and are relatively common (FIG. 3). However, most of the more ancient rocks have been destroyed or reworked beyond recognition by the Earth's tectonic processes. Only a handful of small localities are known to be older than 3.6 Ga. In "Antiquity of the Oceans and Continents," Allen Nutman reviews studies of these key areas, with emphasis on Isua, Greenland, the most diverse early terrane. In spite of moderate metamorphism, ~3.8 Ga rocks from Isua preserve evidence of plate tectonics, oceans, and perhaps life. The only known older rocks are gneisses from Acasta, Canada, at 4.0 Ga. The only record of rocks older than this comes from isolated crystals of the mineral zircon from Western Australia that are as old as 4.4 Ga.

Zircons are exceptionally robust and retentive. The most ancient grains were removed from unknown parent rocks, transported as wind-blown dust and river mud, and deposited as detrital grains in sedimentary rocks. They carry chemical clues to their origin in the form of mineral inclusions, trace elements, growth zoning, and isotopes of uranium, lead, oxygen, and hafnium (see "Zircons Are Forever": www.geology.wisc.edu/zircon/zircon_home.html). The study of these tiny time capsules requires the use of advanced instruments, including large secondary-ion mass spectrometers called ion microprobes, which measure the age (U-Pb) and oxygen isotope ratio in 10–20 μm domains. These characteristics can be correlated with other features in the 100–300 μm crystals (FIG. 4). The existence of zircons as old as 4.4 Ga indicates that small amounts of granitic (sensu lato) proto-continent existed at that time. Without such buoyant crust, the zircon-bearing rocks would have

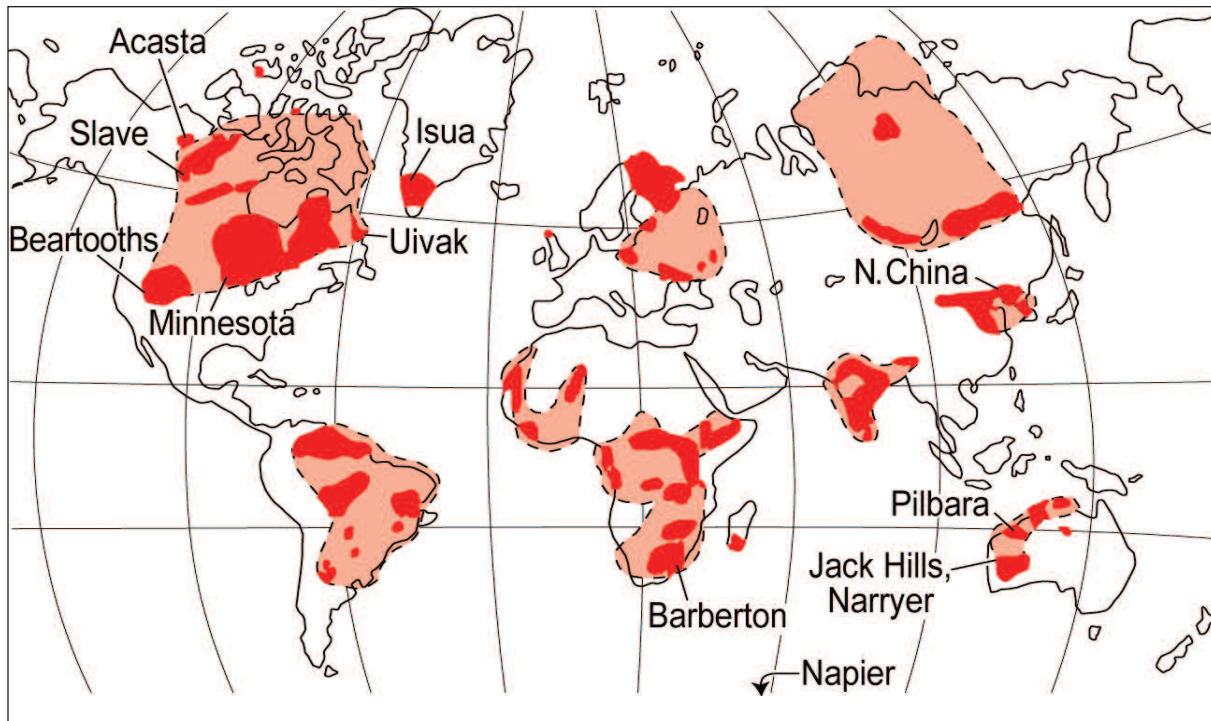


FIGURE 3 Map showing known (dark orange) and suspected (light orange) areas of rocks older than 2.5 billion years. Areas with >3.6 Ga rocks or zircons are labeled by name.

sunk into the mantle and been destroyed. High oxygen isotope ratios in some early zircons suggest that liquid water oceans existed at 4.2 Ga (Fig. 2). Evidence from Ti and Hf has been interpreted as indicating even earlier granites (*sensu stricto*) and that plate tectonics was operating, but the uniqueness of these interpretations is debated (Harrison et al. 2006; Valley et al. 2006).

The oldest-known fossil evidence for life, along with appropriate geochemical signatures, is found in ~3.5 Ga rocks, but this does not necessarily date the emergence of life. If

the first life was at 3.5 Ga, that would suggest that it was delayed by 700 million years after the end of the Hadean. In “The First Billion Years: When Did Life Emerge?” William Schopf discusses the evidence for life found in rocks from the oldest localities. It appears that one-celled organisms were diversified, flourishing, and relatively common by ~3.5 Ga, indicating that the first life came much earlier. If the carbon isotope record in metamorphic rocks is correct, then the emergence of life was before 3.8 Ga. In fact, all of the essential ingredients for life were assembled on Earth as soon as near-surface waters cooled enough for DNA to be stable (~4.2 Ga). If life emerged on Earth or was delivered from space at this time, its main challenge would have been possible annihilation during the Late Heavy Bombardment (~3.85 Ga). Survival chances would have been enhanced if primitive microbes, like archaea, were

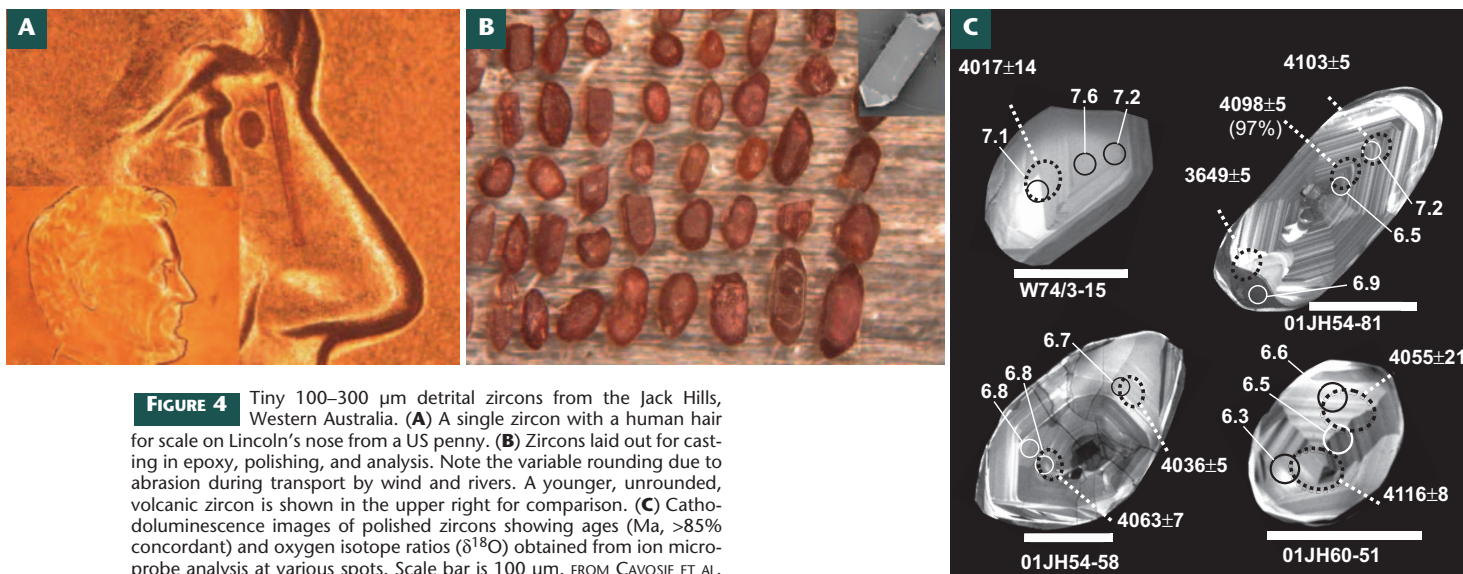


FIGURE 4 Tiny 100–300 μm detrital zircons from the Jack Hills, Western Australia. (A) A single zircon with a human hair for scale on Lincoln’s nose from a US penny. (B) Zircons laid out for casting in epoxy, polishing, and analysis. Note the variable rounding due to abrasion during transport by wind and rivers. A younger, unrounded, volcanic zircon is shown in the upper right for comparison. (C) Cathodoluminescence images of polished zircons showing ages (Ma, >85% concordant) and oxygen isotope ratios ($\delta^{18}\text{O}$) obtained from ion microprobe analysis at various spots. Scale bar is 100 μm. FROM CAVOSIE ET AL. 2005

capable of subsisting underground in the absence of sunlight. Alternatively, the earliest life on Earth may have evolved and become extinct many times before 3.85 Ga, and the present inhabitants of Earth may be descended from the first continuously successful life, but not the first life.

Taken together, these articles summarize a new understanding of the first one billion years of history of our planet and portray its evolution from highly energetic to clement. This is a rapidly emerging field of study that will aid interpretation of other planets and the origin of life, inside the solar system and possibly beyond.

ACKNOWLEDGMENTS

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article. Pierrette Tremblay is especially thanked for her tireless contributions to all aspects of each issue of *Elements*. The author's research is funded by DOE and NSF. ■

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GLOSSARY

Archaea – A recently recognized domain of prokaryotic life. Single-celled organisms, similar in structure to bacteria, but different in metabolism and genotype. They include methanogens and hyperthermophiles that may be similar to the first life.

Archean – Precambrian Eon older than 2.5 Ga and younger than the Hadean

Banded iron formation (BIF) – Layered rock composed of centimeter-scale bands of quartz and iron oxide precipitated from ocean water. The earliest known BIFs formed at 3.8 Ga, whereas the largest BIFs formed between 2.5 and 1.8 Ga, at the same time as the rise of atmospheric oxygen.

Carbon isotopes – The ratios of the stable isotopes of carbon ($^{13}\text{C}/^{12}\text{C}$) are normalized to a marine carbonate standard and expressed as $\delta^{13}\text{C}$ in per mil (‰). Low $^{13}\text{C}/^{12}\text{C}$ results from metabolism and is commonly cited as evidence for biogenicity. Questions arise in ancient rocks regarding the source of carbon, its preservation, and abiogenic reactions.

Cathodoluminescence (CL) – Light emitted by minerals during electron bombardment. Commonly viewed with an electron microscope. CL imaging of zircons can detect growth zoning, inherited cores, and damaged domains.

Hadean – Geological time before the Archean Eon, ~4.5 to 4.2 Ga

Ga – Billions of years before the present

Giant Impact Theory – Widely accepted hypothesis that the Moon was formed when the Earth was struck by a Mars-size planet at ~4.5 Ga

Late Heavy Bombardment (LHB) – Event characterized by a sharp increase in the size and number of meteorites striking the Earth and other bodies in the inner solar system; proposed to have occurred at ~3.85 Ga

Lithophile – Refers to elements that concentrate in silicate minerals and melts and are more abundant in the Earth's crust than in its mantle and core

Ma – Millions of years before the present

Magma ocean – Worldwide ocean of molten rock, initially at the Earth's surface during accretion but later covered by newly formed crust; may have been hundreds of kilometers deep in the Hadean

Oxygen isotopes – The ratios of the most common stable isotopes of oxygen ($^{18}\text{O}/^{16}\text{O}$) are normalized to an ocean water standard and expressed as $\delta^{18}\text{O}$ in per mil (‰). Fractionations are generally mass dependent and used to determine the temperature of geological events. The ratios of $^{17}\text{O}/^{16}\text{O}$ are measured in rocks from extraterrestrial bodies and sometimes Earth to study mass-independent processes.

Planetesimals – Small kilometer-scale rock bodies orbiting the young Sun

Radioisotopes – Isotopes that undergo radioactive decay. The parent–daughter isotope ratio and half-life can be used to determine the age of a rock.

Siderophile – Refers to elements that concentrate in metal and are more abundant in the Earth's core than in its outer parts

SIMS, secondary-ion mass spectrometer – Also called the ion microprobe, an analytical instrument capable of dating zircons and measuring isotope ratios from microscopic spots (typically 10–20 μm) in individual crystals using a highly focused ion beam

Stromatolite – Typically, a finely laminated sedimentary feature formed in shallow water by photosynthetic microbial communities

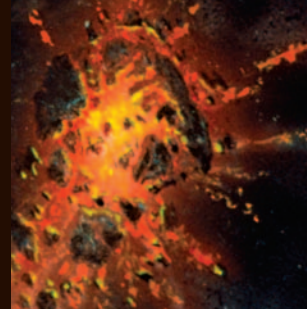
TIMS, thermal-ionization mass spectrometer – An analytical instrument most often used for U–Pb geochronology of single zircons and larger samples. Since precision increases with sample size, ages may be more precise than those obtained with the ion microprobe; however, the ability to analyze zoned or heterogeneous zircons is lost.

Tonalite – Granitic plutonic rock with dominant quartz (>20%) and plagioclase [Plagioclase/(Alkali feldspar + Plagioclase) >90%]

Zircon – Common trace mineral (ZrSiO_4) that is highly resistant to mechanical and chemical alteration. It yields the most reliable estimates of the U–Pb age and oxygen isotope ratio for ancient rocks. In situ analysis by ion microprobe can resolve the ages of inherited cores and younger overgrowths.

The Origin of the Earth What's New?

Alex N. Halliday¹



Progress in understanding the origin of the Earth has been dramatic in recent years, which is timely given the current search for other habitable solar systems. At the present time we do not know whether our solar system, with terrestrial planets located within a few astronomical units² of a solar-mass star, is unusual or common. Neither do we understand where the water that made Earth habitable came from, nor whether life in the Universe is rare or plentiful. Perhaps something unusual happened here on Earth. However, the timescales over which the Sun and solar system formed, as well as the detailed mechanisms involved, have been the subjects of extensive recent studies. Discoveries have resulted mainly from improved mass spectrometric measurements leading to a resolution of just 100,000 years in some cases. This short review explains some of these developments.

KEYWORDS: early Earth, solar system, core formation, planets, geochemistry, cosmochemistry, isotopes

THE BIRTH OF THE SUN

The solar system formed 4.5–4.6 billion years ago (Patterson 1956) by collapse of a portion of a molecular cloud of gas and dust rather like the Eagle or Orion nebulae. Some of the star dust from the solar nebula has now been isolated from primitive meteorites. The isotopic compositions of many elements in these grains are vastly different from those of our solar system and provide fingerprints of the stars that preceded our Sun (Nittler 2003). These include red giants, supernovae and novae.

Why this cloud of stellar debris collapsed to form our Sun has been uncertain, but recent discoveries provide support for the theory that a shock wave from a supernova explosion provided the trigger. The former presence of short-lived radionuclides at the start of the solar system has been detected from the isotopic compositions of their corresponding radiogenic daughter elements in meteorites (TABLE 1). Some of these radionuclides, such as calcium-41, aluminum-26 and iron-60, have such short half-lives that they must have been formed at, or shortly before, the start of the solar system, or else they would no longer have

been present. The relative proportions of aluminum-26 and iron-60 are consistent with production in a supernova.

DISKS AND PLANET FORMATION

Immanuel Kant (1724–1804) and Pierre-Simon de Laplace (1749–1827) both argued that the solar system originated from a swirling disk of gas and dust (FIG. 1). In 1755, Kant proposed the idea that the planets accreted from circumstellar dust under gravity. Laplace presented a similar model in 1796 and explained mathematically the rotation of the disk and planets. This resulted from the increase in angular momentum associated

with the contraction of the solar nebula as it collapsed to form the Sun. Although this model has been debated over the years, the Hubble Space Telescope has now provided fascinating images of young stars embedded in such opaque, dusty disks around stars in the Orion Nebula. These young (<1 Myr old) objects are thought to develop into very energetic T-tauri stars characterised by excess infrared radiation emanating from circumstellar dust. The rates of accretion of gas and dust onto a star have been studied by examining the inner edge of the disk spectroscopically (Hartmann 2000). These rates suggest that the disk's dust and, presumably, gas are consumed within a few million

TABLE 1 SOME SHORT-LIVED RADIONUCLIDES IN THE EARLY SOLAR SYSTEM

Nuclide	Half-life (Myr)	Daughter
³⁶ Cl	0.3	³⁶ Ar, ³⁶ S
⁴¹ Ca	0.1	⁴¹ K
²⁶ Al	0.73	²⁶ Mg
¹⁰ Be	1.5	¹⁰ B
⁶⁰ Fe	1.5	⁶⁰ Ni
⁵³ Mn	3.7	⁵³ Cr
¹⁰⁷ Pd	6.5	¹⁰⁷ Ag
¹⁸² Hf	8.9	¹⁸² W
²⁰⁵ Pb	15	²⁰⁵ Tl
¹²⁹ I	16	¹²⁹ Xe
⁹² Nb	36	⁹² Zr
²⁴⁴ Pu	80	¹³⁶ Xe
¹⁴⁶ Sm	103	¹⁴² Nd

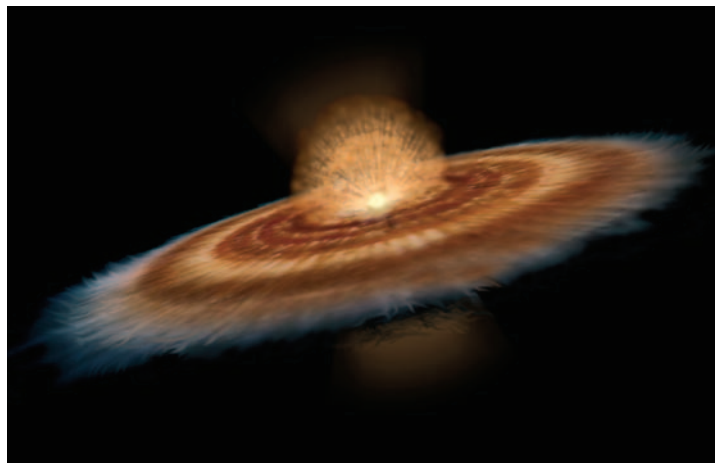


FIGURE 1 Artist's impression of the circumstellar disk of gas and dust from which the planets in our solar system grew. This disk was probably similar to some of those observed in the Orion Nebula. IMAGE COURTESY OF DON DIXON

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² One astronomical unit (AU) = the distance from the Earth to the Sun

years. Dynamic simulations applied to our solar system show that dust and small objects would have been quickly swept into the Sun, unless incorporated into planetary objects.

Accretion of the terrestrial planets is usually modeled (Chambers 2004) in terms of four mechanistically distinct stages:

1. Settling of circumstellar dust to the mid-plane of the disk
2. Growth of planetesimals of the order of 1 km in size
3. Runaway growth of planetary embryos of the order of 1000 km in diameter
4. Growth of larger objects through late-stage collisions

Stage 1 would have taken no more than thousands of years and provided a dense plane of material from which planetesimals grew. Stage 2 is poorly understood but must have happened if sufficient mass were to accumulate for gravity to play a major role, as required by stage 3. Scientists have succeeded in growing in the laboratory centimeter-sized fluffy aggregates of dust held together with electrostatic and Van der Waals forces but do not know how to make something that is the size of a house, say. One suggestion is that some kind of glue was involved, but ices would not have condensed in the inner solar system. Another idea is that there was local sorting and clumping of gas and dust in the swirling disk, leading to regions of localized higher gravity.

However planetesimals first formed, runaway growth then transformed these ~1 km sized bodies into ~1000 km sized planetary embryos. The term “runaway” is used because the bigger the object the larger it becomes until all of the material available within a given heliocentric distance (‘feeding zone’) is incorporated. Models indicate that planetary accretion of this type took no more than a few hundred thousand years. The ultimate size depended on the amount of material available – even Mars-sized (but not Earth-sized) objects could have originated in this fashion.

How much nebular gas was present during these early growth stages is unclear. The presence of at least a small amount of nebular gas would have dampened eccentricities and would therefore explain the near-circular orbits of the planets. At one time it was thought that the planets were dominated by ‘planetary’ noble gases, probably derived from dust and different from the composition of the Sun or solar wind. However, noble gases with solar relative proportions and solar isotopic compositions have now been detected in the mantles of both Earth and Mars. Whether these solar noble gases were acquired by being dissolved into a magma ocean in the presence of a heavy nebular atmosphere, or were contributed to the Earth and Mars by the later accretion of planets and planetesimals is a matter of current debate.

George Wetherill (1986) ran Monte Carlo simulations of terrestrial planetary growth in the absence of nebular gas and succeeded in generating planets of the same size and distribution as Mercury, Venus, Earth and Mars. Most of the mass was accreted in the first 10 Myr, but significant accretion continued for up to 100 Myr. Wetherill tracked the provenance of material that built the terrestrial planets and showed that, in contrast to the runaway growth epoch, there was no localized feeding zone. His simulations suggested that the bits and pieces that built the Earth came from distances that extended over more than 2 AU. These planetary-scale collisions were catastrophic (FIG. 2) and would have raised the temperature of the Earth by thousands of degrees. The most widely held theory for the formation of the Moon is that a Mars-sized planet collided with the proto-Earth when the latter was approximately 90% of its current mass (Canup and Asphaug 2001). The putative impactor planet, sometimes named Theia (the mother of Selene, who was the goddess of the Moon), struck the proto-Earth with a glancing blow, accounting for the high angular momentum of the Earth–Moon system.



FIGURE 2 Artist's impression of collisions between planetesimals – a gravitationally driven mechanism for accretion of the planetary embryos that eventually built the Earth. IMAGE OF DON DIXON

UNRAVELING CIRCUMSTELLAR DISKS AND EARLY PLANETARY GROWTH IN THE ISOTOPE LABORATORY

The same short-lived nuclides with half-lives of ≤ 100 Myr that yield so much information on the birth of the Sun also provide powerful tools for reconstructing the earliest history of the solar system (FIG. 3). The advantage of short-lived nuclides is that the changes in daughter isotope abundances took place over a restricted and definable early time window. Hence, for samples formed while the parent nuclide was still extant, high-precision analyses of the isotopic composition of the daughter can, in principle, result in high temporal precision. A disadvantage is that the parent isotope can no longer be detected, so its abundance at the start of the solar system must be determined by comparing the isotopic composition of the daughter element in rocks and minerals of independently known age. Only then can the isotopic compositions be calibrated with an absolute timescale. Determining the initial abundance is difficult, and some former nuclides still have uncertainties of more than an order of magnitude as a result of conflicting results or poor constraints. Time differences can be determined precisely without this information, however, as long as it can be safely assumed that the short-lived isotope was homogeneously distributed over the region of interest in the early solar system.

The events at the very start of the solar system provide dramatic examples of the information afforded by short-lived nuclides. The clues to the very earliest events are found in chondrites, a class of meteorite with compositions similar to that determined spectroscopically for the Sun's photosphere. Chondrites are composed of a range of early debris, much of which had not been processed by melting in planetary objects. They come from asteroids that accumulated as rubble piles of this circumstellar debris. Many chondrites contain calcium–aluminum-rich refractory inclusions (CAIs), which are usually a few millimeters in size and composed of silicates and oxides. CAIs are enriched in the major and trace elements calculated to condense at high temperatures from a cooling gas of solar composition. Unlike presolar grains they have relative abundances of stable isotopes that are almost identical to those found in the terrestrial planets and meteorites. Therefore, they appear to have formed within our solar system but in a very hot environment, possibly very close to the Sun, and probably at a very early stage. They were then scattered across the swirling circumstellar disk of gas and debris that became the birthplace of the planets. Using $^{235/238}\text{U}_{-207/206}\text{Pb}$ the absolute ages of some CAIs have been determined to be 4.5672 ± 0.0006 billion years (Amelin et al. 2002). This is impressive precision, yet using $^{26}\text{Al}_{-26}\text{Mg}$ (TABLE 1) it has recently been shown that some CAIs formed within $<100,000$ years of each other (Bizzarro et al. 2004). A recent attempt to combine precise $^{235/238}\text{U}_{-207/206}\text{Pb}$ and precise $^{26}\text{Al}_{-26}\text{Mg}$ chronologies on differentiated meteorites has raised the question of whether the solar system may have started earlier than previously thought, at $>4.5695 \pm 0.0002$ billion years (Baker et al. 2005). Reconciling these apparently conflicting results requires further work.

Most chondrites also contain chondrules – drop-shaped Mg-rich silicate objects with textures, thought by many to reflect rapid heating, melting and quenching of pre-existing dust in the circumstellar disk. Using $^{26}\text{Al}_{-26}\text{Mg}$ techniques it can be shown that many chondrules formed within 1 to 2 Myr of CAIs (Kita et al. 2005) (FIG. 3). Therefore, the disk must have persisted for at least 2 million years in the region where chondrules formed, unless they formed from secondary dust produced by destruction of pre-existing planetesimals. It also follows that chondrites – the primitive,

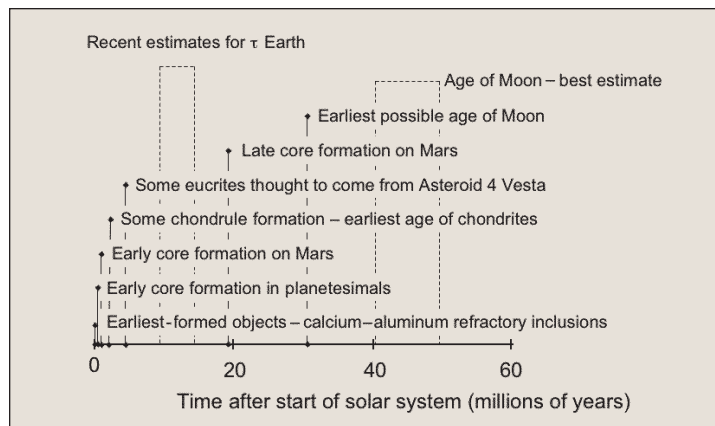


FIGURE 3 The current best estimates for the timescales over which very early inner solar system objects and the terrestrial planets formed. The approximate mean life of accretion (τ) deduced for the Earth is based on W and Pb isotopes. The term “mean life” is used in the same way as in nuclear physics and corresponds to the inverse of a time constant for an exponentially decreasing quantity. In radioactivity it is the inverse of the decay constant. The earliest age of the Moon assumes separation from a reservoir with chondritic Hf/W. The best estimates are based on the amount of radiogenic W that accumulated in the interior of the Moon. See text for further discussion.

undifferentiated meteorites that contain both CAIs and chondrules – must have formed at least a few million years after the start of the solar system. Though primitive, they are not the equivalents of the first planetesimals and planetary embryos predicted from theory.

TUNGSTEN ISOTOPE TESTS FOR TERRESTRIAL PLANET FORMATION

Hafnium-182 (TABLE 1) has been a particularly useful short-lived nuclide for studying planetary growth and differentiation for four reasons:

1. Its half-life (8.9 Myr) is ideal for evaluating the first 50 Myr of solar system history.
2. The initial abundance of ^{182}Hf was relatively high ($^{182}\text{Hf}/^{180}\text{Hf} = 10^{-4}$), producing isotopic effects that are easily resolved.
3. Hafnium and tungsten are fractionated by core formation, which is considered to be an early process in planetary development.
4. Hafnium and tungsten are both refractory, so the parent/daughter ratios and W isotope compositions of bulk planets are usually chondritic, and hence well defined.

Two recent reviews of ^{182}Hf – ^{182}W isotope systematics, but with different emphases, are provided by Jacobsen (2005) and Halliday and Kleine (2006). Hafnium/tungsten ratios are changed by core formation because W tends to partition into metal whereas Hf remains in silicates. The silicate Earth has a ^{182}W atomic abundance that is high relative to chondrites, which represent average solar system (Kleine et al. 2002; Schönberg et al. 2002; Yin et al. 2002). Therefore, a portion of the (high Hf/W) silicate Earth formed during the lifetime of ^{182}Hf . The isotopic effect on the $^{182}\text{W}/^{184}\text{W}$ ratio is only ~ 200 ppm, and the growth of the Earth must therefore have been protracted. If the Earth and its core formed within a million years of the start of the solar system, the isotopic effect would be close to 2000 ppm.

The more exact interpretation of this isotopic difference in terms of timescales is model dependent. In the simplest case, the atomic abundance of ^{182}W could date an instantaneous core formation at 30 Myr in a fully formed Earth (FIG. 4A). However, such a model is inconsistent with other

evidence for how the Earth formed (including Wetherill's modeling and the Giant Impact hypothesis for Moon formation). With a half-life of 8.9 Myr, W isotopes will not record Hf/W changes >60 Myr after the start of the solar system. In principle roughly half the Earth's core could have formed at the start of the solar system and the other half during the Archean or any other period of Earth history, and the W isotopic result would not be different from that measured. Geochemical evidence against such a protracted development of the core comes from the constancy of the relative concentration of certain key trace elements in basalts over time. Those elements that like to partition into core-forming metal and sulfide liquids should have decreased in the mantle in response to core growth. In fact they appear to have stayed approximately constant since the early Archean. Furthermore, the average Pb isotope compositions of the crust and mantle (or the combined bulk silicate Earth) plot close to the geochron determined by Patterson (1956) for the solar system. The geochron represents the line of equal age, corresponding to Pb isotope compositions of objects formed at the start of the solar system. The Pb isotope composition indicates that the bulk silicate Earth separated from the core in the first ~100 Myr of solar system history. Therefore, it is clear that the W isotope composition has to be interpreted in terms of a relatively simple early growth history of the Earth and its core.

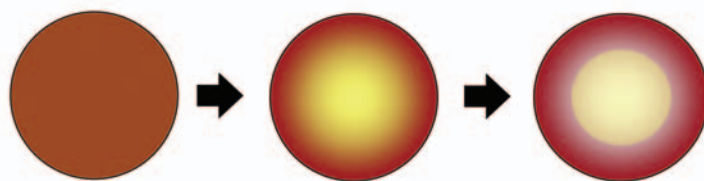
A more realistic model may be that of a planet and its core growing over tens of millions of years as implied by the Monte Carlo dynamic simulations of Wetherill (1986) (Fig. 4B). The W isotope composition then is limited by the overall longevity of planetary growth. The simulations approximate to exponentially decreasing rates of growth, and on this basis Yin et al. (2002) calculated a mean-life of 11 Myr for the accretion of the Earth. The mean-life is the inverse of a time constant for exponential change. For example, in nuclear physics it is the inverse of the decay constant. In the context used here it corresponds to the time taken to achieve 63% planetary growth, and this is in excellent agreement with the timescales inferred directly from the simulations of Wetherill (1986).

FASTER ACCRETION OF SMALLER OBJECTS

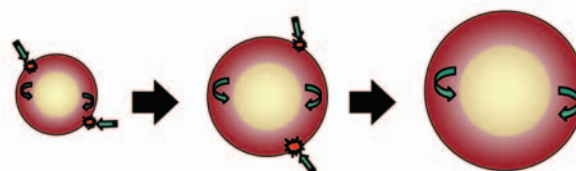
Although the Earth accreted over a long period of time, the information from studying smaller planetary objects is in fact different. The most recent data for Martian meteorites (Foley et al. 2005) confirm earlier evidence that accretion and core formation on Mars were fast. Some recent models (Halliday and Kleine 2006) place the time required for formation of the core of Mars at <1 Myr (Fig. 3). If this is correct, Mars probably formed by a mechanism such as runaway growth, rather than by protracted collision-dominated growth. Mars may be an example of a large planetary embryo with a totally different accretion history from that of the Earth.

A similar story is being recovered from iron meteorites. Very precise W isotope measurements provide evidence that accretion and core formation were short-lived (Markowski et al. 2006; Scherstén et al. 2006). It can be demonstrated that some magmatic iron meteorites, thought to represent planetesimal cores, formed within 500,000 years of the start of the solar system, assuming this corresponds to the time calibrated by using the W isotope compositions of CAIs (Fig. 3) (Markowski et al. 2006). Therefore, they too appear to be examples of early planetary embryos, as predicted from dynamic theory.

(A) Instantaneous core formation from a fully formed planet



(B) Continuous core formation and impactor – mantle equilibration during planetary growth



(C) Core-core mixing without metal-silicate equilibration during planetary growth



FIGURE 4 Schematic representation of core formation scenarios and how they translate into isotopic models and timescales. **(A) Instantaneous core formation.** In this model an age is calculated as the point in time when a fully formed planet segregated into core and silicate reservoirs. **(B) Continuous core formation.** The planet grows by accretion of material with a chondritic Hf/W ratio and W isotope composition. Newly accreted material is continuously mixed with W in the outer silicate portion prior to the segregation of new iron and siderophile elements (including W) into the core. Most models assume an exponentially decreasing rate of overall growth for the planet and its core. **(C) Core-core mixing.** Terrestrial planets appear to have formed from material that was already differentiated into silicate and metal. How much equilibration between accreted metal and the planet's silicate reservoir occurs [an explicit requirement in calculating an age with model **(B)**] is not well understood at present. The net result, if calculated with continuous core formation and equilibration as in model **(B)**, is that the rate of growth of the planet appears faster than it really was.

THE ORIGIN OF THE MOON

Although the details vary, most Giant Impact models predict that the Moon formed after the Earth had achieved more than 80% of its current mass. The W isotope compositions of lunar samples provide support for the Giant Impact theory. The first attempts at these analyses revealed high ^{182}W atomic abundances in many lunar samples. Subsequently it was shown that in some cases, a portion of the ^{182}W was cosmogenic, formed from cosmic rays converting ^{181}Ta to ^{182}Ta , which decays to ^{182}W . This can be corrected using exposure ages or internal mineral systematics (Lee et al. 2002). Kleine et al (2005) used native iron with low Ta/W from lunar basalts. The amount of excess ^{182}W that is not cosmogenic can be compared with the parent/daughter (Hf/W) ratios modeled for the lunar interior to determine a time at which the Moon formed. All of these approaches are consistent with an age for the Moon of 30–55 Myr after the start of the solar system. Such a late origin is not predicted

by all models of lunar formation but is fully consistent with accretion from debris produced in a collision between already-formed planets, as in the Giant Impact theory.

Strictly speaking what is being dated in these studies is the differentiation of the lunar mantle as a high Hf/W reservoir in the lunar magma ocean. The earliest age of the Moon is provided by the time it is calculated to have last equilibrated with a chondritic object. This time is 30 Myr after the beginning of the solar system (Kleine et al. 2002; Yin et al. 2002). But the Moon was formed from the silicate reservoir of a differentiated planet (Canup and Asphaug 2001). The lunar initial W isotope composition provides an alternative constraint of >40 Myr after the start of the solar system (Halliday 2003). This is more consistent with the $^{235/238}\text{U}_{-207/206}\text{Pb}$ age of Pb loss from the material that formed the Moon (Hanan and Tilton 1987).

CORE FORMATION, ACCRETION AND THE EARLY EARTH – THINKING BEYOND THE STANDARD MODELS

Theories of core formation were originally based on the concept of metal segregation from a fully formed Earth. The models range variously from intergranular percolation (Rushmer et al. 2000) to descending diapirs (Stevenson 1990). Similarly, the models upon which we base our many ideas of partitioning of trace elements in a magma ocean assume a fully formed Earth undergoing metal segregation. These models form the backbone of thinking about the physical and chemical processes by which the Earth's core was formed. The challenge is now to develop them into more sophisticated theories that take account of the concurrent increase in size of the Earth and mass transfer processes as accretion and core formation proceeded over tens of millions of years (FIGS. 4B AND C). This is partly a question of tracking the phase changes, reactions and changes in physical properties as the Earth increased in size (Wade and Wood 2005).

What is harder to quantify, however, is the direct effect of planetary collisions. Impacts may have produced magma oceans that facilitated core formation, but they may also have blown off blanketing proto-atmospheres, leading to cooling and crystallization (Ahrens 1990). Furthermore, collisions between differentiated planetary bodies may have resulted in the metal in each planetary core simply merging (Yoshino et al. 2003). With mounting evidence of very early asteroidal melting and core formation, this could have been the norm. The growth of the Earth's core would then have been via core–core mixing (FIG. 4C), rather than by metal segregation from silicate.

The core–core mixing process would affect ^{182}Hf – ^{182}W chronometry. In calculating accretion timescales, it is assumed that accreted W equilibrated isotopically with W in the silicate Earth (FIG. 4B). But if a fraction of the incoming W was in metal that mixed directly with the Earth's core (FIG. 4C), then the ^{182}Hf – ^{182}W “age” of the Earth or its core would appear older than it really is (Halliday 2004). It is essential to understand the details of these processes. As the planet and its core fragment during impact, Rayleigh-Taylor instabilities will form. These are disruptions caused by layers of lower density and viscosity rising and impregnating overlying material. We need to know the size distributions of the resultant droplets of metal in silicate and silicate in metal before a realistic assessment can be made of the degree and processes of equilibration. We still have a primitive understanding of what happens when planets tear each other apart.

An alternative approach is to use isotope geochemistry to infer the physics. If we know the age of the Moon, we also know the timing of the last major accretion stage in the history of the Earth. From this we can determine the extent to which the W isotope composition of the silicate Earth reflects planetary-scale disequilibrium of material added during accretion. Preliminary attempts at this (Halliday 2004) show that on average the degree of equilibration between incoming metal and the silicate Earth must be high (70–90%) and would be even higher if the Moon formed before 45 ± 5 Myr after the start of the solar system. Therefore, full equilibration with incoming material has been the norm. However, a very large event, such as the Giant Impact, could have resulted in considerable disequilibrium, with between 40 and 60% of the incoming W in metal *not* equilibrating with the silicate Earth, if at other times metal and silicate were fully equilibrated.

DIFFERENT TIMESCALES FOR DIFFERENT CHRONOMETERS

Following the classic study of Patterson, several scientists tried to estimate the average Pb isotope composition of the bulk silicate Earth and found that it lies below and to the right of the slope defined by the geochron. In other words the classic piece of evidence that the Earth and solar system all formed at the same time has revealed evidence of a relatively small time difference as more data have been acquired. The standard explanation for this is that the Earth or its core formed somewhat later than the first objects in the solar system. As such, Pb and W are in qualitative agreement. In fact, since both U/Pb and Hf/W are fractionated by core formation, the W and Pb isotope compositions of the silicate Earth should yield the same protracted timescales if modeled in the same manner. Instead, the timing based on W appears faster than that based on any of the estimates of the Pb isotope composition of the silicate Earth (Halliday 2003). Given the difficulty with defining a meaningful average, it is very possible that all the Pb isotope estimates are wrong. The silicate Earth must then have a higher $^{207}\text{Pb}/^{206}\text{Pb}$ than currently estimated.

It is also very likely, however, that the rates of transfer of W and Pb to the core were different (Wood and Halliday 2005). Tungsten is partitioned into metal, whereas Pb is thought to be more readily partitioned into sulfide liquids, which would not have become stable until the Earth cooled following the Giant Impact. Removal of this sulfide to the core may have been responsible for a late-stage increase in U/Pb in the silicate Earth that over time generated the observed Pb isotope compositions. Very roughly speaking, the Earth's upper mantle appears to have cooled from temperatures of about 7000K at the time of the Giant Impact to about 3000K, when sulfides would have become stable, in tens of millions of years (Wood and Halliday 2005).

LINKS TO HADEAN MANTLE DEPLETION, CRUST FORMATION AND HABITABILITY

There must be overlap between the events discussed above and the mounting evidence of mantle differentiation events recorded in other studies. Those links are unclear because the models are under-constrained and some of the data are open to alternative interpretation. This will change as more data are acquired. The Hadean zircon archive is particularly exciting. For example, Wilde et al. (2001) reported a $^{235/238}\text{U}_{-207/206}\text{Pb}$ age of a terrestrial zircon that formed in the first 200 Myr of the solar system and argued that it provided evidence of continental crust and a hydrosphere. Watson and Harrison (2005) used Ti geothermometry to show that Hadean zircons crystallized at temperatures consistent with water-saturated crustal melting, which implies

that a regulated mechanism of melt production was in place. Harrison et al. (2005) have argued that mantle depletion by partial melting probably linked to crust formation occurred within the first 70 Myr, based on ^{176}Lu - ^{176}Hf isotope data from these early zircons.

These new Hf data display more variability than the previously reported relatively precise measurements of later Hadean zircons (Amelin et al. 1999) but in broad terms are consistent with the modeling of Caro et al. (2003), who used the ^{146}Sm - ^{142}Nd chronometer (TABLE 1) to estimate that the mantle's earliest melt depletion event occurred in the first 220 Myr of the solar system. More extreme is the proposal of Boyet and Carlson (2005), who used ^{146}Sm - ^{142}Nd systematics to argue that a hidden reservoir in the Earth's mantle formed within the first 30 Myr. However, these data could reflect a slight difference in Sm/Nd between the Earth and chondrites or even minor nucleosynthetic effects.

Crucial issues in which we are likely to make progress over the next few years include (1) the interfacing of these geochemical approaches with the physics of accretion dynamics, (2) changes and mechanisms of oxidation of the Earth's mantle, (3) the origin of the Earth's water, and (4) the nature of the late (post-core) veneer of accreted material that is widely considered to be responsible for the surprisingly high budgets of platinum-group elements in the silicate Earth. These issues provide essential background information to the many studies that are developing on the Earth's earliest crust, atmosphere and hydrosphere. In fact, without this understanding we cannot know whether habitable planets like the Earth are common or rare. Thus, the current developments in isotope geochemistry play into many of the most important issues in experimental astrophysics and the search for Earth-like planets beyond the solar system. ■

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Impact Processes on the Early Earth

Christian Koeberl¹



At the beginning of the solar system, impacts and collisions were dominant processes. After an early collision that may have led to the formation of the Moon, both Earth and Moon suffered intense post-accretionary bombardment between about 4.5 and 3.9 billion years before present. There is evidence from lunar rocks for an intense “Late Heavy Bombardment” at about 3.85–3.9 Ga, which must have had severe consequences for Earth as well, even though no terrestrial record has yet been found. Several 3.4 to 2.5 Ga old spherule layers in South Africa and Australia and two impact craters near 2 Ga represent the oldest terrestrial impact records found to date. Thus, the impact record for more than half of Earth’s geological history is incomplete, and there is only indirect evidence for impact processes during the first 2.5 billion years of Earth history.

KEYWORDS: Impact processes, Late Heavy Bombardment, shocked minerals, Hadean, impact craters

IMPORTANCE OF CRATERING PROCESSES

The importance of impact processes on a planetary scale has been recognized only fairly recently, after it became evident that not only our Moon (FIG. 1), but all other bodies in the solar system with a solid surface are covered with meteorite impact craters (FIG. 2). Impact cratering is a high-energy event that occurs at more or less irregular intervals (although over long periods of time, an average cratering rate can be established). Recognition of the vestiges of impact events on Earth is difficult because terrestrial processes either cover or erase the surface expression of impact structures. Important witnesses of impact processes are melted, shocked, and brecciated rocks that are found either directly at or within a crater, or have been transported, in some cases considerable distances from the source crater. The latter are called ejecta.

To determine if certain rocks are related to an impact or not, criteria must be identified that allow us to distinguish the effects of such processes from those resulting from normal terrestrial geological processes. Only the presence of diagnostic shock-metamorphic effects and, in some cases, the discovery of meteorites (or traces thereof) are evidence for an impact origin (cf. Koeberl 2002). Most shock features are microscopic (FIG. 3). The same two criteria apply also to

distal impact ejecta layers and allow researchers to confirm that such material originated in an impact event at a possibly still-unknown location. Currently, 172 impact structures have been identified on Earth based on these criteria (see <http://www.unb.ca/passc/ImpactDatabase> for information and updates). With one exception, all of these are younger than 2 Ga (billion years).

Another important line of evidence for impact processes comes from geochemical indications of an extraterrestrial component in breccias or melt rocks. Only elements that have high abundances in meteorites and low contents in terrestrial crustal rocks are useful for such studies – for example, the siderophile platinum-group elements (Ru, Rh, Pd, Os, Ir, and Pt) and other siderophile elements (e.g. Co, Ni). Better still are isotopic tracers for extraterrestrial components; the isotopic compositions of the elements osmium and chromium are mainly used. These methods allow the very sensitive determination of the presence of an extraterrestrial component (down to 0.1% for Os isotopes) and, in the case of the Cr isotopic method, even allow us to determine the type of impactor.

ACCRETION OF THE EARTH, AND THE MOON-FORMING IMPACT

The planets – including Earth – formed by collision and hierarchical growth, starting from small objects, i.e. from dust to planetesimals to planets. Late during the accretion of Earth (some time around or after 4.5 billion years ago), when Earth had acquired about 70–90% of its final mass, it probably collided with a Mars-sized body. This is the prevailing hypothesis for the origin of the Moon (e.g. papers in Canup and Righter 2000), and it is thought that most of the Moon was derived from the impactor. Accretion of the Moon from the proto-lunar disk followed very rapidly. The volatile-poor and refractory-rich composition of the Moon

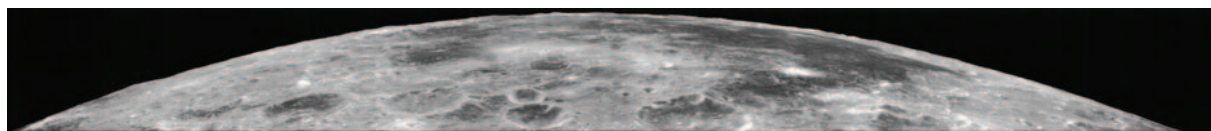


FIGURE 1 Densely cratered part of the surface of the Moon (APOLLO 17, PHOTO P-2871)

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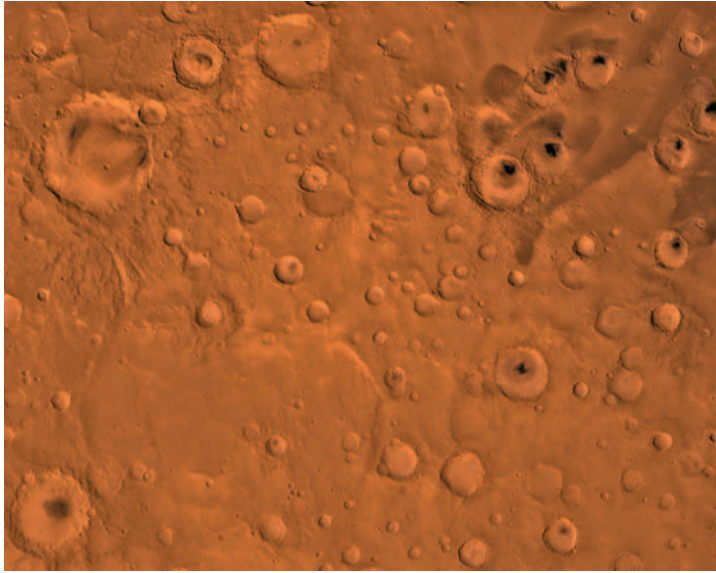


FIGURE 2 Heavily cratered ancient highlands dominate the Arabia quadrangle on Mars. FROM VIKING IMAGE PIA00172; WIDTH OF IMAGE 1000 KM

agrees with such a formation mechanism. The impact event is thought to have been the last of the major collisions involved in the accretion of Earth. The consequences of such an event for the proto-Earth would have been severe, ranging from almost complete melting and formation of a magma ocean, thermal loss of pre-existing atmosphere, changes in spin rate and spin-axis orientation, to accretion of material from the impactor, directly or through rapid fallout from orbital debris.

The period on Earth between the end of accretion and the beginning of the continuous terrestrial rock record is commonly referred to as the Hadean Eon. Its terminal boundary on Earth was suggested to be at 4.2 Ga based on zircon geochemistry (Cavosie et al. 2005), while on the Moon it is equated with the formation of the Orientale basin.

EARTH AFTER THE GIANT MOON-FORMING IMPACT EVENT

The terrestrial rock record, in the form of crustal rocks, extends back through only about 89% of the history of the planet to ~4.0 Ga (with the oldest rocks showing very limited exposures at Isua and Akilia, Greenland, and Acasta, Canada). Rare detrital zircon grains in rocks from Western Australia have ages up to 4.4 Ga (Wilde et al. 2001). It is likely that the Moon-forming impact led to large-scale melting of the Earth at ~4.5 Ga (Halliday 2006) and the formation of an early magma ocean. Mantle temperatures in the Hadean were much higher than today (heat flow was about five times higher) due to greater concentrations of radioactive elements and to thermal energy released during the impact of late accretionary bodies. Because of higher mantle temperatures and the temperature dependency of the dehydration reactions that control how much water is recycled to the mantle, the Hadean mantle was drier than its modern counterpart. Most of Earth's water was contained in an ocean, which already existed probably as early as 4.2 Ga (Cavosie et al. 2005); its volume may have been up to twice that of today's oceans (Russell and Arndt 2005).

The nature and abundance of the earliest crust on Earth have been debated, but comparison with other planets indicates a basaltic crust. Russell and Arndt (2005) suggested that high-degree melting of hot, dry Hadean mantle at

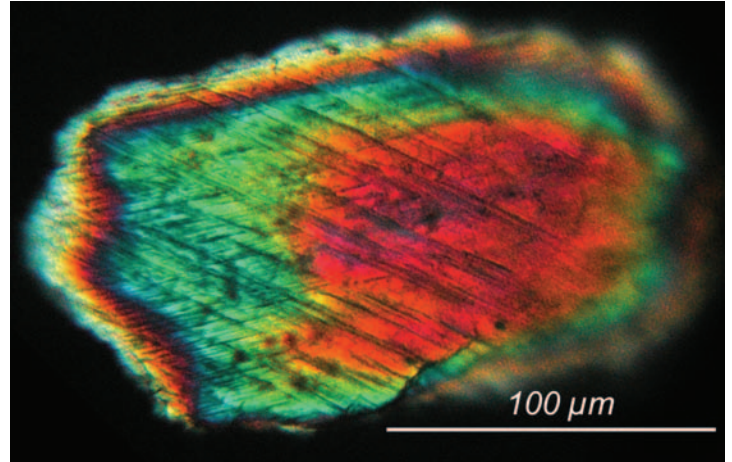


FIGURE 3 Micrograph (crossed polarizers) of shocked quartz grain from ejecta of the Manson crater (USA), demonstrating the characteristic “planar deformation features” (PDFs). These features are straight, penetrate the whole crystal, and occur in more than one orientation. Wavy lamellae, observed in some quartz grains, are not characteristic of shock.

ocean ridges and in plumes resulted in an oceanic-type crust about 30 km thick, overlain in places by extensive and thick mafic volcanic plateaus; ‘continental’ crust, by contrast, was relatively thin and mostly submarine. Characteristics of the 4.4–4.0 Ga zircons indicate a composite granitoid source. Thus, at least minor amounts of felsic igneous rocks existed during the Hadean, produced from remelting of basaltic crust that sank back into the mantle. The Hadean oceanic crust was much thicker than today, as thick as or thicker than the Early Archean continental crust. Due to the larger ocean mass, a greater area of Earth's surface was flooded. In contrast to today, most of the continents were submerged, and only mountain ranges at convergent margins and vast volcanic plateaus occasionally breached the ocean surface. Thus, the Hadean Earth was most probably characterized by a thick basaltic crust covered by an ocean, with very little dry land mostly composed of felsic rocks (granitoids) (Fig. 4).

Grieve et al. (2006) calculated that early large-impact events could lead to the formation of felsic crust on the Hadean Earth. They found that, on Earth, impact melt volumes exceed transient crater volumes at transient crater diameters greater than approximately 500 km. Thus, the initial basaltic Hadean crust would have been reprocessed to produce pockets of felsic crust by crystal fractionation. Scaling of lunar impact basins yields a cumulative melt production related to the formation of such basins on the Hadean Earth of about 10^{11} – 10^{12} km³. Grieve et al. (2006) suggested that the cumulative felsic rocks produced through differentiation of such impact melt pools could approach a volume equivalent to 50% of today's continental crust.

There is evidence (involving the short-lived ¹⁴⁶Sm–¹⁴²Nd decay; half-life 103 Myr) that Earth's upper mantle had already undergone some differentiation shortly after accretion (e.g. Boyet and Carlson 2005). Evidence for recycling of early crust, coupled with the higher heat flow, seems to demand that plate tectonics, even in limited form, and accretion of felsic crust were operating shortly after the solidification of the magma ocean. Alternatively, the impact mechanism suggested by Grieve et al. (2006) may also account for the production and recycling of differentiated early crust.



FIGURE 4 A possible view of the early Earth, sometime between 4.4 and 4.0 billion years ago. There is now evidence of rather clement conditions starting several tens of millions to 300 million years after the Moon-forming impact event. The young Moon is much closer to Earth than today and does not yet have any of the maria that dominate its Earth-facing side today. Towards the end of planetary accretion, a higher impact rate than today led to a barrage of both Earth and Moon. One medium-size impact event can be seen occurring in the right side of the image, while several smaller events are happening on the Moon. An ocean dominates the surface of Earth, but island-arc formation and associated intense volcanism indicate the presence of early continental crust. The Earth is covered by a dense, CO₂-dominated atmosphere. PAINTING BY DONA JALUFKA 2005

The magma ocean may have been shorter lived than previously thought, and differentiation and recycling could have started shortly after the Moon-forming impact. Variations in the oxygen isotope composition of zircons with ages of 4.2 Ga indicate that these zircons grew in evolved granitic magmas and that low-temperature surficial processes, including diagenesis, weathering, and low-temperature alteration, were operating (e.g. Cavosie et al. 2005). Thus, liquid water seems to have been present on the surface of Earth early on, and granitic (not just basaltic) pockets of continental crust were present (Valley et al. 2002); we can infer that the frequency of meteorite impacts during the time span between 4.4 and 4.0 Ga may have been less than previously thought.

These zircons are the only record that has persisted from Hadean times. It would be interesting to study them (or at least their cores, as most of them have younger overgrowths) for shock effects, although this may be difficult due to later annealing and because any early Hadean crust would have been destroyed at around the same time as massive impacts reshaped the surface of the Moon.

A LATE HEAVY BOMBARDMENT AT 3.9 Ga?

In contrast to the youthful age for most of Earth's crust, the surface of the Moon displays abundant evidence of an intense bombardment at some time between its original crust formation and the outpourings of lava that form the dark mare plains. The ages of the highlands have been interpreted to represent either a short and intense 'late' heavy bombardment (LHB) period at 3.85 ± 0.05 Ga (e.g. Ryder et al. 2000) or the tail end of an extended post-accretionary bombardment (Fig. 5).

The lack of lunar impact melts older than ~3.95 to 3.92 Ga can be taken as evidence that there were no significant impact events on the Moon prior to that time, in agreement with the 'cool early Earth' between about 4.4 and 4.0 Ga (Valley et al. 2002). All large impact basins on the Moon have formation ages of about 3.8 to 4.0 Ga (the magma that

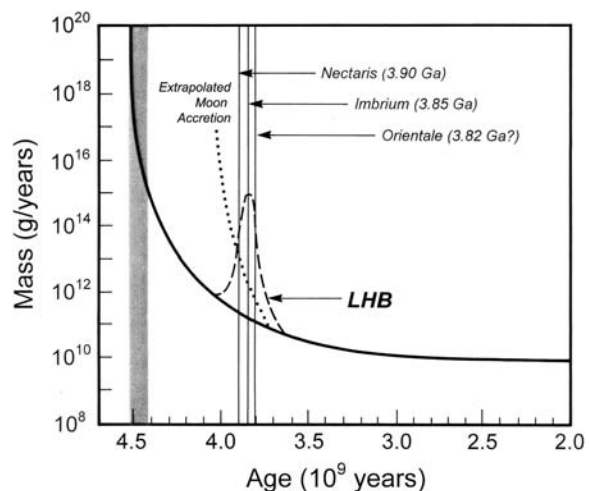


FIGURE 5 Various interpretations of the mass flux (accretion rate) on the Moon. Ages of the most important impact basins are indicated. The solid line is the present-day background flux extrapolated back to the origin of the solar system. LHB indicates the spike in the accretion rate representing the Late Heavy Bombardment. The dotted line indicates an accretion curve that includes the masses of the basin-forming projectiles; this curve is unlikely to be correct, because it implies accretion of the Moon at 4.1 Ga. The gray band marks the age of the Moon obtained from measurement of radiogenic isotopes. AFTER KOEBERL 2006

filled these impact basins to form the maria is younger, at about 3 Ga (Ryder et al. 2000). Work on lunar meteorites has confirmed that there was considerable bombardment of the Moon in the 60 million years between 3.90 Ga and ~3.84 Ga (e.g. Kring and Cohen 2002). An independent argument in favor of an LHB can also be made using the masses of basin-forming projectiles on the Moon, as shown in Fig. 5. Back-extrapolating the masses of basin-forming projectiles accreting onto the Moon between 3.8 and 4.0 Ga leads to the conclusion that the present-day mass of the Moon can be accounted for if it formed at about 4.1 Ga instead of 4.5 Ga. The exact mechanism that produced this spike in impact flux in the inner solar system is not known, although the delayed migration of Uranus and Neptune towards the outer solar system and the resulting disturbance of Kuiper Belt objects may provide an explanation (Gomes et al. 2005).

The question arises as to whether or not any evidence of this bombardment is preserved on Earth. In any given time span, Earth was subjected to a higher impact flux than the Moon because Earth has a larger diameter and a much larger gravitational cross-section. The oldest rocks on Earth, from Acasta in Canada and the Isua/Akilia area in Greenland, are the obvious places to conduct such a search. Unfortunately, searches for an extraterrestrial signature based on platinum-group elements and for shocked zircons in the earliest rocks from Greenland have so far been unsuccessful (Koeberl et al. 2000). This could be for several reasons. First, the number of samples studied was probably too small. Second, it is possible that very large impacts form more melt than shocked rocks, leading to a preservation problem. Third, it is not certain that the rocks at Isua really have an age >3.8 Ga (e.g. Lepland et al. 2005).

Tungsten isotope anomalies found in ca. 3.85 Ga metasedimentary rocks from Greenland were interpreted to indicate an extraterrestrial component as a result of the LHB (Schoenberg et al. 2002). However, it is difficult to understand why a similar meteoritic signal would not show up in the platinum-group element abundances, as high W abundances are not common in meteorites. In fact, Frei and Rosing (2005) used the chromium isotope method on Isua rocks and found no trace of an extraterrestrial component. Thus, little or no evidence of an LHB phase at 3.85 Ga has been found so far on Earth.

IMPACTS AND THE ORIGIN OF LIFE ON EARTH

The impact rate in the inner solar system between the Moon-forming event and ~4.0 Ga seems to have been lower than previously assumed. If the impact energies associated with the lunar bombardment between about 4.4 and 3.9 Ga are scaled up to Earth (Ryder 2002), they may not have been high enough to produce ocean-evaporating, globally sterilizing events, in agreement with the conclusions of Valley et al. (2002). Compared with the LHB of the Moon, the impact flux on Earth from ca. 4.4 to 3.9 Ga may have been subdued, and the impacts themselves during that time could have been thermally and hydrothermally beneficial.

However, if the LHB really happened, severe environmental changes would have occurred on Earth at about 3.85 Ga. During this cataclysm, Earth would have undergone impact events an order of magnitude larger than those affecting the Moon and would have experienced many more such events than the Moon had to endure. Hundreds of objects with sizes similar to those of the Imbrium and Orientale impactors must have struck Earth during the basin-forming era. Nonetheless, even an Imbrium-sized impactor scaled to terrestrial collision energy would have had only 1% of the

energy needed to evaporate Earth's oceans and would have vaporized only the upper few tens of meters of ocean. The impact would have produced a transient atmosphere of hot silicate vapor, which would have heated the ocean from above. Even impacts orders of magnitude larger would have been far from sufficient, boiling off only a few hundred meters of ocean water (see, for example, Ryder 2002).

LATER (EARLY ARCHEAN) IMPACT EVENTS

In the absence of any conclusive impact record in the oldest rocks on Earth, we need to look at 'younger' rocks. The earliest 'real' rock record of impact events has been dated at ~400–500 million years after the end of the LHB. This record takes the form of (distal?) impact ejecta layers (e.g. Simonson and Glass 2004). Spherule layers, interpreted as possible impact debris layers, have been documented in 3.47–3.2 Ga Archean successions in the Barberton Greenstone Belt (South Africa) (Fig. 6A) and Pilbara Craton (Australia). Unlike modern impact deposits, many of these spherule layers show extreme enrichments in platinum-group elements, and they lack shock features, but Cr isotope anomalies in samples from some of these layers seem to support the presence of an extraterrestrial component (Kyte et al. 2003). Similar spherule layers (of ca. 2.63–2.5 Ga age) have

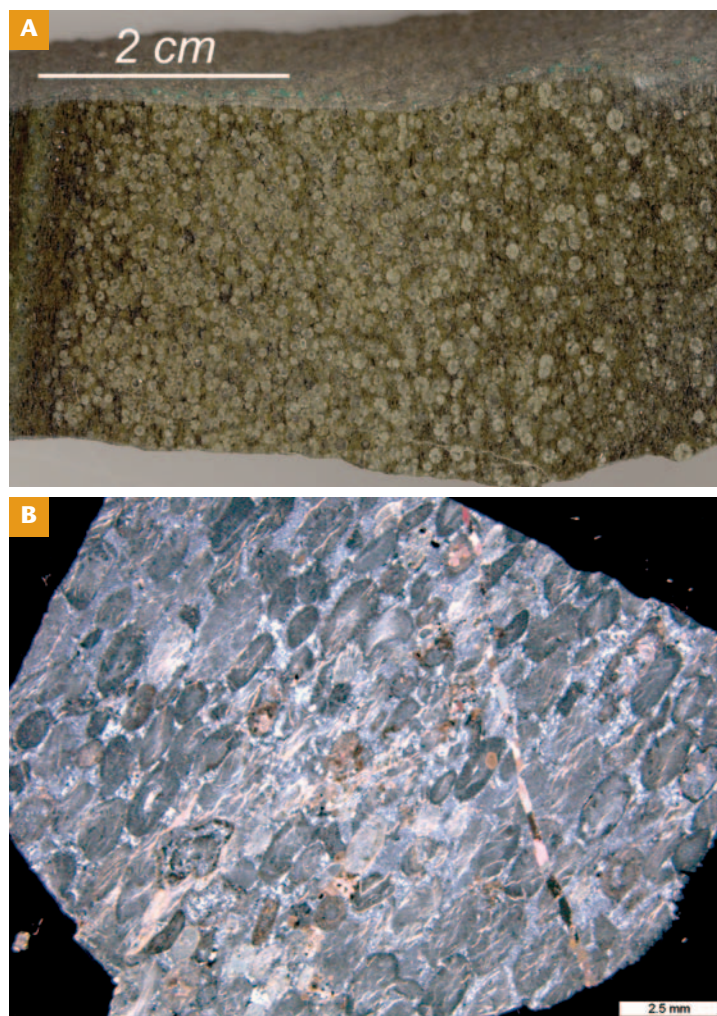


FIGURE 6 (A) Well-sorted, millimeter-sized spherules in a 3.48 Ga impact-derived layer, Barberton, South Africa. (B) Image of tectonically deformed spherules from one of the impact-derived spherule layers at Barberton, South Africa. Cross-polarized view of an optical thin section. The mineralogy of the spherules is most likely of secondary origin and comprises quartz and sericite.

been found in the Hamersley Basin in Australia and in the Monteville Formation of the Transvaal Supergroup in South Africa (FIG. 6A, B); these Australian and South African layers may be correlated with each other. The spherules are mostly quenched melt droplets, up to a few millimeters across, some of which may have formed by condensation from vapor clouds (FIG. 6). The spherule layers are coarse grained and have been interpreted to reflect high-energy depositional events in otherwise low-energy, quiet-water environments. The original mineralogical and chemical compositions of the spherules have been almost completely changed by alteration (FIG. 6B). Until recently, no shocked quartz – commonly regarded as unambiguous evidence for a hypervelocity impact event – has been found in distal ejecta horizons older than ~600 Ma; an exception is a single shocked quartz grain from the 2.63 Ga Jeerinah impact layer in Australia (Rasmussen and Koeberl 2004). The exact number of impact spherule layers is not known, as it is not clear which ones might correlate with each other, but a minimum of seven different events in the age ranges 3.4–2.5 Ga and 2.1–1.8 Ga have been identified.

Unfortunately, no definitive criteria for the identification of Archean impact deposits have yet been established. So far no source craters have been found for the South African (Barberton and Monteville) or Australian spherule layers, and given the scarcity of the Early Archean geological record, it is unlikely that they will ever be found. It is not clear why impact events in the Archean would predominantly produce large volumes of spherules, whereas they are mostly absent from post-Archean impact deposits (i.e. those for which source craters are known). Distal ejecta from the 1.85 Ga Sudbury impact structure also have spherules (Addison et al. 2005). Some (comparatively small) spherules are associated with ejecta from the 65 Ma Chicxulub and the 35 Ma Popigai impact events (Simonson and Glass 2004), but these layers are thinner than the Archean spherule layers. Compositional differences between the Archean and present-day continental crusts could have influenced the composition and preservation of the ejecta.

THE OLDEST IMPACT STRUCTURES PRESERVED ON EARTH

The earliest remnants on Earth of actual impact structures – excluding the more controversial and difficult-to-quantify evidence from the Early Archean spherule beds – date to about 2 billion years ago. Thus, for more than half of the ‘life’ of our planet – the first 2.5 billion years – we do not have any substantiated preserved remnants of the many impact structures that must have formed; the only evidence we have is indirect, for example by comparison with lunar impact structures of similar age. The oldest known terrestrial impact structures are the Vredefort and Sudbury structures with ages of 2023 ± 4 and 1850 ± 3 Ma, respectively (see Reimold and Gibson 1996) – these represent the complete, documented, pre-1.85 Ga terrestrial impact record.

The Vredefort Dome (South Africa) is the deeply eroded central uplift of a large (initial diameter about 200–300 km), complex impact structure. The rocks show the variety of impact-related features described at the beginning of this

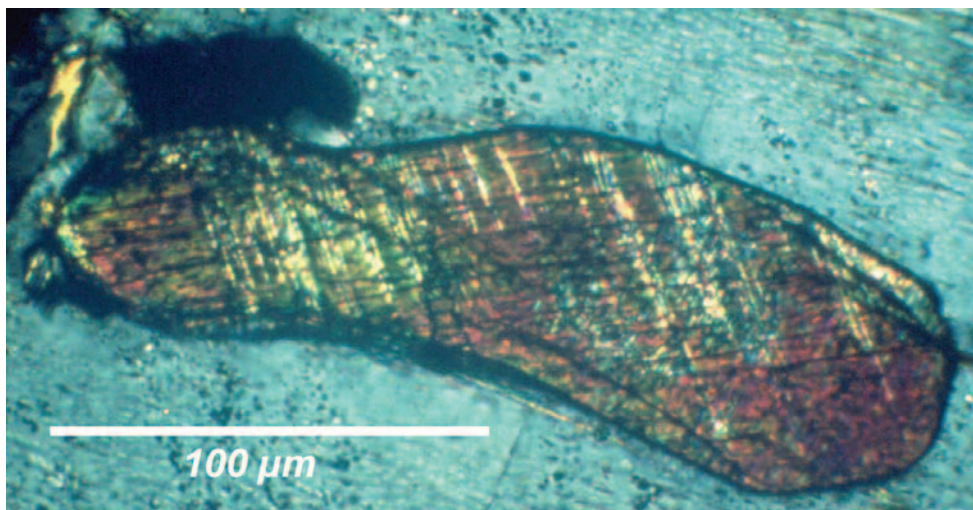


FIGURE 7 Micrograph (crossed polarizers) of shocked zircon grain from the Vredefort structure, South Africa. PHOTO COURTESY R. GIBSON AND U. REIMOLD

article, including shatter cones, coesite and stishovite (high-pressure polymorphs of SiO_2), shocked quartz and zircon (FIGS. 3 AND 7), dykes of impact melt breccia, and abundant pseudotachylitic (melt) breccias. The absence of a definitive crater morphology, a coherent impact melt body, and fallback breccias indicate that considerable erosion has taken place since the impact event, removing the top 5–10 km of the post-impact surface. In contrast to the 1.85 Ga Sudbury structure, for which impact ejecta (including a spherule layer up to 10 cm thick) have recently been identified in Minnesota and western Ontario 650–875 km from the impact site (Addison et al. 2005), no confirmed ejecta related to the Vredefort impact have to date been discovered.

CONCLUSIONS

The early record of impacts on Earth is limited and mostly circumstantial. There is no record for the first one billion years and the later preserved rock record shows few events (just seven or eight documented impact layers) between 3.5 and 2.4 Ga. The oldest confirmed crater on Earth is 2 Ga old, and the impact record during the following one billion years is sparse in terms of both craters and ejecta layers. Three impact structures are known for the time period between 2.1 Ga and 700 Ma and the rest of the some 170 currently known impact structures are all younger than 700 Ma. Clearly the ‘early’ impact record on Earth, which spans more than half of the age of our planet, its most active period, is still a wide-open field of research. A more detailed discussion of this topic is given in the review by Koeberl (2006).

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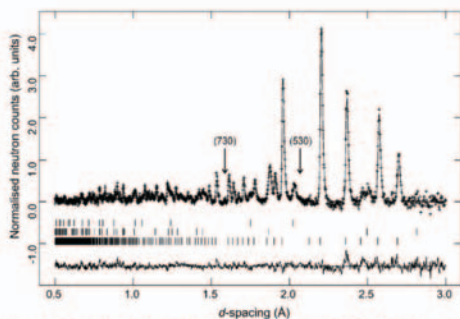
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Earth's Earliest Atmosphere

Kevin J. Zahnle¹

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The aftermath of the Moon-forming impact left Earth with a hot, CO₂-rich steam atmosphere. Water oceans condensed from the steam after 2 Myr, but for some 10–100 Myr the surface stayed warm (~500K), the length of time depending on how quickly the CO₂ was removed into the mantle. Thereafter a lifeless Earth, heated only by the dim light of the young Sun, would have evolved into a bitterly cold ice world. The cooling trend was frequently interrupted by volcanic- or impact-induced thaws.

KEYWORDS: Hadean Earth, Moon-forming impact, origin, evolution of the atmosphere, zircon

INTRODUCTION

The newly made Earth is widely and enduringly pictured as a world of exuberant volcanoes, exploding meteors, huge craters, stifling heat, and billowing sulfurous steams—a world of fire and brimstone punctuated with blows to the head. The popular image has drawn to it the name Hadean, a name that celebrates our mythic roots. But the infernal image of the earliest Earth also has purely scientific roots. A hot early Earth is a consequence of fast planetary growth. Any lingering doubts were vaporized by the success of the Moon-forming impact hypothesis (Canup 2004). Earth as we know it emerged from a fog of silicate vapor.

THE YOUNG SUN

The Sun took ~50 million years to contract to the Main Sequence (FIG. 1). Contraction stopped when the Sun's core became hot and dense enough to fuse hydrogen into helium. The stable state in which starlight is fueled by hydrogen burning in the center of a star is called the Main Sequence. It lasts as long as the hydrogen fuel in the core lasts. While on the Main Sequence, the Sun steadily brightens as its mean molecular weight increases. The standard model predicts that the Sun was only 71% as bright as it is now when it reached the Main Sequence and that it brightened 7% over the next billion years.

The faint young Sun imposed a stringent constraint on the climate of the young Earth (Sagan and Mullen 1972). Without potent greenhouse gases, the early Earth should have been at most times and places frozen over.

The only plausible way to make the young Sun brighter is to make it more massive. Adding 6% more mass would make it as bright as it is now (Sackmann and Boothroyd 2003). The Sun does lose mass through the solar wind, but at current rates it would lose only 0.01% of its mass over

4.5 Gyr. By studying stellar winds from nearby stars that are Sun-like but younger, Wood et al. (2002) deduced that our Sun has lost less than 0.5% of its mass since it reached the Main Sequence. This is too small to be important. Evidence bounding mass loss from still younger stars is indirect, but the empirical upper limit on X-ray emission implies a parallel upper limit on mass loss that is less than 1% of the initial mass. The range of solar evolutions permitted by

mass loss is shown in FIGURE 1.

In contrast to luminosity in general, the active young Sun was a much stronger source of ultraviolet light, X-rays, and solar wind than it is today (FIG. 1). This inference is based on empirical observations of hundreds of young solar analogs. The theory is not fully developed, but in broad outline stellar activity (sunspots, flares, UV, X-rays) is related to the strength of the magnetic field, which in turn is gener-

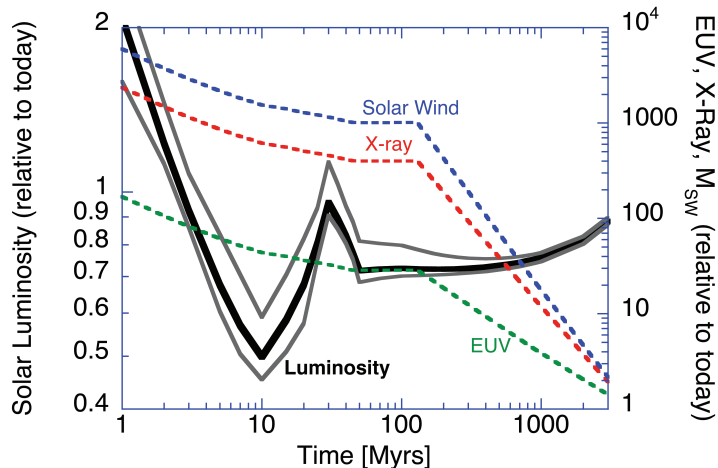


FIGURE 1 The first 3 billion years of solar evolution. The solid curves show luminosity evolution. The Sun reached the Main Sequence after 50 Myr. Main Sequence luminosity evolution follows Sackmann and Boothroyd (2003). Pre-Main Sequence evolution is adapted from D'Antona and Mazzitelli (1994). Inconstant luminosity before reaching the Main Sequence is a consequence of gravitational settling. The range of uncertainty (shown by grey solid curves) is determined by mass loss. Mass loss follows Wood et al. (2002). Sensitivity to mass loss is scaled from Sackmann and Boothroyd (2003). Dashed curves show nominal solar wind (M_{sw}), X-ray, and extreme ultraviolet (EUV) histories (Wood et al. 2002). The observed scatter in X-ray luminosities of stars like the young Sun implies an order of magnitude uncertainty in these quantities for the Sun during the Hadean.

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ated from the star's rotation. As the star ages it loses angular momentum through the stellar wind. Solitary stars are like spinning tops—they all slow down.

ORIGIN OF EARTH'S ATMOSPHERE

Earth's atmosphere is often described as secondary, a word that implies a history. The primary atmosphere is defined as gas captured gravitationally from the solar nebula (the primordial cloud of gas and dust from which the Sun and planets were formed). Like the Sun itself, a primary atmosphere is overwhelmingly made of hydrogen. In principle small planets like Earth could have captured significant primary atmospheres, depending on how long the nebula lasted (Hayashi et al. 1979).

Traditional arguments for and against a primary atmosphere are based on the abundances of noble gases (Fig. 2). A primary atmosphere provides a way to inject ^3He and solar neon into a molten mantle. But atmospheric neon argues otherwise. First, the $^{20}\text{Ne}/^{36}\text{Ar}$ ratio is ~ 30 in the Sun but ~ 0.3 in the atmospheres of Earth, Mars, and Venus—a hundred-fold discrepancy. It is even more telling to compare neon to nitrogen. Nitrogen is one of the most volatile elements apart from the noble gases. The solar N/Ne ratio is unity. In Earth's atmosphere that ratio is 86,000. Either Ne

escaped from Earth 86,000 times more efficiently than N, or the major source of N was in a condensate of some kind. If N was delivered in a condensate it is by definition secondary.

Traditionally, the secondary atmosphere is composed of volatiles delivered to Earth in solid bodies (akin to meteorites) that degassed after a primary atmosphere, if any, was lost. This is sometimes taken to mean that Earth's atmosphere degassed from the solid Earth into a primordial vacuum. However, most volatiles accreted by Earth as solids would have entered the atmosphere directly on impact (Ahrens et al. 1989). This would generally be the case for asteroids and meteors once collision velocities became high enough (collision velocities get bigger as the planet gets bigger), and it would probably be the case for comets at pretty much any collision velocity.

Another factor affecting atmospheric composition is that gases escape to space. The active young Sun was a powerful source of ultraviolet radiation (Fig. 1). Far UV wavelengths between 100 and 200 nm are absorbed by H_2O and CO_2 and cause these molecules to break up into atoms or into simpler molecules such as H_2 and CO . The survivors are in general poor infrared coolants. The more energetic UV (EUV, <100 nm) is strongly absorbed at very high altitudes where only poor infrared coolants remain. Without effective

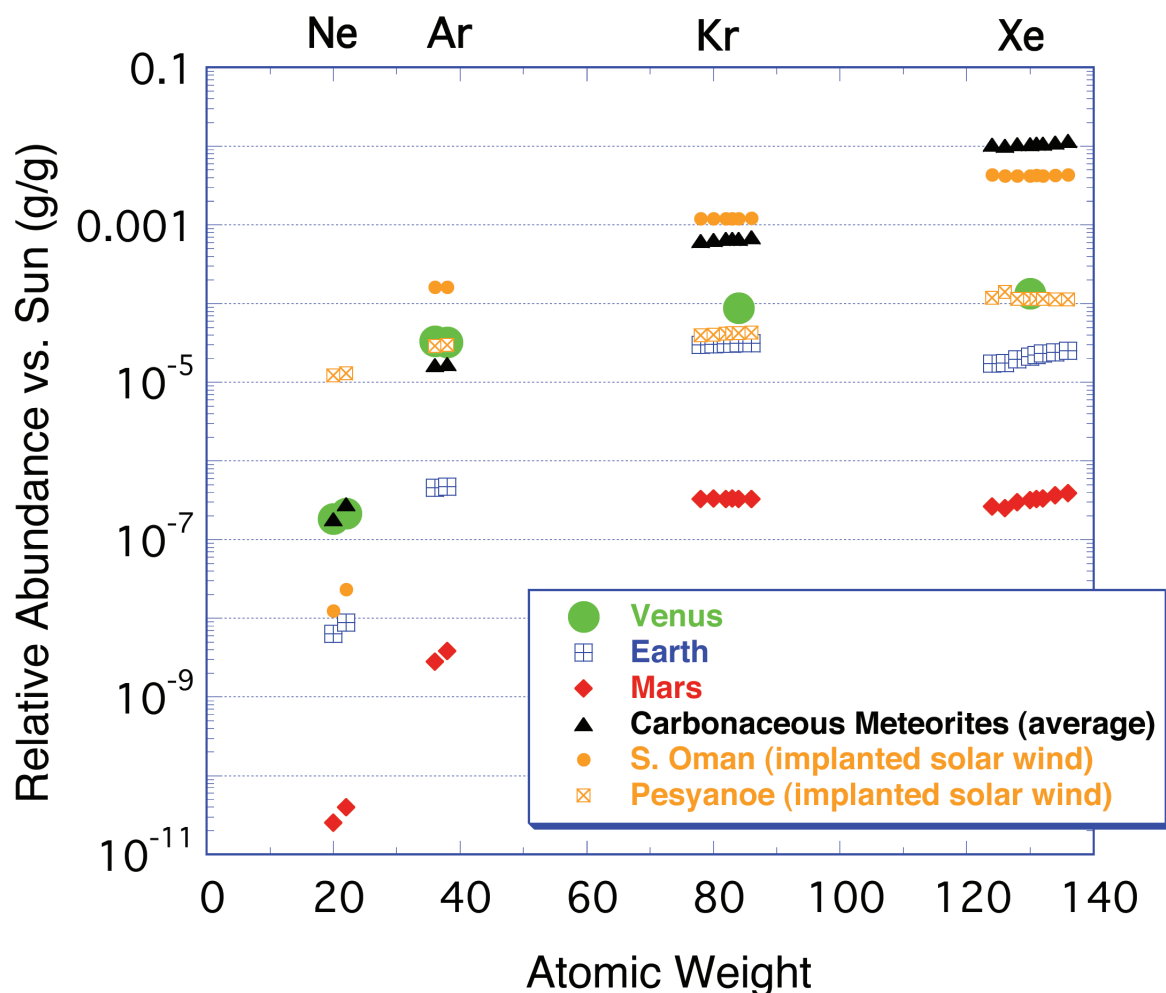


FIGURE 2 Noble gas isotopic abundances are shown relative to their abundances in the Sun. A purely solar abundance pattern would be a horizontal line. Apart from Xe, the noble gases on Earth and Mars resemble those in carbonaceous meteorites (Pepin 1991), although the planets are greatly depleted. Xenon is discrepant both in quantity and isotopic pattern. Evidence that Earth experienced vigorous hydrogen escape is preserved in the mass-fractionated isotopes of Ne and Xe (Ozima and Podosek 2002). Xenon—the heaviest gas in the

atmosphere—is strongly mass fractionated compared to any plausible source; hydrogen escape to space can produce the observed isotopic fractionation (Pepin 1991). The required hydrogen flux to space is high but within the range permitted by EUV emission from the active young Sun. Venus more closely resembles the solar wind noble gases implanted in the meteorites Pesyanoe and South Oman, although the data for Venus are poor (isotope ratios are effectively unconstrained, Kr is very uncertain, and Xe is an upper limit).

coolants the EUV makes the thin gas very hot. If hydrogen is abundant the hot gas can balance its energy budget by hydrogen escape. Evidence that Earth experienced vigorous hydrogen escape is preserved in the mass-fractionated isotopes of Ne and Xe (FIG. 2). Missing radiogenic xenon provides another strong argument that xenon escaped (Porcelli and Pepin 2000).

Water catches more interest than any other volatile, perhaps because water is more interesting than noble gases and its behavior is simpler than carbon's. Most water accreted by Earth was probably delivered in the form of hydrous silicates. Water can also be made in situ by oxidizing H₂ or by oxidizing organic molecules (Abe et al. 2000), but neither works well for Earth: the former gives a D/H ratio that is too low while the latter gives a C/H ratio that is too high. The hydrous silicates were themselves secondary, products of chemical reactions with liquid water. The water was first condensed as ice, either locally in the planetesimals from which the bulk of Earth was made (Abe et al. 2000), or in more distant planetesimals scattered from what is now the asteroid belt (Morbidelli et al. 2000), or in comets. The likelihood that any known source could deliver an ocean of water to Earth after the Moon-forming impact is demonstrably small (Levison et al. 2001).

AFTER THE MOON-FORMING IMPACT

Although the Moon-forming impact may not have been the last big impact, it probably was the last time that Earth was hit by another planet. The impact is currently thought to

have occurred at around 40–50 Ma (see Halliday 2006). By coincidence the Sun reached the Main Sequence at ~50 Ma. This is a good place to take up Earth's story (FIG. 3).

Most of the mantle was melted by the Moon-forming impact, and some of it was vaporized (Canup 2004). Immediately after the impact, the atmosphere was mostly rock vapor topped by ~2500K silicate clouds. For a thousand years the silicate clouds defined the visible face of the planet. The new Earth might have looked something like a small star or a fiery Jupiter wrapped in incandescent clouds. Silicates condensed and rained out at a rate of about a meter a day. Mixed into the atmosphere, at first as relatively minor constituents but becoming increasingly prominent as the silicates fell out, were the volatiles. Because convective cooling requires that every parcel be brought to the cloud tops to cool, the mantle should have largely degassed, with the notable exception of water, which remained mostly in the molten mantle and which degassed as the mantle froze. When the silicates were gone, a hot CO₂-CO-H₂O-H₂ atmosphere remained, although at first most of Earth's water would have been dissolved in the molten mantle. Also left in the atmosphere were nitrogen, the noble gases, and possibly moderately volatile elements such as Zn and Pb, some of which did not fully condense until after the surface of the magma ocean froze.

How thick the atmosphere was is debatable. The Moon-forming impact may or may not have expelled a significant fraction of Earth's pre-existing volatiles, and Earth may or may not have had abundant volatiles to lose. A primary H₂ atmosphere, because of its low mean molecular weight,

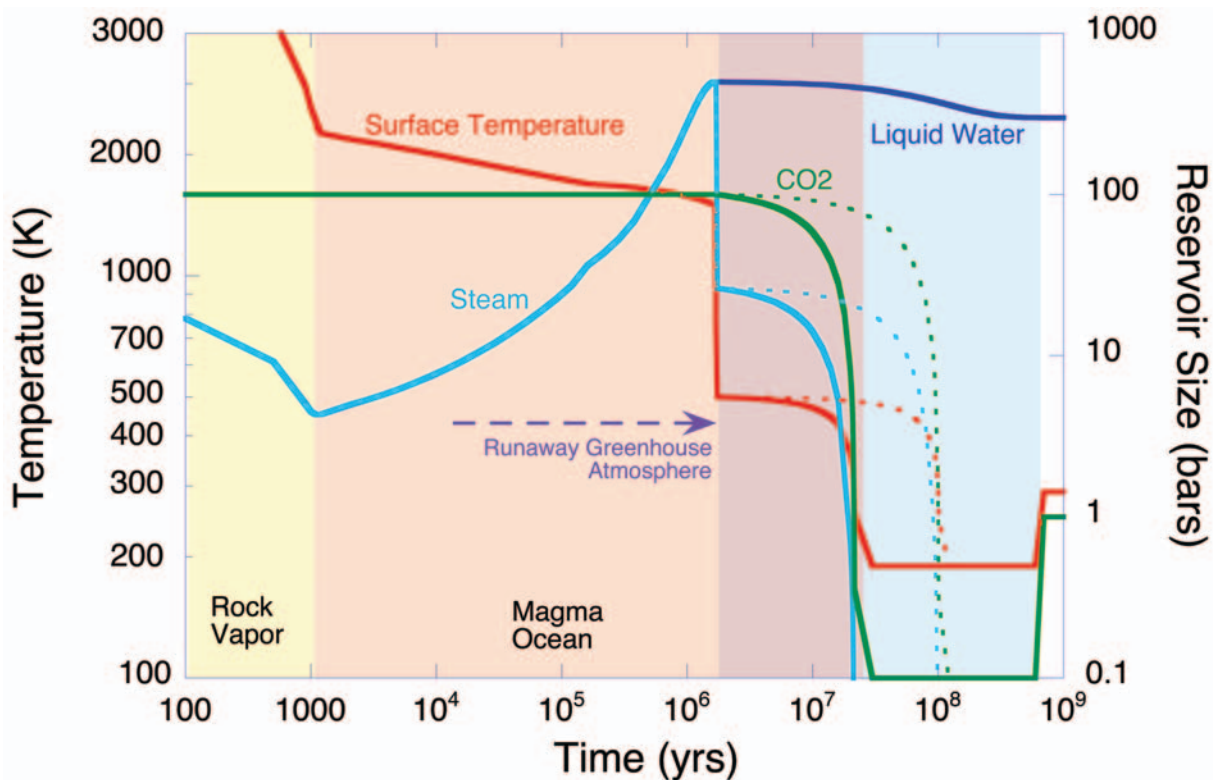


FIGURE 3 A history of temperature, water, and CO₂ during the Hadean. The curves show the surface temperature and the amount of water and CO₂ in the atmosphere and hydrosphere after the Moon-forming impact. Earth's water oceans today are equivalent to 270 bars of steam. Earth was initially enveloped in rock vapor for 1000 years. The magma ocean lasted some 2 Myr, prolonged by the runaway greenhouse effect (FIG. 4). Most of Earth's water degassed as the mantle solidified. After the mantle froze, geothermal heat could no longer sustain a steam atmosphere, and the steam atmosphere condensed to form a warm (~500K) water ocean under ~100 bars of CO₂. This warm wet

early Earth would have lasted as long as Earth's CO₂ stayed in the atmosphere. For specificity, I have assumed that CO₂ is subducted into the mantle on either a 20 Myr (solid curves) or 100 Myr (dashed curves) timescale. The asymptotic level of CO₂ is presumed to be controlled by chemical weathering of oceanic crust and abundant impact ejecta. Prior to the origin of life, in the absence of an abundant potent greenhouse gas, the surface should have been icy, although occasional impacts would have caused thaws. After the Late Heavy Bombardment, the CO₂ is allowed to return to ~1 bar in order that the surface be clement; this is arbitrary.

would have readily escaped. But a secondary atmosphere would have to be pushed off. It is generally agreed that the volatiles on the side of Earth that got hit were lost, but it is an open question how volatiles on the other side could be lost. Recent theory suggests that the answer depends on whether there had been a deep liquid-water ocean on the surface. A thin atmosphere above a thick water ocean can be expelled. Otherwise the atmosphere is retained (Genda and Abe 2005). One notes that water is retained in either event. The view taken here is that the planet that became Earth was water rich.

Thermal blanketing by the atmosphere controlled the cooling rate of the magma ocean (FIG. 3). When hotter than 2000K, cooling rates were high, although well short of what they would be for a bare planet (Abe et al. 2000). But after the surface cooled below ~1700K, the thermal blanketing became extremely effective and the atmosphere relaxed into a runaway greenhouse state (FIG. 4) sustained by sunlight and geothermal heat flow. The runaway greenhouse limit for Earth is ~310 W/m². With sunlight accounted for, the runaway greenhouse limit tells us that the geothermal heat flow was ~140 W/m² (FIG. 4). As the Earth cooled the surface was kept molten by a stabilizing feedback between water vapor's control over the surface temperature and water's solubility in the melt (Abe and Matsui 1988). Because of this feedback, the mantle degassed most of its water towards the end of the runaway greenhouse phase (Zahnle et al. 1988). Once the runaway greenhouse was in place, it took ~2 million years to cool the mantle to the freezing point. This history is depicted in FIG. 3.

Once the mantle was mostly frozen, the mantle cooled by solid-state convection with a vigor set by the viscosity at the top of the mantle. Heat flow was too small to affect the climate. The mid-ocean ridges, which are somewhat analogous, suggest that the heat flow was no more than 1–10 W/m². At this point the runaway greenhouse collapsed and the steam rained out (at a modest rate of about 1 m/yr). Thereafter the surface was solid and cool and mostly under the waves.

After the Deluge

How hot it was at Earth's surface depends on how much CO₂ was present in the atmosphere and for how long. For as long as most of Earth's CO₂ remained in the atmosphere, the surface temperature would have been ~500K (FIG. 4). Presumably carbonate rock formed quickly during hydrothermal circulation through fresh crust, but the capacity of the crust to store carbonate is limited. At any one time, available divalent cations in the uppermost crust could fix the molar equivalent of ~10 bars of CO₂. The oceanic crust recycles on the order of 1 Myr timescale, resulting in a global heat flow on the order of 1 W/m². Provided that carbonates could subduct into the mantle, it could have taken as little as 10 Myr to remove 100 bars of CO₂. Today most subducted carbonate enters the mantle rather than erupting through arc volcanoes. A hotter mantle made carbonates less stable, but the hotter mantle was also less viscous, letting foundering blocks sink more quickly. If the carbonates did not reach the mantle, the bulk of the CO₂ would have

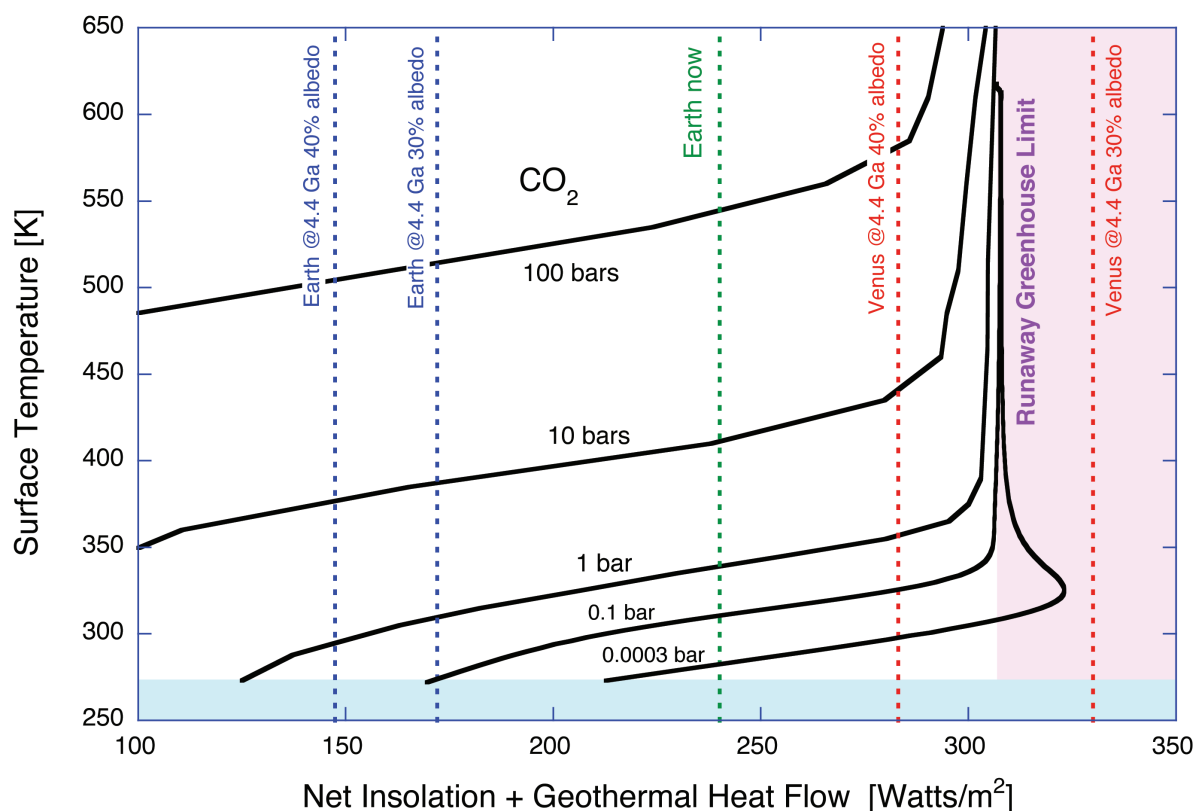


FIGURE 4 The H₂O–CO₂ greenhouse effect. This plot shows the surface temperature as a function of radiated heat for different amounts of atmospheric CO₂ (after Abe 1993). The radiated heat is the sum of absorbed sunlight (net insolation) and geothermal heat flow. Net insolation takes into account reflection. Net insolation for Earth and Venus at ca. 4.4 Ga (after the Sun reached the Main Sequence) are shown at 30% and 40% albedo. The albedo used here refers to all wavelengths of sunlight, visible and invisible. The higher

albedo may be appropriate for a cloudy atmosphere. The plot shows that the atmosphere “runs away” if radiated heat exceeds 310 W/m². In a runaway, the surface temperature rises to the next buffer, which for Earth would be the melting point of rocks. Note that CO₂ does not by itself cause a runaway. Earth entered the runaway greenhouse state only ephemerally after big impacts that generated big pulses of geothermal heat. Venus, on the other hand, would have fallen into the runaway state when its albedo dropped below 35%.

remained in the atmosphere and the surface would have remained at ~500K unless there were stable continental platforms on which to put carbonate rocks (Sleep et al. 2001).

By contrast, hydrous minerals are not very stable at high temperatures and modest pressures. If they survived a fast passage to the mantle, they may not have stayed there. They ought instead to have formed water-rich melts at the base of the magma ocean, which would have ascended as proto-granitic plumes. We therefore expect that the early Hadean mantle was dry and that the early water oceans were if anything deeper than they later became.

The argument that the early oceans were deep presumes that as long as the mantle was vigorously convective, every parcel visited the surface to cool, and therefore its water content was set by conditions near the surface, where hydrous minerals were unstable. Implicit is the assumption that the mantle convected as a whole. If instead the mantle convected in layers, the greater stability of hydrous phases at high pressure becomes relevant. This opens the possibility that substantial amounts of water, initially incorporated as solute in magma, could have remained in the lower mantle. Later, when layered convection broke down, the deep water degassed. In this way it is possible for the oceanic volume to grow over time.

AS COLD AS HADES...

The faint young Sun suggests that, when the Hadean was not infernally hot, it could have been bitterly cold. A temperate Hadean Earth would have needed either enormous geothermal heat flow or abundant potent greenhouse gases. Geothermal heat was insignificant after 4.4 Ga, save immediately following big impacts. Of greenhouse gases the only good candidates are CO₂ and CH₄. (Water vapor is in fact the most important greenhouse gas, but it is a dependent variable, mobilized from oceans and ice sheets as needed.) Methane would be a candidate if there were reducing agents or catalysts to generate it from CO₂ and H₂O. On Earth today methane is mostly of biological origin. Methane is a good candidate for keeping Earth warm once it teemed with life, but it is not clear that there was a big enough source of it when Earth was lifeless.

It takes about one bar of CO₂ to provide enough greenhouse warming to stabilize liquid water at the surface (FIG. 3). Although this represents only about 0.5% of Earth's carbon inventory, it is 3000 times more than is there today. We have suggested that CO₂ would have been scoured from the Hadean atmosphere by chemical reactions of carbonic acid with abundant ultramafic volcanics and impact ejecta (Zahnle and Sleep 2002). The carbonates in the weathered ultramafic sediments—if they subduct—would have left too little CO₂ in the air to avert a snowball Earth.

The resultant ice shell over an early Hadean ocean was, at least in places, thin. For heat flows of 1–10 W/m², the ice would be 10 to 100 m thick. Sunlight diffusing through thin ice supplements the geothermal heat and can stabilize the ice thickness at something like 1–2 m (Pollard and Kasting 2005). This ice is thin enough to break easily, allowing gas exchange between the ocean and the atmosphere. In the late Hadean (ca. 4 Ga), when heat flow had on global average dropped to 0.3 W/m², we would expect that heat flow was patchy and that over large regions heat flow was still 1–10 W/m² and, as a consequence, ice was locally thin.

The late bombardment was another factor affecting the Hadean surface environment (Koeberl 2006). During the Hadean, the average energy flux delivered by impacts was about a tenth that delivered by geothermal heat flow. Given that impact effects are strongly focused on the

surface, we might expect impacts to be as important to the surface as geological forces, and occasionally much more important. We have discussed the environmental effects of big impacts in detail elsewhere (Zahnle and Sleep 1997). Here we simply note that a big impact could transform a snowball Earth into a water world and that the change could have lasted for a considerable time, especially if it released pent-up greenhouse gases. For impacts similar to those resulting in the bigger lunar basins, the thaws would have lasted at least 100 years, and there would have been hundreds of such events on Earth. There were probably thousands of impacts big enough to melt the ice. Each such impact triggered a brief impact summer.

ZIRCONS

The chief source of terrestrial data for the Hadean are ancient detrital zircons found in Archean and Proterozoic quartzites (Harrison et al. 2005; Valley et al. 2005). U–Pb dating gives accurate ages as old as 4.4 Ga. Oxygen isotopes provide compelling evidence that rocks on Earth were being chemically altered by liquid water before 4.2 Ga and probably before 4.3 Ga (Valley et al. 2005). The zircons are silent on whether the water temperature was 273K or 500K, but the data strongly suggest that Earth's water was in place by 4.2 Ga. A more controversial argument uses the absence of radiogenic Hf in the zircons to suggest that Lu (the parent)—a more incompatible element than Hf and therefore quicker to segregate into a granitic crust—was already separating from Hf at 4.5 Ga (Harrison et al. 2005). The physical separation of Hf-bearing sediment from Lu-bearing sediment might even imply subaerial weathering. In any case the mere existence of old zircons implies that there were places near the surface where zircons could be protected from subduction for hundreds of millions of years. Evidently the processes that built the continents were well underway by 4.4 Ga.

THE ATMOSPHERE ENTERING THE ARCHEAN

Although the Hadean was a time of geologic upheavals and huge climate swings, the system evolved quickly, and Earth's youthful excesses were mostly soon forgotten. It seems reasonable to think that the atmosphere and hydrosphere at the beginning of the Archean were not hugely different from what they are now.

The most important distinctive qualities of the Archean atmosphere are the absence of O₂ and the presence of a strong greenhouse effect. Oxygen's history has been recently reviewed by Canfield (2005). It has been argued that the Archean was very warm (Knauth and Lowe 2003); to our knowledge it has not been argued that the Archean was bitterly cold. If the Archean was warm, potent greenhouse gases were needed to counter the faint Sun (Sagan and Mullen 1972). The leading candidates remain CO₂ and CH₄. Methane is the better choice if the Archean were biologically productive, while CO₂ is the better choice if Earth were lifeless or nearly so.

The early Archean ocean could have been deeper than it is now. There are two reasons to suggest this. One is the expectation that a hotter upper mantle takes up water less easily and degasses water more easily. The other is the inevitable steady loss of hydrogen to space. Hydrogen escape is not negligible (Catling et al. 2001). If methane were the greenhouse gas of the Archean, hundreds of meters of water were lost to space.

A discussion of the early atmosphere seems incomplete without mentioning the most abundant gas in the atmosphere. Earth has 0.78 bars of N₂ in air and a roughly comparable amount in the crust; the mantle inventory appears

to be ten times smaller. The crustal reservoir may be linked to biological activity. The small mantle reservoir is isotopically lighter than either of the big reservoirs. This may mean that light nitrogen has been preferentially subducted, or it may mean that the surface inventories have grown heavier by escape of light nitrogen. Overall, these observations imply that before the origin of life there may have been 2 or 3 bars of N₂ in the atmosphere, an amount approaching what we see in the atmosphere of Venus today.

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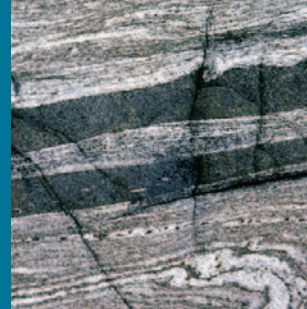
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Antiquity of the Oceans and Continents

Allen P. Nutman¹



Tracing the origin of the oceans and the division of the crust into distinct oceanic and continental realms relies on incomplete information from tiny vestiges of surviving oldest crust (>3.6 billions years old). Billions of years of tectonism, melting and erosion have obliterated the rest of that crust. Oceans and continental crust already existed almost four billion years ago because water-laid sedimentary rocks of this age have been found and because tonalites dominate in gneissic sequences dating from this period. Tonalites are igneous rocks produced by partial melting of hydrated basaltic crust at convergent plate boundaries. Collisional orogenic systems produced granites by partial melting of tonalite crust 3.7–3.6 billion years ago. Thus the oldest rocks can be understood in terms of a plate tectonic regime. The chemistry of even older detrital zircons may argue for continental crust and oceans back to 4.4 and 4.2 billion years ago, respectively. Maybe only within the first 200 million years was Earth's surface hot, dry and predominantly shaped by impacts.

KEYWORDS: Early Earth, zircons, Acasta, Isua, Akilia, Jack Hills, oceans, continents

INTRODUCTION

There must have been a time long ago when geological processes were vastly different from today's. Major questions related to this are: How old are the oceans? When did the crust divide into distinct basaltic oceanic and granitic continental domains? When did plate tectonics begin to dominate over impacts as the main process crafting the crust? Understanding this beginning makes study of the earliest Earth exciting and centres on interpretations of the tiny fragments of crust discovered from Earth's first billion years, i.e. pre-3.5 Ga (e.g. Black et al. 1971; Moorbath et al. 1973; Compston and Pidgeon 1986; Bowring and Williams 1999). This article focuses on evidence that the oceans, continental crust and some form of plate tectonics all existed four billion years ago, and maybe even earlier.

THE OLDEST GEOLOGICAL RECORD (4.4–3.6 Ga)

Almost undeformed and unmetamorphosed volcanic and sedimentary rocks have survived from 3.5 billion years ago, greatly aiding interpretation of the early Earth. However, a major problem for interpreting the oldest, ≥ 3.6 Ga geological record is that the evidence occurs in gneiss complexes where the original character of the rocks has been mostly obliterated (FIG. 1A). Fine-scale resolution of the chronology

of these gneiss complexes is an important starting point for establishing the timing of events on the early Earth. This has been made possible by zircon dating using the coupled ^{235}U – ^{207}Pb and ^{238}U – ^{206}Pb radioactive decay systems (shortened to U/Pb). Sensitive, high mass-resolution ion microprobes date domains typically 20 μm wide by 1 μm deep within single zircons. Guided by cathodoluminescence imaging, individual igneous growth and recrystallised domains can be dated in this way to obtain accurate, complex geological histories for zircon populations from single rocks (FIG. 1B). U/Pb zircon analysis by thermal ionisation mass spectrometry can now date single fragments of large grains, and also provides valuable information on the early Earth (e.g. Crowley et al. 2002).

There are now numerous accurate U/Pb zircon dates on the oldest rocks and minerals, with errors of only a few million years (i.e. only 0.1% of a >3.5 Ga age).

The Global 4.0–3.6 Ga Rock Record

Rocks preserved from the 4.0–3.6 Ga period occupy about a millionth of Earth's crust; the remainder were destroyed by tectonic activity, melting and erosion over billions of years. These old rocks have been discovered in Greenland, Australia, Canada (three localities), Antarctica and China (summary in Nutman et al. 1996 apart from Stevenson et al. 2006 for the most recent Canadian one). Some 4.0–3.6 Ga detrital zircons have survived in post-3.6 Ga sedimentary rocks but are not discussed further here because they provide no additional information to that obtained from surviving 4.0–3.6 Ga rocks. Earth's oldest known rocks are 4.03–3.96 Ga old (Bowring and Williams 1999) and form small domains ($\ll 1 \text{ km}^2$) in the *Acasta Gneisses* of north-western Canada. The *Acasta Gneisses* are migmatites—rocks formed from several generations of deformed and metamorphosed igneous intrusions—from which it is difficult to obtain samples of only one generation for chemical and isotopic study (Bowring and Williams 1999).

The oldest gneiss complexes are composed of >90% of rocks of intrusive origin, now strongly deformed (FIG. 1A). Rare areas of relatively little deformation show that these usually formed from older tonalitic and younger granitic components. Tonalites are potassium-poor intrusive rocks generated by melting of hydrated mafic crust after transformation into garnet amphibolite or eclogite, probably in the ancient equivalent of subduction zones (summary by Martin et al.

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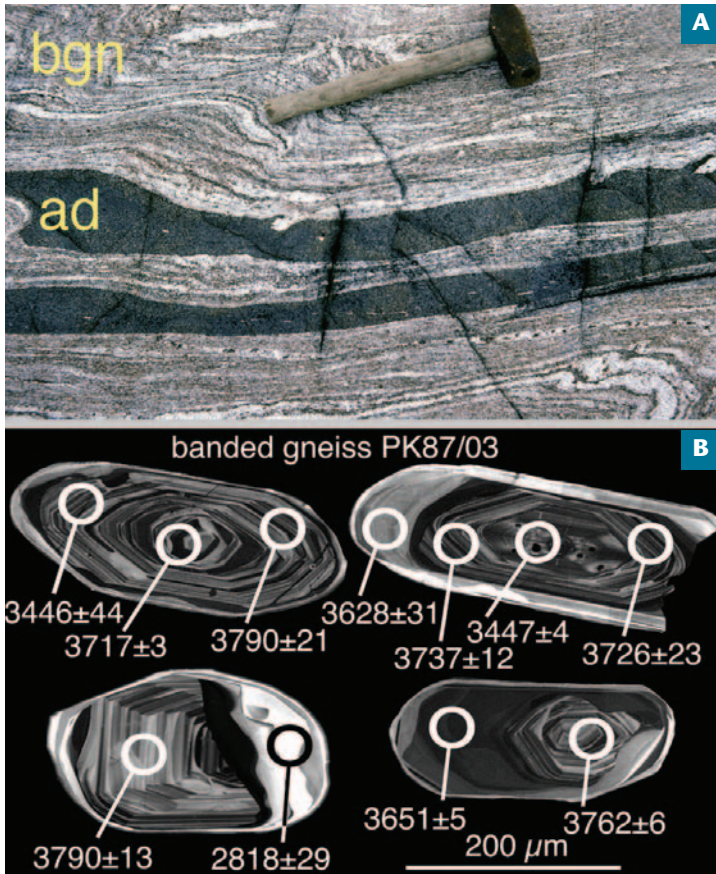


FIGURE 1 (A) Typical banded gneiss (bgn) consisting of older tonalite (>3.7 Ga, grey) and younger granite (3.65 Ga, white), Itsaq Gneiss Complex, Greenland. The gneiss was cut by a mid-Archean dyke, now an amphibolite (ad), which was strongly deformed at 2.7 Ga. **(B)** Cathodoluminescence images of typical zircons separated from banded gneiss. Zircons were embedded in epoxy resin and sectioned prior to imaging. 3.79 Ga oscillatory-zoned igneous zircons were partly replaced and overgrown during high-grade metamorphism and deformation over the following one billion years. Dates are expressed in millions of years, with 1σ analytical errors.

2005). The granites were produced by remelting of predominantly tonalite crust during superimposed orogeny (Friend and Nutman 2005). In the *Itsaq Gneiss Complex* of Greenland (summary in Nutman et al. 1996), tonalites of different ages (FIG. 2) dominate and are infiltrated by granites, whereas in the Narryer Gneiss Complex of Western Australia, granites predominate with only rare surviving tonalites (Kinny and Nutman 1996). Volcanic and sedimentary rocks form <10% of the >3.6 Ga rock record. The volcanic and sedimentary rocks are scattered through the gneisses as enclaves and tectonic slivers. These range in size from the 35 km long *Isua supracrustal belt* of the Itsaq Gneiss Complex down to one-metre pods. Gabbros and ultramafic rocks are more widespread, and occur in small amounts in most >3.6 Ga gneiss complexes (see Nutman et al. 1996). Small areas of weakly deformed rocks have been found in the Itsaq Gneiss Complex. These rocks provide important information on the early Earth that is harder to obtain from other localities, and therefore they are emphasised in this article.

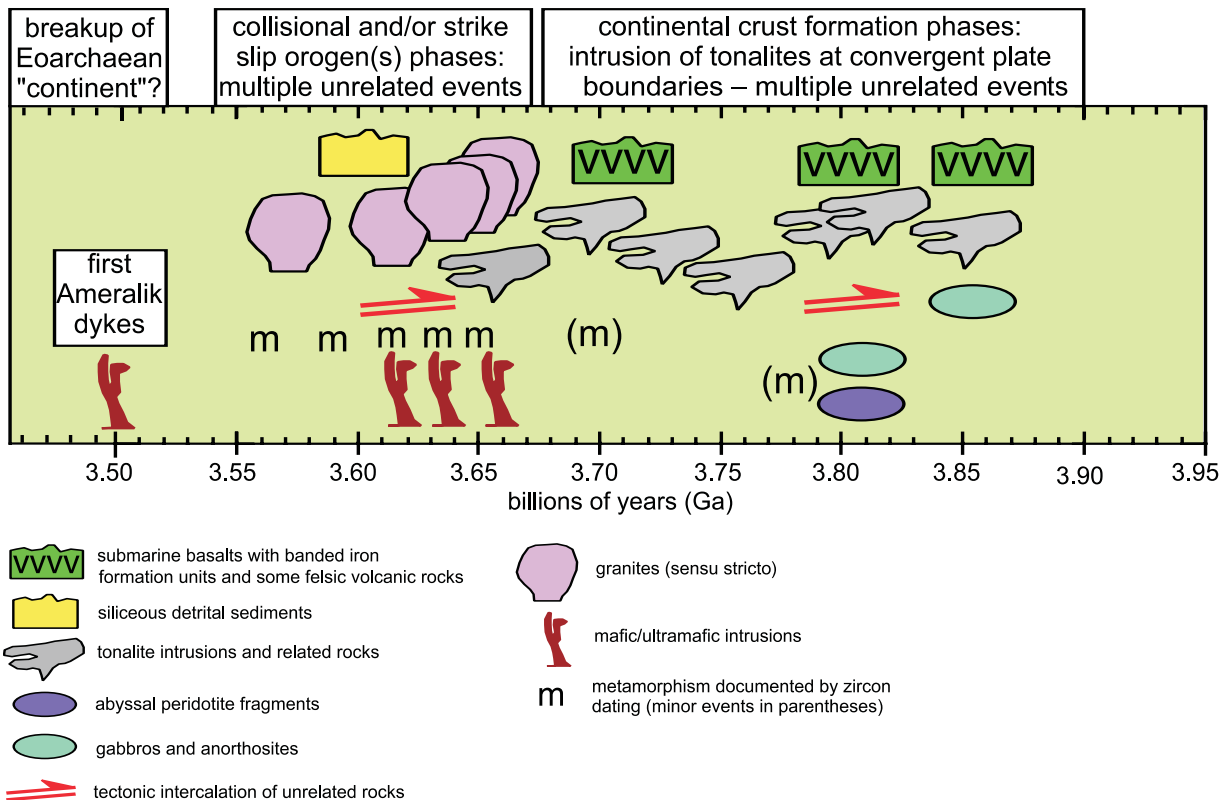


FIGURE 2 Schematic evolution for the Itsaq Gneiss Complex, southwest Greenland. This interpretation is based on extensive fieldwork coupled with zircon dating of more than 100 rocks (Friend and Nutman 2005). The figure illustrates the complexity of crustal evolution shown by all surviving fragments of oldest crust. Each pictogram represents a generation of rocks whose age is known from zircon dating.

Each generation of granite and tonalite has a single population of oscillatory-zoned igneous zircons (Nutman et al. 1996, 2000; Friend and Nutman 2005). The figure is arranged such that generations of volcanic and sedimentary rocks are shown near the top, granites and tonalites in the middle, and mafic intrusions and abyssal peridotite (mantle) fragments near the base.

Antiquity of Oceans from the Oldest Water-laid Sediments and Basalts

The strongly deformed amphibolite facies volcanic and sedimentary rocks that dominate the Isua supracrustal belt are tectonic fragments of unrelated 3.7 and 3.8 Ga sequences (Nutman et al. 1997). Rocks with surviving volcanic and sedimentary structures form a tiny amount of the belt. In these rocks, Komiya et al. (1999) recognised unambiguous relicts of pillow structures in amphibolites (FIG. 3A). Because pillow structures form when basalt lavas are erupted under water on the seafloor, they prove the submarine origin of these Isua amphibolites. The associated Isua quartz–magnetite banded iron formations (BIFs) are water-laid sedimentary rocks (Moorbath et al. 1973). Their generally fine-scale banding is a deformational structure (FIG. 3B LEFT), and only in rare, relatively undeformed zones is genuine sedimentary layering preserved (FIG. 3B RIGHT).

The island of Akilia consists of Itsaq Gneiss Complex gneisses derived from multiple generations of strongly deformed 3.85–3.62 Ga tonalites and granites (Nutman et al. 1996, 2000). The gneisses contain lenses of amphibolite and layers of siliceous rocks (FIG. 3C). These are all more strongly deformed and thus are harder to interpret than some of the Isua rocks. Magnetite-bearing varieties of the Akilia siliceous rocks have been interpreted as sedimentary in origin because they have trace element signatures similar to Isua BIF (Friend et al. 2002) and show iron isotope fractionation unlike that in igneous rocks (Dauphas et al. 2004). A 3.84 Ga minimum age has been proposed for Akilia amphibolites and associated siliceous layers (e.g. Nutman et al. 2000), but doubts have been voiced concerning this age (e.g. Whitehouse et al. 1999). Isua currently remains the universally accepted site of the oldest direct evidence for oceans, as shown by 3.8–3.7 Ga BIF sedimentary rocks and pillow lavas, while debate continues on whether the Akilia rocks push this direct evidence for oceans back to ≥ 3.85 Ga. Other localities with >3.6 Ga volcanic or sedimentary rocks are definitely the Saglek area of Labrador (Canada) and possibly near the northern edge of the Superior Province on the shores of Hudson Bay (Canada).

Formation and Evolution of 3.9–3.6 Ga Continental Crust Using the Plate Tectonic Model

Plate tectonic processes are sufficient to explain 3.9–3.6 Ga crust formation, deformation and metamorphism in the Itsaq Gneiss Complex (Friend and Nutman 2005). In the vicinity of the Isua supracrustal belt, intrusive, volcanic and sedimentary rocks of different ages had been juxtaposed along early mylonitic shear zones and already folded by 3.6 Ga (Nutman et al. 1996, 1997, 2002; Crowley et al. 2002). This style of geological evolution probably reflects the operation of some form of plate tectonics by 3.8–3.6 Ga, in which compression at destructive plate margins caused the interleaving of unrelated rocks (Komiya et al. 1999; Hanmer and Greene 2002). Zircon dating of more than 100 Itsaq Gneiss Complex samples, combined with fieldwork, has led to an understanding of the typical evolution of ancient crust (FIG. 2). Multiple generations of 3.85–3.6 Ga intrusive rocks are recognised. From 3.85 to 3.69 Ga, episodic growth of new continental crust took place via emplacement of tonalites, derived from partial melting of hydrated basalt, into sequences of basalt with BIF layers. This was followed between 3.65 and 3.55 Ga by episodic granite production through melting of tonalite crust, as well as by high-grade metamorphism and complex deformation. These events are interpreted to reflect collisional and/or strike-slip orogenic phases (Friend and Nutman 2005). In other examples of the world's oldest gneiss complexes (e.g. the Narryer Gneiss Complex of Western Australia;

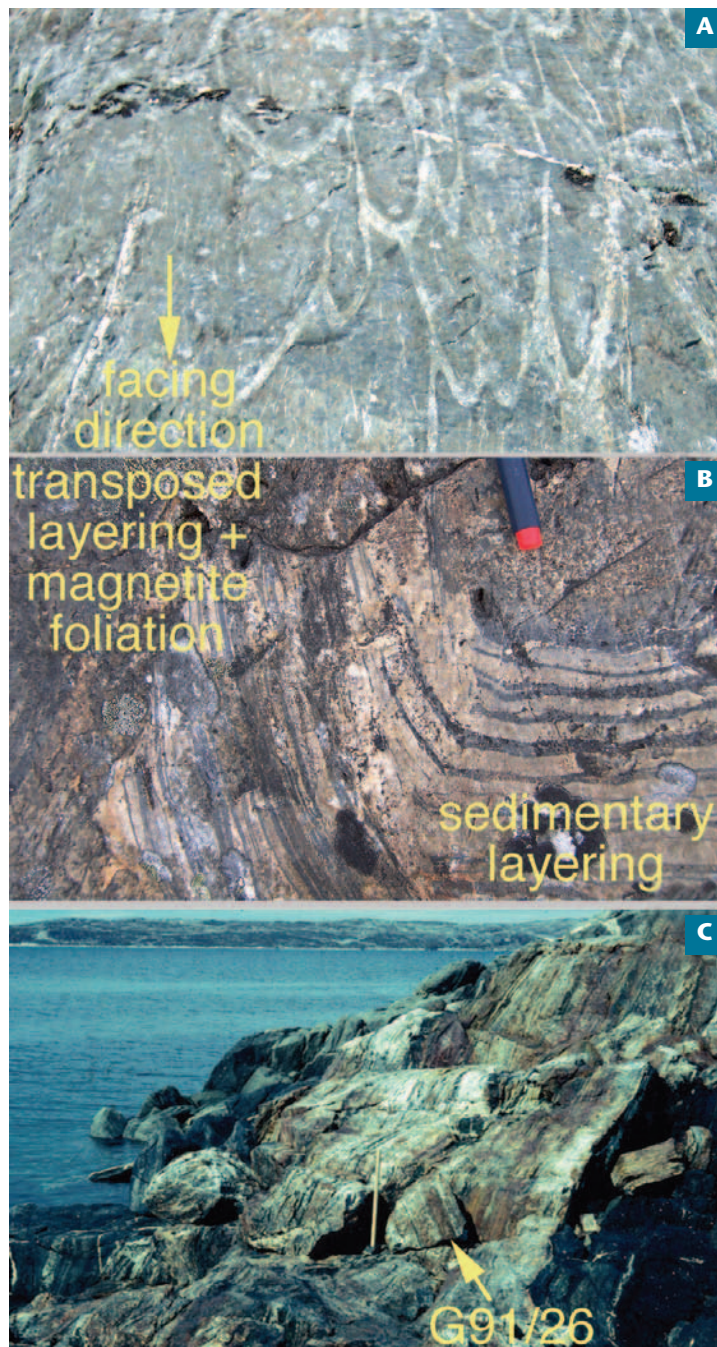


FIGURE 3 Candidates for the oldest volcanic and sedimentary rocks from the Itsaq Gneiss Complex, southwest Greenland. (A) Rare pillow lava structure in Isua amphibolites (discovered by Komiya et al. 1999). The shape of the pillows is well-enough preserved to allow determination of the top direction (arrow indicates facing direction). (B) Low-strain area of the water-laid banded iron formation in the Isua supracrustal belt. Original, albeit deformed, sedimentary layering (right) is rotated, strongly attenuated and overgrown by a magnetite foliation to form the typical regional banding in these rocks (left). (C) Approximately 5 m thick siliceous layer in amphibolites, Akilia Island. G91/26 marks the site of a magnetite-bearing unit with trace element and iron isotope signatures similar to those in Isua BIF. This is the contested candidate for Earth's oldest preserved sediment.

Kinny and Nutman, 1996), 3.65–3.55 Ga was an important period for high-grade metamorphism and granite formation. This might reflect an early 'global' collisional orogeny, during which blocks of crust dominated by tonalite were amalgamated to form a larger domain of continental crust.

Understanding the Pre-4.0 Ga Earth Using the Oldest Detrital Zircons, Western Australia

The oldest fragments of Earth's geological record are rare 4.4–4.0 Ga, <500 µm detrital zircons (Fig. 4) from Precambrian metaquartzites in the Yilgarn Craton of Western Australia. These zircons are mostly from the Jack Hills (Compston and Pidgeon 1986; Mojzsis et al. 2001; Wilde et al. 2001), but have also been recovered from other Yilgarn localities (e.g. Wyche et al. 2004). Rare >4.0 Ga zircons have also been found in 2.7–2.6 Ga Yilgarn granites (Nelson et al. 2000).

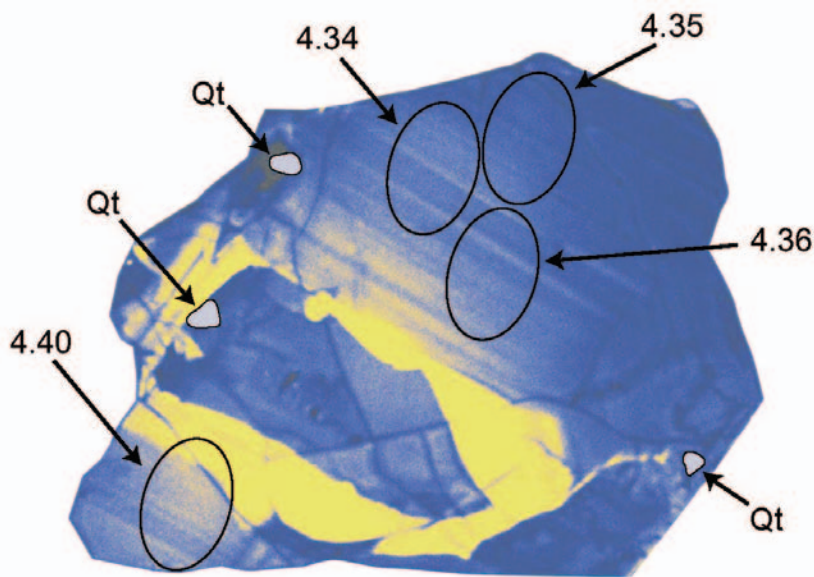


FIGURE 4 False colour cathodoluminescence image of the 200 µm diameter, approximately 4.4 Ga Jack Hills zircon. This zircon is the oldest-known part of Earth. Ion microprobe analytical sites are indicated by black ellipses with ages in billions of years. Qt denotes quartz inclusions in the zircon crystal. IMAGE SUPPLIED BY JOHN VALLEY

The ancient zircons contain inclusions of quartz (Cavosie et al. 2005) and thus were produced from silica-saturated igneous rocks, suggesting that granites (*sensu lato*) existed before 4.0 Ga (e.g. Wilde et al. 2001). The >4.0 Ga Jack Hills zircons have isotopically heavy oxygen ($\delta^{18}\text{O} = 5.0$ to 7.3 per mil) compared with the mantle, giving rise to proposals that well before 4.0 Ga, granites had been produced by melting of older crust previously hydrated by cool surface waters (Mojzsis et al. 2001; Wilde et al. 2001; Valley et al. 2005). The strands of evidence for this proposal are the focus of debate and scrutiny. If this is correct, granitic 'continental' crust and oceans (or at least cool surface conditions with standing water) occurred very early in Earth's history. The preservation of these very old zircon crystals indicates that magma oceans had solidified to form crust by 4.4 Ga, though the nature of this crust and the composition of the source rocks of the 4.4–4.0 Ga zircons are not resolved: Were these zircons derived from tonalites formed by melting of pre-4.0 Ga hydrated basalt in a world dominated by oceanic crust? Or were they derived from low-temperature granites formed by melting, under an essentially modern tectonic regime, in a 4.4–4.0 Ga world containing extensive continental crust (Watson and Harrison 2005; Harrison et al. 2005)?

THE YOUNG EARTH

Oceans, as well as crust divided into distinct domains of hydrated basalt and granitic continents, were definitely established by almost 4 Ga and maybe as early as 4.4 Ga. An inherent feature of this crustal dichotomy would have been linear crustal accretion and collisional orogeny at convergent plate boundaries (de Wit 1998), although the architecture of these systems may have differed from that at modern plate boundaries. However, it is increasingly apparent that an arid, hot surface, with a crust entirely unlike today's, was restricted to the earliest part of Earth's history. This earliest terrestrial crust may have been like the Moon's crust, but on Earth, four billion years of geological activity have obliterated it.

An important unresolved issue is whether the volume of continental crust before 3.6 Ga was similar to or larger than today (Armstrong 1991), or if it increased as Earth aged (summarised by Bennett 2003). This question concerns destruction rates of early crust and is separate from the undeniable evidence that, since at least 4.0 Ga, new crust of tonalite was formed repeatedly by partial melting of an oceanic crust of hydrated basalt (summarised by Bennett 2003 and Martin et al. 2005).

Earth suffered numerous impacts in its earliest history (Glikson 2005; Koeberl 2006). However, since 3.8 Ga (oldest water-laid sediments) and maybe since 4.4 Ga (zircons from the oldest igneous rocks produced by partial melting of hydrated source materials), impact energy did not preclude the existence of oceans, and impacts were not the main crust-forming process. Instead, Earth's early crust would have been shaped by an early form of plate tectonics driven by greater internal heat (Davies 2006), with impacts only disrupting this process. Discoveries of relatively undeformed metasediments (like those in Fig. 3B) offer greater hope of finding the impact layers that must have been more common on the early Earth but that have largely eluded geochemical searches.

No rocks and minerals formed during Earth's first 150 million years, i.e. prior to 4.4 Ga, have survived for direct geological observation. Despite this, Nd and Hf isotope signatures from 4.4–3.6 Ga rocks and minerals provide evidence of a planetary-scale event during Earth's first 100 million years, an event that entailed major chemical fractionation in the mantle and probably featured an early magma ocean (e.g. Caro et al. 2003; Bennett 2003). These isotopic signatures are the only records of processes occurring prior to the beginning of a geological record in 3.6–4.4 Ga rocks and minerals.

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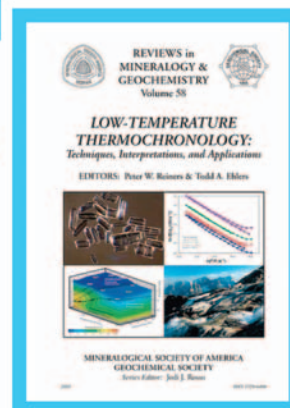
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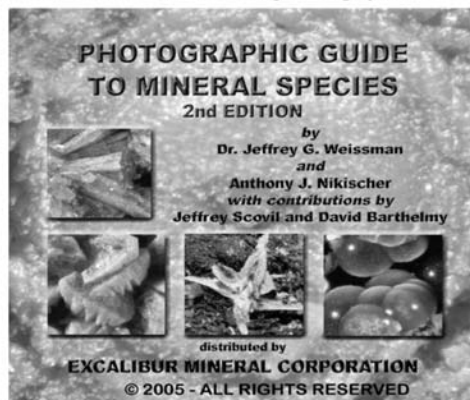


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The First Billion Years: When Did Life Emerge?

J. William Schopf¹



There are three principal lines of evidence from which we can infer the timing of the origin of life on Earth: stromatolites, microfossils, and carbon isotope data. All indicate that life emerged earlier than ~3500 million years ago, but the details and exact timing of life's beginnings remain unknown.

KEYWORDS: Archean, stromatolites, microfossils, carbon isotopes, oldest fossils, origin of life

INTRODUCTION

Although the overall pathway of the origin of life seems well defined—extending from biogenetic elements to organic monomers, then polymers, then information-containing macromolecules encapsulated in cells (Schopf 2002)—the details of this event, the how and when of life's beginnings, remain a mystery. Can the geosciences contribute to solving these problems?

Unfortunately, even the most detailed studies of the ancient rock record are unlikely to reveal the how of life's beginnings. Because all biomonomers and biopolymers are geochemically unstable, it is implausible that evidence of intermediate stages in the emergence of life could be preserved in ancient rocks. As to the timing of life's origin, the geosciences can provide only a partial answer—paleobiological studies of microbe-produced stromatolites, cellular microbial fossils, and carbon isotope evidence of microbial physiology have set a minimum date for life's existence, but none has revealed the *actual* age of life's emergence. Such insight might be obtained by tracing biological signals back through time and, at a particular horizon in the rock record, see them vanish and be replaced in older units by evidence of planet-wide sterility. One might even hope to find carbonaceous deposits that could plausibly be interpreted as the residuum of a life-generating “primordial soup.” Such, however, is not the case. Here, again, the problem is one of preservation—not of remnants of life but of the geological record itself.

According to Garrels and Mackenzie (1971), the average lifetime of sedimentary rocks—those in which fossils typically are preserved—is about 200 million years (Myr), and about 50% of such units that have survived to the present are Phanerozoic (<550 Ma in age), the remainder dating from the earlier, ~4000 Myr long Precambrian. “About 90 percent of the Precambrian once deposited is gone” (Garrels and Mackenzie 1971, p. 275), preserved units petering out with increasing geological age to yield a severely depleted

Archean (>2500 Ma) rock record. The age of the oldest-known sedimentary rocks—localized slivers of the highly metamorphosed Isua supracrustal belt of southwestern Greenland—is about 3800 Ma (Moorbath 2005). Only two thick ancient sedimentary sequences are known, those of the Pilbara Craton of Western Australia and the Barberton Greenstone Belt of South Africa and Swaziland, both with

ages between ~3500 and 3000 Ma and both regionally metamorphosed to greenschist facies.

Given the markedly depleted Archean rock record and the fossil-destroying effects of metamorphism, it is not surprising that the early fossil record is sparse. Nevertheless, both of these thick Archean sedimentary sequences contain megascopic stromatolites, microscopic fossils, and carbonaceous matter of biological isotopic composition. Thus, the documented history of life extends to at least ~3500 Ma, earlier chapters in the story having been lost as the older rock record was geologically recycled and destroyed.

EARLY ARCHEAN EVIDENCE OF LIFE

Hints of Life >3500 Ma in Age

The carbon isotope composition of particulate graphite in metasediments of the ~3800 Ma old Isua supracrustal belt of southwestern Greenland has long been interpreted as evidence of biological activity, a view supported by a recent report of ¹³C-depleted detrital carbonaceous microglobules in this sequence (reviewed by Schidlowski 2001). Graphite particles have also been reported from rocks of similar age at Akilia Island, near the Greenland coast (Moorbath 2005). Yet the Isua rocks are metamorphosed to amphibolite facies and those at Akilia Island to even higher grade, conditions that can reset carbon isotope values, such that original compositions can only be inferred (Schidlowski 2001). Additional studies are probably needed before the reduced carbon in these ancient units can be regarded as a firm indicator, rather than only a strong hint, of the existence of life.

Early Archean Stromatolites (>3000 Ma)

As used here, the term “stromatolite” refers to accretionary sedimentary structures, commonly thinly layered, megascopic and calcareous, inferred to have been formed by mat-building communities of mucilage-secreting microorganisms, mainly photoautotrophic microbes. Such structures can be difficult to differentiate from nonbiogenic look-alikes (geyserites, cave deposits, tectonically deformed sediments, and the like). Buick et al. (1981) and Walter (1983) proposed that a prime indicator of biogenicity is the presence of fossilized microbes within such a structure. To some, however,

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ARCHEAN STROMATOLITES

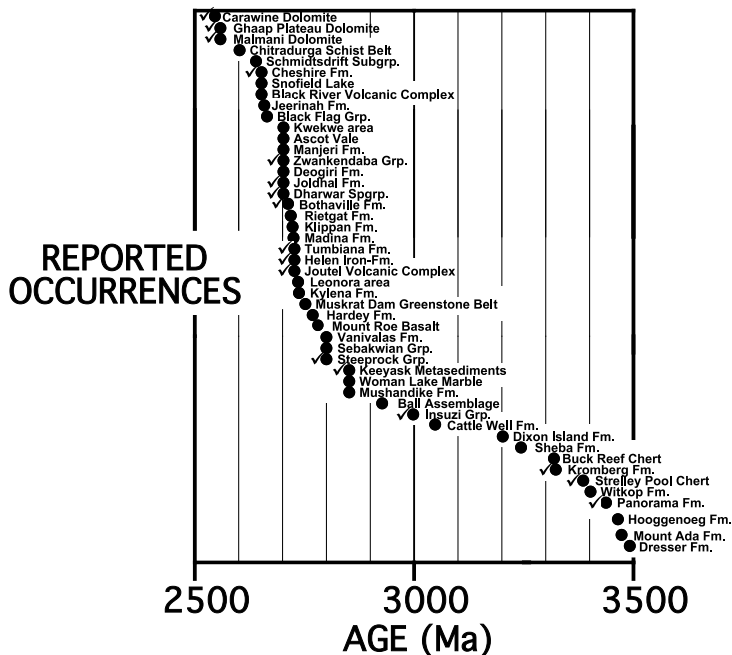
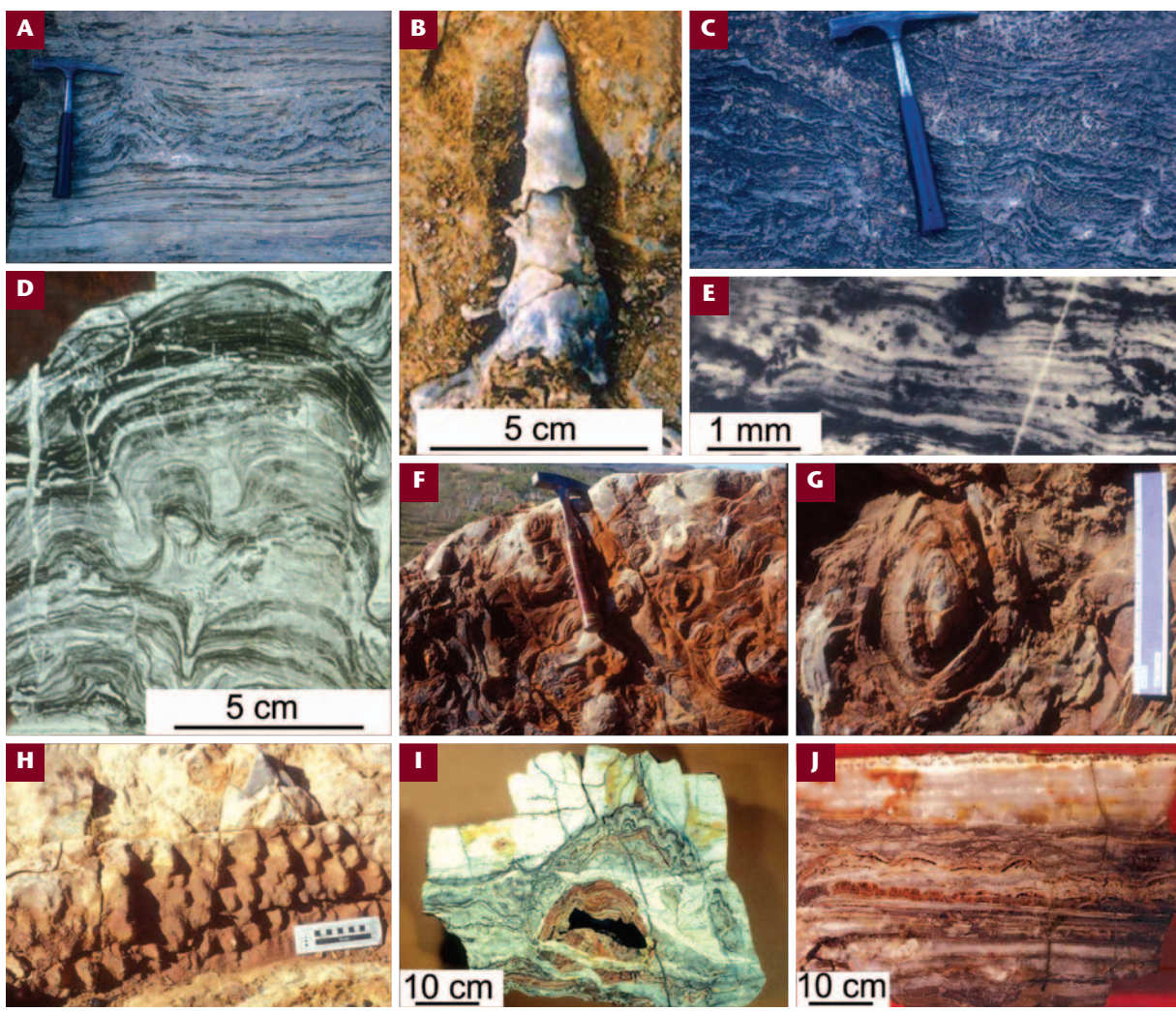


FIGURE 1 Archean geological units containing stromatolites; checkmarks denote conical stromatolites. DATA FROM HOFMANN 2000 AND SCHOPF 2006

this criterion falls short, since the mere presence of such microbes cannot prove that they actually built the structure. Moreover, because stromatolites typically are calcareous, their formative microbial communities tend to be obliterated by the growth of carbonate grains during diagenesis. Fossilized stromatolite-forming microbes have therefore been reported almost entirely from rare cherty stromatolites, in which the initial carbonate matrix was replaced by silica prior to cellular decay and destruction of the microbes by growth of carbonate grains. Thus, "it is probably conservative to estimate that less than one percent of all stromatolites ever described have a fossilized microbiota associated with them" (Grotzinger and Knoll 1999, p 316).

Because of the absence of microfossils in most stromatolites, it is perhaps impossible to *prove* the biogenicity of the vast majority of such structures, even those of the Proterozoic (<2500 Ma) Precambrian. Yet Proterozoic stromatolites are

FIGURE 2 Representative Archean stromatolites/microbial mats (for primary references, see Hofmann 2000 and Schopf 2006). (A–C) Stratiform and conical stromatolites from the ~2985 Ma Insuzi Group, South Africa; PHOTO IN B COURTESY OF N.J. BEUKES. (D) Laterally linked, low-relief, stratiform to domical stromatolitic mats from the ~3245 Ma Fig Tree Group of South Africa; PHOTO COURTESY OF D. R. LOWE. (E) Stratiform microbial mats from the ~3320 Ma Kromberg Formation of South Africa. (F–H) Conical stromatolites from the ~3388 Ma Strelley Pool Chert of Western Australia; scale in G = 20 cm; scale in H = 10 cm. (I) Domical and (J) stratiform stromatolites from the 3496 Ma Dresser Formation, Western Australia.



widespread and abundant, and their biological origin is backed by studies of their morphology, fine structure, environmental setting, and, in numerous examples, fossilized formative communities. In the Archean, however, because of the scarcity of preserved sediments, stromatolites are relatively rare. Nevertheless, recent studies show them to be appreciably more abundant and diverse than has generally been assumed (FIG. 1). Their biogenicity can be assessed by the same criteria we apply to stromatolites of the Proterozoic.

Two major conclusions can be drawn from the compilation of Archean stromatolitic occurrences shown in FIGURE 1. First, the temporal distribution of stromatolites between 2500 and 3500 Ma is more or less continuous and parallels the rock record. Thus, stromatolites are relatively abundant between 2500 and 3000 Ma and less common between 3000 and 3500 Ma. Second, conical stromatolites have been recorded in 17 of the 48 units listed (Hofmann 2000). Present in fully one-third of these deposits—notably including the Strelley Pool Chert and the Kromberg and Panorama formations, all >3300 Ma—such distinctive structures require “both highly motile [microbial] mat builders and pencon-temporaneous mineral precipitation” (Grotzinger and Knoll 1999, pp 342-343). Thus, the accretion of such stromatolites, “especially the conical structures found in 3.45 Ga rocks of the Strelley Pool Chert,” shown in FIGURE 2 F–H, “may have been facilitated by microorganisms” (Knoll 2003).

Early Archean Microfossils (>3000 Ma)

In recent decades, rules for accepting Precambrian microfossil-like objects as *bona fide* fossils have become well established. Such objects must be demonstrably biogenic, and must also be indigenous to and have formed at the same time as rocks of known provenance and well-defined Precambrian age. To address biogenicity—the most difficult of these criteria to satisfy—a nested suite of seven traits has been proposed (Buick 1990); characteristics identifying spheroidal or filamentous fossil microbes, the predominant Precambrian morphotypes, have been specified (Schopf 2004); and the usefulness of such traits has been documented (Schopf et al. 2005).

A prime indicator of the biological origin of microscopic fossil-like objects is the co-occurrence of distinctive biological morphology and geochemically altered remnants of biological chemistry. Thus, chemical data demonstrating that populations of “cellular microfossils” are composed of carbonaceous matter would be consistent with a biogenic interpretation. Available analytical techniques permit a one-to-one correlation, at micron-scale resolution, of cellular morphology and carbonaceous chemistry: ion microprobe (House et al. 2000) and Raman spectroscopy (Arouri et al. 2000) for specimens exposed at the surface of a sample, and two- and three-dimensional Raman imagery (Schopf et al. 2005; Schopf and Kudryavtsev 2005) for specimens in petrographic thin sections. Such imagery, new to paleobiology, provides the means to map the spatial distribution of carbonaceous matter and associated minerals in submicron-thick optical slices of fossil specimens. The technique provides detailed chemical maps that, if acquired sequentially throughout a fossil, can be “stacked” to produce an image showing the fossil and its matrix in three dimensions. Raman imagery has been used to correlate biological morphology and carbonaceous composition in putative microfossils from three particularly ancient deposits (Schopf et al. 2002). These are the >3300 Ma Kromberg Formation (FIG. 3 G, H) and the Strelley Pool (FIG. 3 I, J) and Apex cherts (FIG. 3 K–M). Raman point spectra have been used to support a biological interpretation for the oldest fossil-like objects known, those in the Western Australian ~3490 Ma Dresser Formation (Ueno et al. 2004).

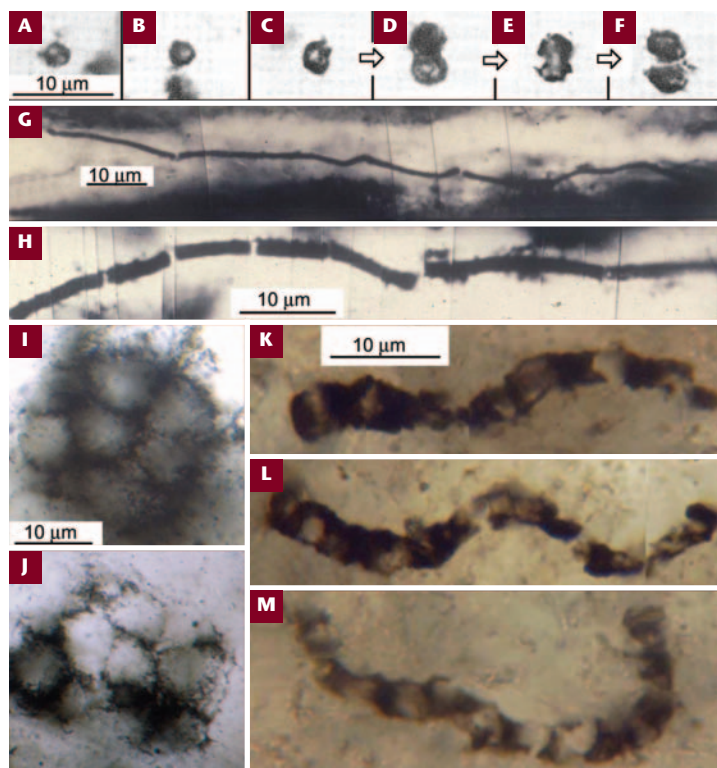


FIGURE 3 Representative >3200 Ma Archean microfossils. (A–F) Solitary and paired microbial unicells from the ~3260 Ma Swartkoppie Formation of South Africa; in C–F, arrows indicate sequential stages of cell division (modified after Knoll and Barghoorn 1977); scale for A–F shown in A. (G) Narrow bacterium-like filament and (H) broader microbial filament from the ~3320 Ma Kromberg Formation of South Africa (Walsh and Lowe 1985). (I, J) Colonial ensheathed cyanobacterium-like coccolidal unicells from the ~3388 Ma Strelley Pool Chert of Western Australia (Schopf and Packer 1987); scale for I and J shown in I. (K–M) Unbranched microbial filaments from the ~3465 Ma Apex chert of Western Australia (Schopf 1993); scale for K–M shown in K.

Despite such data, questions have been raised (Brasier et al. 2002) about the biogenicity of fossils reported from the ~3465 Ma Apex chert (Schopf 1993)—sinuous microbe-like filaments composed of carbonaceous cell-like segments (FIG. 3 K–M)—primarily because of their preservation in chert of hydrothermal origin (Van Kranendonk 2006). Recently, however, additional specimens, some identical to described Apex taxa (Ueno et al. 2004), have been discovered in three other hydrothermal cherts: the ~3490 Ma Dresser (Ueno et al. 2004), ~3240 Ma Kangaroo Caves (Rasmussen 2000), and ~3200 Ma Dixon Island (Kiyokawa et al. 2006) formations. Moreover, microbes of similar size and shape are abundant in hydrothermal settings today (e.g. Renault and Jones 2000), even at abyssal depths (Jannasch and Wirsén 1981).

Representative Early Archean microfossils are illustrated in FIGURE 3. These and fossils reported from the other >3200 Ma units listed in FIGURE 4 are all composed of carbonaceous matter. All satisfy specified biogenicity criteria (Schopf 2004). All exhibit distinctive biological morphology: spheroidal specimens are juxtaposed in addressed pairs (FIG. 3 D–F) or in well-defined colonies (FIG. 3 I, J), presumptive evidence of biologic cell division; and filamentous forms (FIG. 3 K–M) are composed of boxlike chert-filled segments defined by carbonaceous walls, presumptive cell lumina (cellular cavities) that are an identifying characteristic of filamentous microbes.

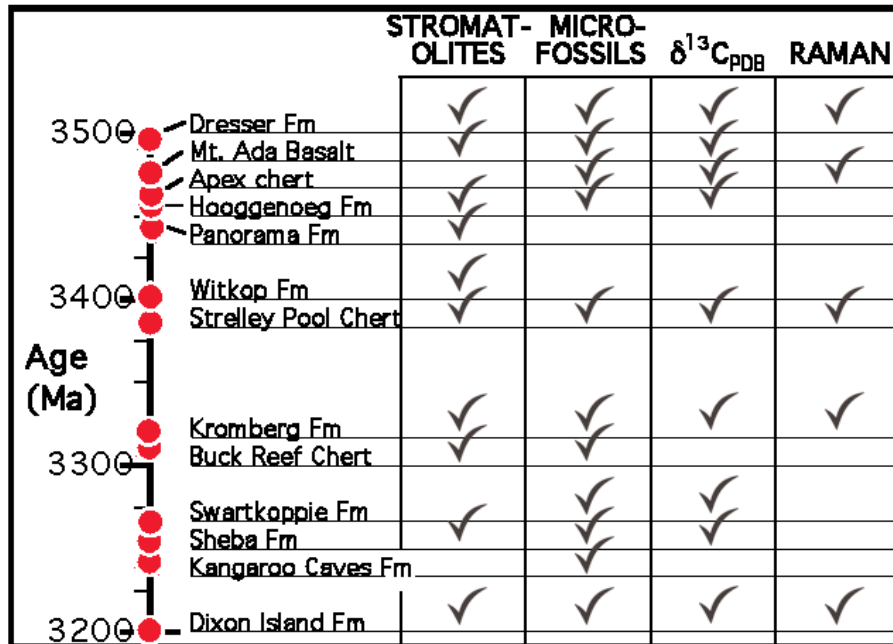


FIGURE 4 Early Archean (>3200 Ma) evidence of life. DATA FROM SCHOPF 2006

Some 40 types of *bona fide* microfossils, comprising six distinct categories, have been reported from the Archean (Schopf 2006). All are morphologically simple—rod-shaped bodies, unornamented coccoids, or sinuous tubular or uniseriate cellular filaments. Such fossils, common also in Proterozoic biological communities, evidence a microbial evolutionary continuum that extends from the Early Archean to the present.

Early Archean (>3000 Ma) Carbon Isotopes

FIGURE 4 summarizes paleobiological data from thirteen geological units in the two extant, relatively thick, Early Archean sedimentary sequences, those of the Pilbara Craton and the Barberton Greenstone Belt. As shown, ten of these especially ancient units contain stromatolites; eleven contain microbial fossils; nine have available carbon isotope data, including measurements on individual fossils in the oldest unit, the ~3490 Ma Dresser Formation; and five have provided Raman spectra and/or images of the carbonaceous components of microfossils.

In FIGURE 5, carbon isotope data from an extensive suite of Precambrian deposits show that over this vast sweep of geological time, average $\delta^{13}\text{C}_{\text{PDB}}$ values for carbonate carbon center at ~0‰, whereas those for biologically produced carbonaceous organic carbon are centered at -25 ± 10 ‰. As shown in FIGURE 6, the Early Archean microfossil-bearing deposits exhibit essentially identical $\delta^{13}\text{C}_{\text{PDB}}$ values—about 0‰ for carbonate carbon and -27 to -32 ‰ for the particulate carbonaceous kerogen. As in the Proterozoic, the values measured are consistent with carbon isotope fractionation by autotrophic microorganisms (-25 ± 10 ‰) and, thus, with a biological origin for the reduced carbon (cf. Hayes et al. 1992).

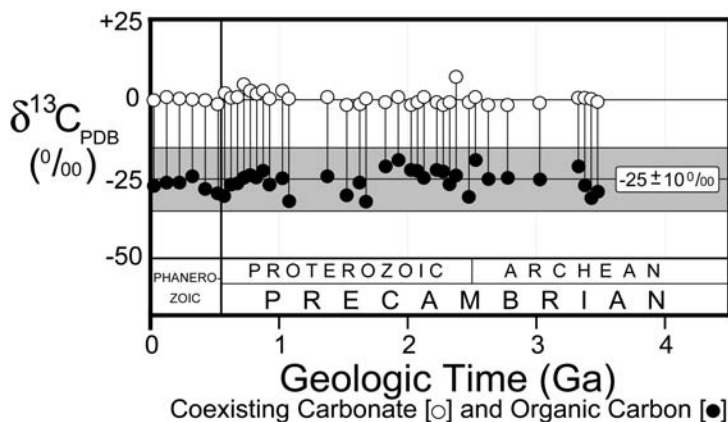


FIGURE 5 Carbon isotope values for coexisting carbonate and organic carbon measured in bulk samples of Phanerozoic and Precambrian sedimentary rocks (Strauss and Moore 1992). The Precambrian is represented by data from 100 fossiliferous cherts and shales, and the data are shown as average values for groups of samples from 50 Myr long intervals.

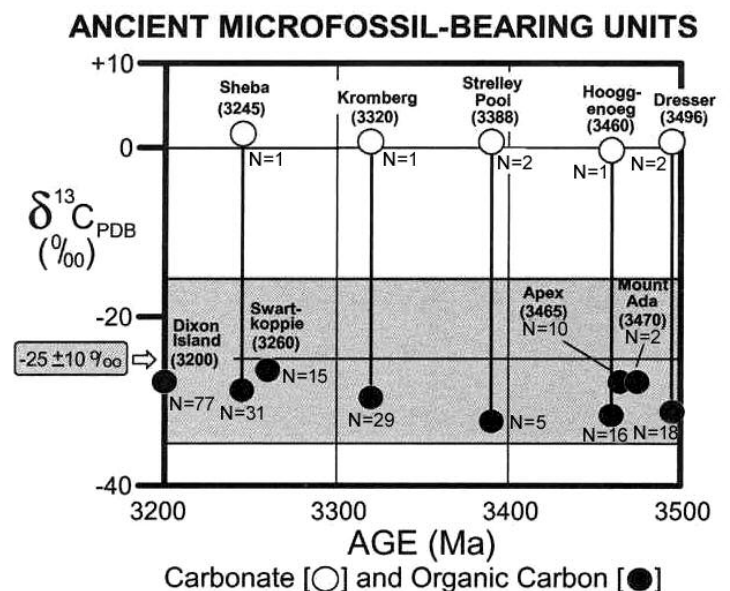


FIGURE 6 Carbon isotope values for carbonate and organic carbon measured in bulk samples of nine ~3200 to ~3500 Ma microfossil-bearing geological units (Strauss and Moore 1992; Schopf 1993; Brasier et al. 2002; Ueno et al. 2004). Ages (Ma) are shown in parentheses; N = number of analyses.

SUMMARY

Taken together, the evidence from stromatolites, microfossils, and carbon isotopes seems irrefutable: life was extant, and indeed flourishing, as early as ~3500 Ma ago. Where does this leave us regarding the time of life's emergence? Certainly, life began before 3500 Ma, during Earth's first billion years, but exactly when and how remain unknown. Most "origin-of-lifers" would set the date at around 4000 Ma. But that estimate will ultimately be placed on firm footing only by discovery of direct evidence from Earth's earliest rock record.

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This article is based on a longer, extensively referenced article (Schopf 2006) that includes discussion of the complete Archean (2500 to 3500 Ma) paleobiological record as now known. I thank J. Shen-Miller, W. Barker, and J. Valley for suggestions for improvement of an earlier version of this contribution. This work was supported by NASA Exobiology Grant NAG5-12357 and by CSEOL, the IGPP Center for Study of the Origin and Evolution of Life at UCLA. ■

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Interdisciplinary Graduate Student Research Symposium

Crystal P. Mann¹



How does the malaria parasite handle iron in the human blood? What is the ecological footprint of international trade? Do magma reservoirs recharge with magmas of similar composition? Can top quark events be identified?

These research questions and more were discussed at the Interdisciplinary Graduate Student Research Symposium: Scientific Approaches to Complex Natural Systems, 16–17 March 2006, McGill University, Montréal, Québec, Canada. The event, which featured 84 student presentations, was organized by graduate students for graduate students. Participants included the McGill departments of Atmospheric and Oceanic Science, Biology, Chemistry, Earth and Planetary Sciences, Geography, Mathematics and Statistics, Natural Resource Science, Physics, Psychology, School of Computer Science, and School of the Environment, and graduate students from Concordia, Centre de Recherche en Géochimie et en Géodynamique, Michigan Technological University, Queen's University, Université de Montréal, University of Windsor, and Université du Québec à Montréal.

The objectives of the symposium were for students to (1) communicate their research across disciplines, (2) enrich their own research by exchanging ideas with researchers from different scientific backgrounds, (3) give and receive valuable feedback on presentation formats, and (4) develop skills to network with other researchers and industry



Sylvie Tissandier, Biology/Redpath Museum, McGill University, presenting "Morphological Changes in the Pectoral Fins of Ray-Finned Fish" on 17 March 2006

personnel. To create a sense of continuity amongst the various disciplines, the sessions were designed to reflect scale: nanoscale, microscale, macroscale, and planetary and cosmological scales. Students were asked to present at the session that best encompassed their research topic and objectives, that concerned the scale applicable to their own research, and that provided them with the type of feedback they desired. Judges, recruited from both academia and industry, provided students with written feedback covering a range of criteria, from soundness of research to presentation format. Cash awards were given out for outstanding oral and poster presentations.

The symposium opened with a keynote address by Dr. Don L. Anderson, a noted geophysicist

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Cherry-Picking Your Results

Kaspar Mossman²



It's mid-June, and peaches and strawberries are in season at the farmer's market in Berkeley, California. Yum! But there's a catch. Ripe peaches and strawberries are soft and fragile, and impossible to transport to market without damage. So vendors rotate the peaches in the bins and flats to hide the bruises. They pick moldy berries off the tops of the baskets; I find the others when I get home. The perfect fruit on the top doesn't honestly represent the contents of the container.

I'm familiar with this kind of trick not only from the market, but also because I see it all the time in scientific journals, and I do it myself when I present my research at seminars. I pick the best-looking images, which I then claim represent my experiments.

As a PhD student in biophysics, I study how T cells communicate. T cells are white blood cells that play important roles in the immune system. Characterizing T cells is different from measuring the properties of an element like titanium. Every time you measure the electrical conductivity of pure titanium, you get the same answer. But not all T cells are the same, even if they come from the same genetically engineered mouse. They may be at different stages in their growth cycles, or have been exposed to slightly different concentrations of hormones. When I observe them under the microscope, every cell behaves in a slightly different way. Some cells completely defy expectation, and either don't adhere as I think they should, or just crawl around like slugs, leaving fluorescent trails as they shed molecules.

To get useful information from images, I have to discard the deviants—some of which may not even be T cells—like a farmer picking the really moldy strawberries out of the basket. Then I'm left with an ensemble of cells, all of which are doing more or less the same thing. In the language of statistics, there's an average and a standard deviation. Every experimental scientist who works with complex natural systems, such as cells, petroleum deposits, or the geomagnetic field, faces a similar challenge: to identify and delete outlying data points, and obtain data that agree with their model of the system.

In a 2005 survey by the Office of Research Integrity, American scientists were polled on whether they'd committed a "scientifically dubious act" in the last two years: anything from publishing the same result in two different journals to outright falsifying their data. Of the respondents, 30% said yes. But I'd argue that nearly all cell biologists—including me—regularly misrepresent their results when it comes to publishing images. Rest assured that only rarely this extends to outright fraud.

For a start, no image makes it into a paper in *Cell* without the author spending hours massaging it in Adobe Photoshop, to enhance what the author wants you to believe are the important regions. There is an honour code governing this manipulation: you're not allowed to add anything that isn't there or highlight

some aspect of the image that doesn't represent "true" results. Beyond this, though, researchers always pick what they believe are the "best" images for publication. What do I mean by "best"?

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¹ Crystal P. Mann is a PhD candidate in volcanology at the Department of Earth and Planetary Sciences, McGill University. She received her MSc also at McGill and her BSc at the University of Washington, Washington State, United States. Her PhD research thesis is focused on the transfer of volatiles during recharge of a more mafic magma into a shallow magmatic reservoir.

² Kaspar Mossman recently graduated with a PhD in biophysics from the University of California, Berkeley. He studied meteor dynamics for his BSc at Mount Allison University and high-temperature superconductivity for his MSc at the University of British Columbia. A stint masquerading as a radio-frequency engineer in Santa Barbara ended when he saw the glory of biophysics.

ROBERT WILHELM BUNSEN MEDAL TO RICHEL



The French scientist Pascal Richet has won the prestigious Wilhelm Bunsen Medal of the European Geoscience

Union (EGU) for his seminal achievements in advancing our fundamental understanding of geomaterials and for providing conceptual frameworks for the thermodynamic and transport properties of matter within the Earth. The Wilhelm Bunsen Medal was established by the Division of Geochemistry, Mineralogy, Petrology and Volcanology in recognition of the scientific achievements of Robert Wilhelm Bunsen. It is awarded for distinguished research in geochemistry, mineralogy, petrology and volcanology. Pascal Richet works at the Institut de Physique du Globe de Paris. He has been a pioneer in mineral and melt physics for a quarter of

a century. His early work on the thermodynamic and transport properties of silicate melts led to remarkable insights and provided a thermodynamic basis for the calculation of transport properties that is still being analyzed and tested to this day. His groundbreaking studies of pre-melting in crystals have contributed substantially to the understanding of elastic modulus variations in sub-melting temperature solid phases. Finally, his calorimetric studies of silicates have significantly advanced our picture of melt energetics. Without Pascal Richet, our present picture of silicate melts would be much more primitive than it is, full of many of the myths and uncertainties that he has almost single-handedly banished from the literature. Professor Richet accepted his medal and gave his medal lecture 'Volcanic Eruptions and Physics of Lavas' during the EGU General Assembly, in Vienna, Austria, 2-7 April 2006.

EWING RECEIVES DANA MEDAL



Rod Ewing received the Dana Medal of the Mineralogical Society of America (MSA) at the 2006 Joint Assembly of the American Geophysical Union, in Baltimore, May 23-26, 2006. The medal was presented to Rod by MSA president John Valley before his Dana Lecture "Plutonium, Mineralogy and Radiation Effects." The lecture was the inaugural talk of the Dana symposium "Mineral-

ogy and the Nuclear Fuel Cycle," convened by A. Navrotsky and L. Wang and organized by the Mineralogical Society of America. Many colleagues and former students participated in the symposium. Rod particularly appreciated the chance to meet with old friends and discuss the scientific progress that has been made during the past several decades.

Interdisciplinary Graduate Student Research Symposium

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and philosopher of science from California Institute of Technology. To choose the speaker, the organizing committee asked the participating McGill departments for nominations, compiled the names, and sent out the list of nominations for student vote. Dr. Anderson was the top student pick with over 100 votes.

The interdisciplinary graduate student symposium was conceived and organized by a group of graduate students doing science research. As a member of this committee, I can speak on behalf of my teammates when I say that our drive came from the importance of being stimulated by research outside our own discipline and the necessity of good communication and networking.

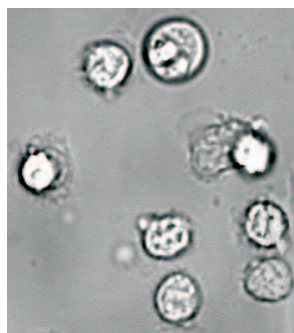
Was the event a success? You decide. Here are a few of my observations. During one question period, a graduate student in the audience offered his lab computer with a high memory capacity to one of his peers to tackle a research question for which the required resources were not available. Questions for the

speakers were from fellow graduate students with different backgrounds, forcing the speakers to think outside the "box." A faculty member, excited about research being done by a graduate student in a different department, offered this student a post-doc position after graduation. Judges from industry gave business cards to students in their last term.

Without the much-needed financial support from the Canadian Society of Petroleum Geologists, the Post Graduate Student Society, the Geological Association of Canada, the Environmental Sciences Research Centre, Falconbridge, Esso, GENEQ Inc., McGill Institute of Advanced Materials, Fisher Scientific, Vancouver Petrographics Ltd., and alumni from the Department of Earth and Planetary Sciences, this student initiative would not have been possible. We would like to acknowledge not just the financial support, but also the continual encouragement from the academic faculty within the different departments and the dean of the Faculty of Science, Dr. Martin Grant.

Cherry-Picking Your Results

Cont'd from page 234



T cells are white blood cells that play important roles in the immune system.

Out of the thousands of cells in the experiment, the cell in the image chosen for the paper is the finest example of what the scientist thinks the cells should be doing. This is like the farmer at the market rolling the peaches over so the bruises don't show. When you read a biology paper, you know that the images in the paper are absolutely the best ones the scientist had, so if the images are sketchy, you know the actual data were far worse.

Live cells and animals are notoriously complex, and therefore biologists may have the greatest opportunities to develop pet theories and claim that their cells or mice are behaving just as they predicted. But I imagine that a geologist

with a sack of ore samples, some of which feel heavier or look more silvery than others, might choose to send off for assay the samples that fit best with his theory (or investment portfolio).

Are we wrong to pick what we think is the best micrograph to go in a paper? It depends. If the "best" sample truly represents the average behavior, that's OK. But if the image in question is an extreme example, then we should be careful. Our theory might be wrong. By choosing to publish data that support our theory, we not only risk misleading others for our own profit, we risk that tomorrow someone else could embarrass us with more honest results—turning our perfect peach over to reveal the moldy underside.



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IAGC NEWS

IAGC's 40th Birthday Celebrations

In 2007, the IAGC will be 40 years old. We plan to recognize the birthday in conjunction with the next Goldschmidt Conference in Cologne, Germany, 19–24 August 2007. The IAGC anniversary celebration will take the form of a special one-day symposium, dedicated to Al Levinson, on Saturday, 18 August 2007. In addition, the first round of IAGC awards, postponed from 2006, will be presented, including Certificates of Recognition and Goldschmidt Conference awards (Vernadsky Medal, Ebelman Medal, Hitchon Award and Faure Award).

The special scientific symposium will be held on the afternoon of Saturday, 18 August, either at the Goldschmidt Conference site or at the Universität Köln. Jochen Hoefs and Herbert Palme have agreed to organize the meeting. A reception will follow the symposium to celebrate this important IAGC anniversary. The reception will honor the living past presidents and other important figures in IAGC history, to be selected by the IAGC executive. An organizing committee is being established. A special issue of *Applied Geochemistry*, dedicated to Al Levinson, is planned to mark the special scientific symposium.

More details are provided in the spring IAGC Newsletter #44.

Upcoming IAGC-Sponsored Meetings

ISEG-7

The 7th International Symposium on Environmental Geochemistry is to be held 24–27 September 2006, in Beijing, China. IAGC support is being provided for this meeting. The main thematic sessions of the conference are as follows: Geochemical Records of Change and Contamination, Geochemistry and Health, Fragile Habitats (e.g. karst), Organic Pollutants, Coal, Water Resources, Environmental Management and Analytical Geochemistry.

IAGC-Sponsored Sessions at GSA 2006

The following thematic sessions have been proposed for the next Geological Society of America (GSA) meeting to be held in Philadelphia, 22–25 October 2006 under IAGC sponsorship: Geochemical Modeling Applications in Ground Water Systems, chaired by June Mirecki and Russell Harmon; Sources, Transport, Fate and Toxicology of Trace Elements in the Environment, chaired by LeeAnn Munk, David Long, and W. Berry Lyons. Details have been posted on the GSA website (www.geosociety.org).

How to Contact Us

To join or renew your membership in the IAGC, subscribe to or track down errant issues of *Applied Geochemistry*, or send in comments, etc., contact IAGC Business Office, Box 501, Pinawa, Manitoba R0E 1L0, Canada. Or check our website www.iagc.ca

Mel Gascoyne

IAGC Business Office Manager & Newsletter Editor

NEWS BRIEF ON APPLIED GEOCHEMISTRY AND ELSEVIER



Friso Veenstra,
Publisher, Elsevier Ltd

At this point, there are two issues that are of direct interest to IAGC members as they have implications for their journal *Applied Geochemistry*.

First of all, I would like to remind you that the free ContentsDirect alerting service closed on 25 May 2006. Therefore, I advise you to sign up to the free ScienceDirect Volume/Issue Alerts service at ScienceDirect (<http://www.sciencedirect.com>) in order to continue to receive the table of contents alerts for *Applied Geochemistry* and all other journals you are interested in. Signing up will only take a few minutes: (1) Visit ScienceDirect (www.sciencedirect.com). (2) Click on the green Alerts tab, top right. (3)

If you are a new user, register for a username and password. (4) Login and follow the instructions for setting up free ScienceDirect Volume/Issue Alerts. If you would like to view a short demonstration on how to sign up for ScienceDirect Volume/Issue Alerts please visit www.elsevier.com/locate/sciencedirectalerts

Second, as of this month, Elsevier is changing its offprints policy as we are implementing **electronic offprints** for all our journals. What it means for *Applied Geochemistry* is that, as of May 29, authors will be given the choice between e-offprints and free paper offprints. This will also apply to special issues.

Friso Veenstra

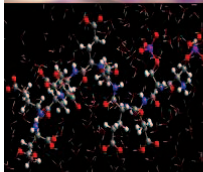
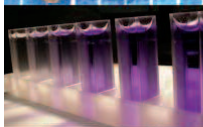
GUNTER FAURE CO-AUTHORS NEW BOOK

Introduction to Planetary Science: The Geological Perspective

by Gunter Faure and Teresa M. Mensing

(to be published by Springer-Verlag, Dordrecht, in 2007)

This textbook is intended to be used in a lecture course for college students majoring in the Earth sciences. Planetary science provides an opportunity for these students to apply a wide range of subject matter pertaining to the Earth to the study of other planets and their principal satellites. In this way, planetary science tends to unify subjects in the Earth sciences that are traditionally taught separately. Therefore, planetary science is well suited to be taught as a capstone course for senior undergraduates in geology departments and as an introduction to the solar system in astronomy departments. Both groups of students will benefit because planetary science bridges the gap between geology and astronomy. It thereby prepares geologists and astronomers to actively participate in the on-going exploration of the solar system.



Medical Mineralogy and Geochemistry

**MSA/GS Short Course
December 8-10, 2006
Menlo Park, California**

Organizers— Dr. Nita Sahai, University of Wisconsin-Madison, Dr. Martin Schoonen, Stony Brook University.

Sponsors—Mineralogical Society of American, Geochemical Society, US Geological Society, National Science Foundation, and US Department of Energy.

More information: www.minsocam.org/MSA/SC

GEOCHEMICAL TRAINING IN DEVELOPING COUNTRIES WORKING GROUP REPORT



Dr. U. Aswathanarayana, chairman of the IAGC Working Group on Geochemical Training in Developing Countries, has submitted the following report, which includes aspects of the application of geochemistry in the food supply of developing countries.

An Integrated Strategy for Food Security in the Developing Countries

It is now widely recognized that issues such as food security, energy security, human health, etc. have so many dimensions that they can only be addressed by a *consilience* (a term coined by Bill Gates that literally means jumping together) of a number of methodologies, technologies and management approaches. Under the auspices of the 93rd Indian Science Congress, and as a part of the event "Science, and the UN Millennium Development Goals", U. Aswathanarayana organized a panel discussion entitled "Biophysical and Socioeconomic Dimensions of Food Security in the Developing Countries", which was held in ANGR Agricultural University, Hyderabad, on January 6, 2006. The output of the panel discussion was the development of an integrated strategy to make use of the consilience among bio-, nano- and information technologies, innovative agricultural and management practices, combined with administrative policies, to achieve the UN Millennium Development Goal of halving, by 2015, the number of undernourished people in the world. Out of about 850 million such people, India has 221 million and China has 142 million.

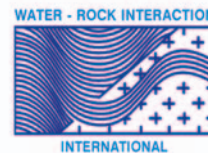
The panel discussion led to the identification of three multi-dimensional approaches to achieve food security in the developing countries.

MORE CROP PER DROP Food and water security are inseparable, as food cannot be grown without water. Ways of optimizing the soil-water-plant system, in order to produce more food crops with less water, were considered. Contributory factors involved management of soil micronutrients, development of drought-resistant and salinity-tolerant crop varieties, preparation of a hydroclimatic calendar, "blue" water irrigation, and dryland agriculture.

FOOD FORTIFICATION This term describes ways of processing foods to improve their nutritional value, so that the same quantity of, say, cereals could provide a nutritious diet to more people. Methods considered were fermentation of cereals, pulses, root crops, vegetables, fruits, milk, meat and fish to create new kinds of foods that are more nutritious, more digestible, and have therapeutic benefits, while improving the taste, flavor and texture, etc.

ACCESS TO FOOD This aspect includes economic instruments and administrative policies that improve access to food. For instance, the government, through a system of incentives (e.g. guaranteed price for coarse grains that need less water) and disincentives (e.g. denial of free electricity for high-water-need crops) could have a profound effect on the production of food crops.

U. Aswathanarayana



TWELFTH INTERNATIONAL SYMPOSIUM ON WATER-ROCK INTERACTION (WRI-12)

Every three years since 1974, the Water-Rock Interaction Working Group of the International Association of Geochemistry (IAGC) has gathered in various venues for about two weeks of science and conviviality. Scientists from all over the world are again cordially invited to attend the *Twelfth International Symposium on Water-Rock Interaction (WRI-12)*, to be held August 13–18, 2007. The WRI-12 symposium will be held at the beautiful setting of the International Conference Center, Kunming, in the center of the Yunnan-Guizhou plateau of southwestern China.



WRI-12 will feature all aspects of weathering, with emphasis on karst geochemistry, hydrothermal systems of tectonically active regions, and water-rock-gas interactions on other planets. Oral and poster presentations are being showcased. The combination of excellent technical sessions, printed proceedings, and interesting and well-organized field trips lasting several days, together with enjoyable social and cultural programs for scientists and accompanying members, will create an atmosphere of informality and easy communication among the participants. The organizing committee will do its best to offer you a symposium worthy of the previous ones.

The symposium website (www.wri12.org) provides details about the oral and poster sessions, accompanying guest program, and social activities. Information on Kunming may be found there, too, as well as information about the several field trips organized for participants. The final circular, containing the final version of the scientific and social programs for WRI-12, will be handed out to participants at registration. The *second circular* is due out in October 2006, with *abstracts due in December*. A list of conference topics can be found on the website. Looking forward to seeing you in Kunming!

Yanxin Wang
Secretary General



www.clays.org

The Clay Minerals Society

CHANGING OF THE GUARD



Richard K. Brown,
CMS President

Outgoing president Cliff Johnston (Purdue University, IN) welcomes incoming president Richard K. Brown (Wyoben, Billings, MT). Other elected positions for 2006 include Ray Ferrell (vice president elect), Andy Thomas (treasurer), Warren Huff (secretary), and new council members James Amonette, Christopher Breen, Victoria Hover, and Sridhar Komarneni. We would also like to welcome Alex Speer and Michelle Johnson, who will be running our new Clay Minerals Society office in Chantilly, VA. The e-mail address for the CMS office remains cms@clays.org. The *Elements* news editor Lynda

Williams passes the baton to Kevin Murphy, news editor for 2006–2007, who will be assisted by co-editor Steve Hillier.

FROM THE PAST PRESIDENT

First, I would like to take this opportunity to express my appreciation to the Society for the opportunity to serve The Clay Minerals Society as president this past year. It has been a year of significant transition for the Society on several fronts with many new opportunities and challenges before us. I would like to express my sincere appreciation to the executive committee for their hard work and commitment to CMS. I am routinely impressed by the professionalism and ability of the members of the executive committee. The president has the opportunity to view the society from a bird's eye perspective, and I am deeply grateful for the efforts of so many volunteers who have committed themselves to our wonderful Society.

OFFICE TRANSITION FROM AURORA, CO, TO CHANTILLY, VA

Certainly the most significant change this past year has been the office transition. I would like to thank Leslie Shivers for her hard work and service to the Society. Leslie faithfully worked as our office manager out of her home in Aurora, Colorado. Although the road map ultimately led to our new office in Chantilly, VA, Leslie wanted to remain in Colorado. She began a new job in January, 2006. Leslie has been missed, but at the same time we are appreciative of the gifts, talents, and energy that she brought to this position. Although the office transition has been challenging, all the indicators suggest that the office move will be very positive for the overall health of the Society.

SHAREPOINT SITE

One of the continuing challenges for CMS is related to the fact that we are a volunteer organization, critically dependent on our committees. In recent years, the effectiveness of the council has been hampered by a lack of communication among the various committees. As one step towards improving communication within CMS, President Johnston implemented the use of a "sharepoint" site. SharePoint is a tool designed

by Microsoft to facilitate collaboration within an organization. Users can use this tool to easily create, manage, and share information and make it available throughout the organization. The sharepoint site for CMS is www.agry.purdue.edu/cms. The site is hosted at Purdue University, and access is anonymous and free to Society members. Additional details about the sharepoint tool can be found at

<http://www.microsoft.com/sharepoint/overview.aspx>

Because our membership and leadership is scattered throughout the world, this site was implemented to post committee reports and minutes from meetings and to provide up-to-date contact information regarding the executive committee, council, and all standing and ad hoc committees. Please provide feedback to determine if we should continue to use and develop this site.

2006 ANNUAL MEETING, POITIERS, FRANCE

We have been extremely fortunate this year to have partnered with the Groupe Français des Argiles (GFA), and this has been coordinated skillfully by Sabine Petit. For the first time in the history of the Society, we are co-hosting a meeting in Europe with one of our sister societies. Sabine did a wonderful job planning the annual meeting, and we are very appreciative of her hard work. In addition, Faiza Bergaya and Katie Carrado should be commended for organizing this year's workshop on nanocomposites and for their successful efforts in securing funding to support the workshop. This meeting was our largest meeting in recent years and provided a terrific opportunity to interact more closely with European clay scientists.

CLAYS AND CLAY MINERALS: DIGITIZING THE ARCHIVE



Following suggestions by some CMS members on the Society list-server, the journal editors have investigated the possibility of digitizing the journal's entire archive, some 25,000 pages dating back to the early 1950s, and making it available online. Recent advances in scanning and "optical-character-recognition" (OCR) technology mean that it is now more feasible and relatively inexpensive (<10% of one year's annual journal production costs) to create a digital version of the whole archive. This has been warmly welcomed by members of council. Negotiations are complete, and by the time this issue of *Elements* is in press, much of the work will be done.

Each paper will be in the form of a pdf file. A "picture" will be taken of each page so an exact facsimile of the original journal page will be presented to the reader. The text on each page will

also be run through a separate "OCR" process, and the resulting text file will form a second invisible layer in the pdf file, thereby making it possible to search (and to cut and paste) the text. Photographs and line-diagrams will be scanned separately and given special treatment, and will be presented at higher resolution. Thus we aim to have the best level of reproduction possible while ensuring that the sizes of individual files do not become unmanageable.

Header material (comprising the title, the authors' names and affiliations, the abstract, the keywords, and the bibliographic material) will be extracted for each paper and saved in a separate XML-tagged file. XML (eXtensible Markup Language) tags will enable the header material to be presented separately, rather like it is in most e-journals, e.g. the Ingenta or GSW version of *Clays and Clay Minerals*. Each paper will also have a digital object identifier (DOI) associated with it. DOIs are stored by an organization called CrossRef™. They are used by most publishers to forge links between the reference lists in one e-journal and the full-text versions of the cited papers in other journals. By depositing DOI information for every paper

ever published in our journal, we will be making it possible for readers of papers published in any journal to hyperlink directly to the original papers published in our journal.

The archive will be housed in a site that is well indexed by the major search engines, including, of course, Google™. A well-indexed site is important because it is crucial that "hits" on our archived content rank highly on search-results pages. Members and others will easily be able to perform searches on that content.

While carrying out the digitization, we have also decided to create a disk version of the archive. Many users would like to have a local copy of all the published material and not have to wait for them all to download from the website! The additional cost of creating a master DVD is not significant, and we will replicate copies of that disk as required. We feel that many libraries will be glad to have the opportunity to purchase such a disk (with our express permission to copy its contents to local servers), giving librarians that much-needed peace of mind about backup for e-resources such as this. We hope to recoup some

or all of the costs of the entire digitization project through such sales.

As the project proceeds, we will ask for journal readers' assistance. With help from some members, we have already obtained a complete set of all back issues of the journal. We'll also need your help to check the material as scanned by our supplier. This will involve ensuring that all the pages have been scanned correctly and that the images are of an acceptable quality. You will appreciate, I'm sure, that this task is beyond the limits of what the editorial team can hope to accomplish on its own. We'll be in touch via the list-server.

The whole project is designed, primarily, to increase usage of both past and future issues of the journal. We hope for some knock-on effects, such as increased traffic to the Society website. We look forward to receiving your comments on and assistance with the project.

Derek Bain, Editor in Chief
Kevin Murphy, Managing Editor

CLAY MINERALOGY: AN INTRODUCTORY COURSE

This is the first in a new multimedia series of educational materials to be sponsored by The Clay Minerals Society. The CD contains material used to support a graduate-level course on clay minerals taught by Professor Ray Ferrell at Louisiana State University. The content is presented in six modules that cover basic mineralogy and classification, geologic origin, aqueous solubility and ion exchange, waste isolation and fluid flow, and X-ray powder diffraction methods for the identification and quantification of clay mineral assemblages. This is not a CD version of a standard textbook. It is a unique compilation of explanatory text, narrated slide shows, computer applications for the XRD analysis of clay minerals, links to selected websites, and copies of required readings. The pedagogical approach challenges the reader to recognize the general principles of clay mineralogy presented in the selected readings rather than simply reading a literature summary in a textbook-style chapter. The author provides some hints for interpretation, but this approach works best when two or more individuals are able to discuss the readings.

The general objective of this presentation is to foster a greater understanding of clay mineral reactions in the environment and the processes controlling their geologic distribution and industrial utilization. The material produces an increased awareness of the relationship between structural/ chemical characteristics of the diverse clay minerals present in rocks, soils, and sediments and their physical and chemical properties. The lessons to be learned are useful in diverse fields of scientific and technical investigation. One point of emphasis is that clay mineral names are mostly applied at the "family" level. Thus smectite represents materials with a wide range of chemical variability and physical characteristics. Smectite, kaolin, chlorite, and illite are terms that are more like plagioclase than names for well-defined mineral species. Within each family, chemical and structural varieties may have considerably different properties. One illite is not identical to all other illites.

Many organizations contributed copyrighted material freely to the production of this CD.

The CD is available at US\$10 per copy (add US\$10 for mailing outside of the US or Canada). Send your orders (with check or credit card authorization, including card verification number) to: The Clay Minerals Society, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1125, USA. Tel. (703) 652-9960; fax: (703) 652-9951; e-mail: cms@clays.org.

REPORT ON THE THIRD REYNOLDS CUP CONTEST (2006)

The third Reynolds Cup contest in quantitative mineral analysis closed at the 2006 annual CMS meeting in Oleron, France, where awards and prizes were presented to the top three contestants (names pending as of *Elements* deadline). Preparations for the event started immediately after the 2004 CMS meeting in Richland, Washington. At the 2005 council meeting, the CMS council decided on a biennial financial contribution towards the event. This year's event was significantly supported by Natural Resources Canada and organized by Dipo Omotoso.

In October 2005, information about the competition was added to the CMS website (www.clays.org), which helped to organize the flow of information to the community. Douglas McCarty and Reinhard Kleeborg also wrote an article about the competition in the December 2005 issue of *Elements*.

Minerals needed for the competition were collected from commercial and private collections. While pure minerals were desirable, minor impurity levels in the mineral specimens were tolerated as long as they could be unambiguously quantified. A total of 60 samples was made available to participants when the competition opened in January 2006. Participants made very positive comments, and felt that the contest was challenging and enjoyable. Most importantly, participants commented that the knowledge gained from the contest will improve the quality of their future quantitative mineral analyses. The reporting this year placed a greater emphasis on the analytical techniques used by the top three contestants. This will provide a useful starting point for less-experienced analysts and students interested in quantitative mineral analysis.

Tribute to Editor in Chief DEREK C. BAIN and Managing Editor KEVIN MURPHY

DEREK AND KEVIN are to be highly commended for their efforts at improving the quality of *Clays and Clay Minerals*, our Society's journal. They have improved the quality of CCM, with a record-high number of manuscripts submitted in 2005–2006; successfully negotiated a contract for the digitization of the journal's entire archive, some 25,000 pages dating back to the early 1950s; observed an increase in the impact factor of CCM; witnessed a successful first full year of *GeoScienceWorld*; and formed a working group to evaluate online manuscript and peer review software, all the while maintaining short submission-to-acceptance-to-publication times.

Derek has graciously agreed to extend his term as editor in chief through 2007, and it will be a high-priority task during the next year to find a replacement editor for CCM.



www.minsocam.org

Mineralogical Society of America

FROM THE PRESIDENT

*The Revolution Will Not Be Televised*¹

As the juggernaut of electronic publishing approaches, we should all consider what this might mean for our favorite journals and the cherished societies that publish them. Fueled by Moore's law, the approach is inevitable, so none should think we can turn back. Indeed, most of us embrace electronic media and eagerly await each new advance. But will there be unanticipated consequences?

Readers of *Elements* should pay special attention to GeoScienceWorld and the issues surrounding "open access" (see *Elements* 1: 244-245). If these terms are not yet on your radar, they will be soon.

Open or public access refers to a range of proposals that scientific articles should be posted on the web and available at no cost to all. In its current form (May 2006), the Cornyn-Lieberman bill requires all articles on research supported by NIH, NSF, DOE, and NASA to be uploaded within six months of publication. This is intended to speed access, enhance searches and indexing, and ease library budgets. If articles are free on the web, costly subscriptions can be cancelled. While these are noble goals, the concept meets stiff, but not universal, opposition by societies and publishers who raise the question: if institutional subscriptions are cancelled, who then pays? Even complete elimination of paper copies, unlikely to happen soon, would save only some of the cost of production of a scientific journal. A majority of the costs go for salaries and expenses of skilled technical editors and staff in order to achieve the widely desired peer review. At present, libraries pay much of this production cost. If libraries cancel subscriptions, will the costs be taken up by federal agencies, personal subscribers, or authors? I suspect not. Alternatively, would you trust the integrity of scientific literature to Wikipedia? We need a new business model.

GeoScienceWorld (GSW) is an exciting new venture that packages digital versions of 30 professional journals in a single subscription for electronic access (see Speer December 2005 *Elements* 313-314). The ease of use and new capabilities are breathtaking. The cost to libraries is significantly less than the sum of the individual journals, but it's all or nothing. Proceeds are returned to publishing organizations based on the number of articles uploaded and the number of internet hits. The first royalty check to MSA (April 2006) was larger than expected, but fell short of start-up costs. *American Mineralogist* is experiencing significant losses in library subscriptions, and these are expected to accelerate as institutions switch to GSW. Will the new GSW income match lost institutional subscriptions? We don't know yet. As a whole, library budgets are a zero-sum game. The new costs associated with GSW draw on this money. I fear that most journals will see reduced income, and without reorganization some will be put out of business.

If, as scientists, we wish to influence these changes that impact us so directly, we need to maintain strong professional societies. At MSA, Executive Director Alex Speer has helped guide GSW from the start and

¹ "The revolution will not be televised, ... the revolution will be live."
Gil Scott-Heron 1974

serves on its board, and past president Doug Rumble has closely monitored GSW and reported on the progress. We think that GSW offers the best path forward, but we are watching the finances with trepidation. This revolution will be live, it will be difficult, and our societies must be prepared.

One significant way you can help strengthen your society is by donating your time and support. I am greatly encouraged by the generosity of MSA members and hope we can do more. A healthy endowment is the best insurance against changing times and dropping subscription revenues. If you already contribute to your favorite society, thank you; if not, please consider a donation now.

John Valley
valley@geology.wise.edu

NOTES FROM CHANTILLY

- During its 2006 spring meeting, MSA Council voted to keep the 2007 professional member dues at \$55 and increase student dues to \$10. Member subscriptions to the paper copy of *American Mineralogist*, which includes online access, will now be differentiated between domestic and foreign member subscription rates to reflect actual costs of producing and mailing the paper journal. Member subscriptions will include a portion of first-copy costs as we shift some of that burden from institutional to individual subscribers. US-member subscriptions (paper and electronic) will be \$50, and foreign-member subscriptions will be \$60. Member web-access-only subscriptions will be \$25. The US institutional subscription price (paper and electronic) is \$725, and the foreign institutional subscription price will be \$750. Included with the institutional subscription are all the current-year issues of *Reviews in Mineralogy and Geochemistry* and *Elements*, as well as access to the electronic journal on the MSA website.
- Last year, members who renewed before December 31 received a \$5 discount in dues. This will change so that those who renew online before October 31 will receive that discount; this change better reflects the true cost savings for MSA.
- MSA 2006 membership renewals will start by October, with membership renewal notices sent electronically. This will be followed by electronic reminders, and a paper copy will be sent to those who do not renew online by the end of October.
- Members and Fellows who are in the senior, honorary, and life categories are also sent renewal notices. These individuals need not pay dues, but are sent notices because this is the best way to update our membership information, particularly mail and e-mail addresses.
- Members who subscribe to other journals through MSA—*Journal of Petrology*, *Physics and Chemistry of Minerals*, *Mineralogical Abstracts*, *Mineralogical Record*, or *Rocks & Minerals*—are encouraged to renew early. MSA needs to forward such renewals to those publishers before your subscription runs out.

J. Alex Speer
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European Association for Geochemistry

THE EUROPEAN ASSOCIATION FOR GEOCHEMISTRY SALUTES ITS 2006 AWARD WINNERS

The EAG awards two medals annually, and together with the Geochemical Society names Geochemical Fellows and the Gast Lecturer.

Urey Medalist



The Urey Medal is given annually by the Society to an individual who has made outstanding contributions to the advancement of geochemistry over his or her career. **Herbert Palme** has been awarded the 2006 Urey Medal. Professor Palme leads the Cosmochemistry Group at the Institute of Geology and Mineralogy, University of Cologne. His research aims at untangling geo- and cosmologic processes by means of analytical work on meteorites. He is

perhaps best known for his work leading to an improved understanding of the origin of the Earth and the Moon. He has also made major advances in a variety of subjects, including the chemical compositions and differentiation processes of large planetary bodies in the solar system (Earth, Moon, Mars); the evolution of isotope ratios connected with core-formation processes; the chemical compositions of primitive bodies in the solar system (asteroids, meteorites); and the processes of condensation in the early solar system (silicates, metals).

Houtermans Medalist



The Houtermans Medal is awarded annually by the EAG to an individual, not more than 35 years of age, who has made exceptional contributions to geochemistry. The 2006 Houtermans Medal has been awarded to **James Badro**, Institut de Physique du Globe, Université Paris VI. James completed his bachelor's, master's and PhD studies at the École normale supérieure in Lyon, France, completing his PhD in October 1997. He then spent two years as a post-

doctoral fellow at the Geophysical Laboratory, Carnegie Institution of Washington, before entering the CNRS in 1999 at the Institut de Physique du Globe in Paris. James' main areas of research interest include mineral physics, the structure, dynamics and composition of the deep Earth, and the evolution/formation of the Earth. Much of his research has focused on quantifying the physical and chemical properties—including wave velocities, elasticities and phase transitions—of minerals at extreme pressures.

Geochemical Fellows

Four geochemists have been selected as Geochemical Fellows of the European Association for Geochemistry and the Geochemical Society in recognition of their contributions to science.

William H. Casey



William Casey is currently professor of aqueous geochemistry at the University of California, Davis. Bill received his Master's degree from the University of California and obtained his PhD from Penn State University under the supervision of Tony Lasaga. Following his PhD, he worked for five years as a geochemist at Sandia National Laboratory before moving on to Davis. He currently serves as associate editor of the journals *Geochimica et Cosmochimica Acta* and the *American Journal of Science*.

Bill has made substantial contributions across the broad field of aqueous geochemistry. He is perhaps best known for his contributions in the areas of the thermodynamics of mineral formation, the mechanics of mineral dissolution, reaction kinetics, and ligand exchange rates. He has applied NMR techniques to study water exchange kinetics in a variety of aqueous systems. His application of the theory and techniques of chemistry and mineral science to kinetics of mineral reactions has enhanced our understanding of fundamental processes occurring at the atomic level.

Brian N. Popp



Brian Popp received his PhD at the University of Illinois in 1986. Over the past 15 years, he has been a professor in the Department of Geology, Geophysics, and Oceanography at the University of Hawai'i. He has served as chief scientist or co-chief scientist for close to a dozen oceanographic expeditions since 1999.

Brian has made significant contributions to the fields of isotope biogeochemistry, the origins of trace gases in sea water, and hydrothermal vent biogeochemistry. He is best known for his contributions to the emerging field of biogeochemistry. Together with Ed Laws and Bob Bidigare, he has published a landmark series of papers on the fractionation of carbon isotopes by marine phytoplankton. By using continuous culture techniques, these investigators developed laboratory systems that faithfully replicated the characteristics of haptophyte algae in nature. This work reveals the importance of growth rate and cell size on carbon isotope fractionation and provides the basis for understanding the isotopic record in marine organic carbon.

Bor-Ming Jahn



Professor Jahn was recently appointed chair and professor of the Department of Geosciences at the National Taiwan University. This appointment follows more than 20 years of work as a professor at the Université de Rennes in France. His research embraces the full range of radiogenic isotope systems including K-Ar, Nd-Sm, Rb-Sr, and U-Pb. This work has been applied to the improved understanding of the evolution of the upper mantle and the petrogenesis of granitic and magmatic rocks. His other major contributions include characterizing the rare earth element content of komatiites and the application of geochemistry to the study of high-temperature metamorphism. He has also served as an associate editor of the journals *Precambrian Research*, *Episodes*, and the *Journal of Asian Earth Sciences*.

Jacques Schott



Jacques Schott has spent most of his scientific career as a Chargé de Recherche and then as a Research Director of the CNRS at the Université Paul Sabatier in Toulouse, France. Over the past 25 years, Jacques developed one of the world's most efficient experimental research laboratories aimed at quantifying water–rock interaction. His major contribution to geochemistry has been in this laboratory, where he and his colleagues have directly measured the thermodynamics and kinetics of mineral–fluid interaction. He, together with his friends and colleagues, has measured and quantified the dissolution rates of over 50 rock-forming minerals. This work has significantly improved our understanding of the solubility of the rock-forming minerals. Jacques has also served as an associate editor of both *Chemical Geology* and *Geochimica et Cosmochimica Acta*, as a councilor of the European Association for Geochemistry, and as the organizer of the 1998 Goldschmidt Conference held in Toulouse.

Gast Lectureship



This lectureship is awarded to a scientist not more than 45 years of age, for outstanding contributions to geochemistry. The 2006 Gast Lecturer is John Eiler of Caltech. John earned his PhD from the University of Wisconsin, where he worked with John Valley on the diffusive re-equilibration of oxygen isotopes in granulites. John is currently an associate professor at Caltech. Already recognized for his scientific contributions, he received both the Mineralogical Society of America Award and the Macelwane Award in 2002.

John Eiler is best known for his application of stable isotope geochemistry to the elucidation of processes and conditions on the Earth and other planets. John has used his expertise with laser fluorination and his geological insight to make landmark contributions to our understanding of the nature and origin of the chemical and isotopic heterogeneity of the Earth's mantle. He has tackled a wide range of new problems in fields outside his nominal areas of expertise, including the conditions of formation of carbonates in meteorites from Mars, the development of the ion microprobe as a quantitative tool for oxygen isotope analysis, the study of isotope fractionations between mineral surfaces and gaseous CO₂ and H₂O and their implications for the cycling of volatiles on Mars, the study of hydrogen isotopes in chondritic meteorites, and the development and application of a new technique to measure D/H ratios in very small amounts of molecular hydrogen from the atmosphere.

Mineralogical Society of America – Geochemical Society
Short Course
Water in Nominally Anhydrous Minerals
 Verbania Italy • October 1-4, 2006
 Organizers: Hans Keppler, Bayerisches Geoinstitut and Joseph R. Smyth, University of Colorado
 an overview of all aspects of water in nominally anhydrous minerals and about water in the interior of the Earth
 For more information about the course and for registration, see <http://www.verbania.bgi.uni-bayreuth.de/>. Registration deadline is June 15, 2006.
 Sponsored by the Bayerisches Geoinstitut, Deutsche Mineralogische Gesellschaft, Geochemical Society, Mineralogical Society of America, and the United States Department of Energy

THE EUROPEAN ASSOCIATION FOR GEOCHEMISTRY INVITES YOU ALL TO
GOLDSCHMIDT 2007
"Atoms to Planets"

The 2007 Goldschmidt Conference will be held in Cologne, Germany, on August 19–24, 2007. The Goldschmidt Conference is the premier annual meeting in geochemistry and mineralogy. In addition to its usual sponsors, the European Association for Geochemistry and the Geochemical Society, the Cologne meeting is co-sponsored by the German Mineralogical Society. This meeting will cover the full range of geochemistry, from cosmochemistry to mineralogy and the origin of life. Sessions are planned on the following themes:

- Analytical Geochemistry
- Atmospheres and Oceans (including Climate Change)
- Biogeochemistry and Geomicrobiology
- Computational Geochemistry
- Cosmochemistry
- Crystal Chemistry and Crystallography
- Environmental Geochemistry and Mineralogy
- Experimental Geochemistry and Mineralogy
- Fluid–Rock Interaction
- Geochemistry and Mineralogy of Surfaces
- Igneous Petrology
- Isotope Geochemistry and Geochronology
- Metamorphic Petrology
- Mineral Deposits and Economic Geology
- Mineralogy
- Organic Geochemistry
- Planetary Geochemistry
- Sedimentary Geochemistry

Cologne has just over one million inhabitants and is the fourth-largest city in Germany. Founded by the Romans, Cologne is the oldest of the major German cities and is still characterized by its 2000 years of history. The metropolis on the Rhine annually attracts many millions of visitors.

To get further information on the 2007 Goldschmidt Conference, please visit the website

www.the-conference.com/gold2007/index.php



www.minersoc.org

Mineralogical Society of Great Britain and Ireland

NOTES FROM LONDON

Strategic Planning

The Mineralogical Society, like many other organisations, has this year begun to develop a strategic plan for the next three years, which will allow the Society to work towards its goal of advancing the mineral sciences in the twenty-first century. A working group was set up under the chairmanship of President Ben Harte and, over two days of meetings in Cambridge in early February, worked through a number of issues. These included membership categories, widening the interest of the Society, the role of the special interest groups, future scientific meetings, publications, marketing and administration.

One of the key benefits of this initiative is that a group of officers, members and staff set aside uninterrupted time to review how the Society was operating and what was working and what was not. A second benefit was that it opened up a dialogue between the Council and the special interest groups, several of which had underlying concerns which were allowed to surface in a frank and open meeting of Council with group chairs and secretaries at the beginning of March. The next steps include the rationalisation of the membership structure and subscriptions, the study of our administrative set up and systems and the development of a marketing plan for membership recruitment and sale of publications.

Frontiers in Mineral Sciences – Cambridge, 26–28 June 2007

In the June issue of *Elements*, we published a full listing of symposia for this key meeting next year, which will address recent advances in research into the properties and behaviour of minerals. Registration is now open, and the deadline for abstract submission and early registration is 28 February 2007. Full details on the conference can be found on the conference web page at www.minersoc.org/Frontiers2007.html

Clay Mineral Stratigraphy of the British Isles

Clay Minerals in Onshore and Offshore Strata of the British Isles: Origins and Clay Mineral Stratigraphy (see advertisement next page) is at last published, and editors Chris Jeans and Dick Merriman are to be congratulated on bringing this major project to a satisfactory conclusion. This book follows on from R.M. Perrin's 1971 book *The Clay Mineralogy of British Sediments*, a masterly compilation of several decades of clay mineral research at the time. This new book fills in the gaps left by Perrin's work and brings the whole subject up to date. It draws on the success of an international series of conferences on clay minerals diagenesis held in Cambridge in the 1980s and 1990s, supported by the petroleum industry. The new book has been supported by funds from the Clay Minerals Group, the now disbanded Joint Association for Petroleum Exploration Courses (JAPEC) and the Society.

Adrian Lloyd-Lawrence

THE SOCIETY'S SPECIAL INTEREST GROUPS THE MINERAL PHYSICS GROUP (MPG)



Michele Warren, secretary of the Society's Mineral Physics Group, describes the ascendancy of mineral physics in the UK in recent years, the excellent resources for research in this area and the contribution of the group to that work. Michele has a background in computational modelling for solid-state physics and is a lecturer in Earth sciences at the School of Earth, Atmospheric and Environmental Sciences at The University of Manchester, one of the UK's major centres for research in mineral physics.

The Mineral Physics Group of the Mineralogical Society was set up in 1996 and exists 'to advance the understanding of the fundamental physical and chemical processes that determine the properties of minerals'. Research in mineral physics now covers not only the fundamental structures and properties of bulk minerals under pressure and temperature but also their response to environmental influences, such as radiation damage, toxic trace metals and organic molecules, as well as their growth and stability. While our scope is wide, we always seek to trace the observed behaviour back to the underlying physics and chemistry, usually at the atomic scale.

There is a fairly even balance between experimental and computational work, and a wide variety of techniques is used. The UK has excellent resources for mineral physics and chemistry, both in-house and at central facilities, and group members come from both Earth science and physics communities, with overlaps with several other disciplines, such as materials science, chemistry and, increasingly, biology. Recent UK (NERC) and European (ESF) funding of e-science, molecular environmental science and mineral science has increased both the breadth and depth of this work and allows the mineral physics community to explore the ever more challenging problems. In particular, this last decade has seen a huge growth in the contribution of computer simulation to the mineral sciences.

As a special interest group, we aim to stimulate interest in mineral physics, encourage the exchange of information both within and beyond the group and arrange discussion meetings. The latter often take the form of one-day 'Research in Progress' events, at which research students are particularly welcome. We are planning to hold another of these soon and also hope to elect new committee members at the meeting. If you are interested in finding out more, whether about our interests or how you could help on the committee, please contact John Brodholt (j.brodholt@ucl.ac.uk) or Michele Warren (m.c.warren@manchester.ac.uk).

2006

**Mineralogical Society Training
Workshops in Electron Probe
Microanalysis (EPMA) in Mineralogy
For Postgraduates and Advanced Researchers**



For full details and how to register for these 'hands on' training workshops go to <http://www.minersoc.org/education>

Natural History Museum, London
Final Course Dates for 2006
7-10 November 2006



NEW

Clay Minerals in Onshore and Offshore Strata of the British Isles: origins and clay mineral stratigraphy

Edited by: C.V. Jeans and R.J. Merriman

Clay Minerals in Onshore and Offshore Strata of the British Isles is an invaluable source of information for the professional or student concerned with the:

- role of clay minerals in the geological history of Britain.
- development of hydrocarbon reservoirs
- engineering and agricultural properties of soils
- planning of land use
- extraction of industrial clays

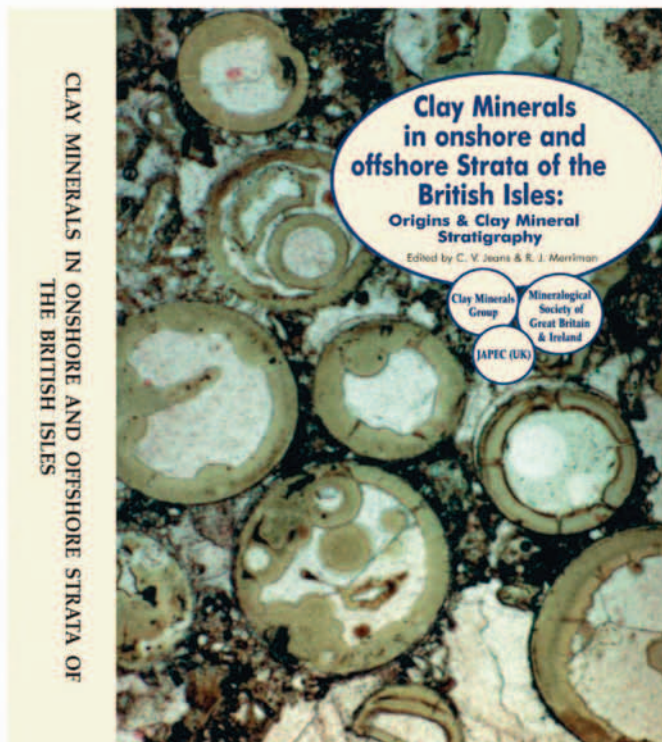
The 10 papers in this book bring together 50 years of research and include many thousands of new clay mineral analyses.

Hardback 512 pages plus index

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Mineralogical Association of Canada

HIGHLIGHTS OF COUNCIL MEETING

Changing of the Guard

The annual council meeting of the Mineralogical Association of Canada (MAC) was, as usual, held just prior to the GAC-MAC conference, this being the fiftieth such meeting of the two organizations. Incoming president Kurt Kyser opened the council meeting by noting some of the highlights, past and present: the highly successful MAC 50th anniversary celebrations; MAC's visibility at the 2005 Goldschmidt Conference; another highly successful short course (#36) in Montreal; planning for the upcoming (July 2007) Frontiers meeting in Cambridge, England, co-organized with MinSoc and MSA; continued sponsorship of students via scholarships and grants to help them attend meetings such as GAC-MAC; and the recent appointment of a short course coordinator, Rob Raeside. However, the association has some notable and immediate challenges to be dealt with, including a significant budgetary deficit for the first time in several years.

The make-up of council at the annual meeting was notably different for the first time in many years: new councilors Marc Constantin, Jim Mungall, James Scoates, and Paula Piilonen joined the new appointees Martine Savard and David Fowle in the positions of treasurer and secretary, respectively. Mati Raudsepp and Andy MacDonald stepped down from the latter positions after years of distinguished service, and their contributions were acknowledged and noted – thanks again to you both. Also obvious was the absence, at times deafening, of the always flavorful Scottish brogue provided for so many years by MAC supporter extraordinaire Norm Halden. We wish Norm well as he deals with other issues in the nearby forests, lakes, and streams.

Some of the important issues dealt with over the two days of meetings are summarized below.

Past Presidents' Medal

In response to a proposal by Ed Nuffield (founding president of MAC) and Bob Ferguson to rename the Past Presidents' Medal, past winners were canvassed out of respect for their concerns. The

near-unanimous support of past winners for this idea moved Council to vote on renaming the medal in honor of the significant contributions of an outstanding Canadian mineralogist or crystallographer to the mineralogical sciences in Canada. A committee has been struck to deal with this name change, the first step being to invite nominations from members. Thus, we are now open to suggestions for renaming this medal and invite all members to submit their ideas in writing or electronically:

Daniel Kontak
Nova Scotia Department
of Natural Resources
P.O. Box 698
Halifax, NS B3J 2T9,
kontakdj@gov.ns.ca

GeoscienceWorld (GSW): The Electronic Age

The continued challenge of dealing with electronic formatting and journal aggregation prompted council, after three years of discussion about GSW, to jump on board. After due consideration, MAC council voted to join GSW because it appears to be a successful venture and will benefit MAC and *The Canadian Mineralogist*.

However, we realize that time will be the final judge. Thus, the journal will become part of a scientific journal aggregate, available to those who subscribe—check with your institution to see if it subscribes to GSW.

Publications News

The Canadian Mineralogist reached 2100 pages last year—a reflection of the popularity of the journal indeed. Editor Bob Martin reported that having three thematic issues in one year, although good in some respects, created delays in publishing regular papers. As no full thematic issues are planned for 2006, it will be easier to return to a regular publishing schedule. Because of the financial impact of so many published pages, council restricted the number of pages to 1600 for 2006, and a color fee per page will be introduced in 2007. Several years ago, MAC was innovative and successful by offering free color to authors, but the financial consequence of this is now apparent. Thus council has moved to recover some of these costs by applying a nominal fee for color, unless there is financial reason to waive the charge.

Projects that are nearing completion and, therefore, heading to the printer in the near future include *Atlas of Migmatites*, by Ed Sawyer (Special Publication 9). Expected to follow in 2007 and 2008 will be the *Atlas of Non-Silicate Minerals in Thin Section* and a book entitled *Pegmatites*, by world authority David London.

Finally, another high-quality short course volume edited by James D. Webster and series editor Rob Raeside was produced in time for the GAC-MAC conference. The volume entitled *Melt Inclusions in Plutonic Rocks* is sure to be a good seller. The list of accomplished contributors was put together by renowned petrologist Jim Webster of the Museum of Natural History in New York. Our thanks to Jim and to the many contributors for all their fine efforts.

MAC Office is Moving!

The decision to consolidate the business offices of MAC was discussed at length, being motivated by several issues affecting the present and near future. Our office in Ottawa has served MAC, its members, and the public well for many years,

and council applauds the extraordinary effort and dedication of Fran and Bob Pinard while running the Ottawa office since 1990. Unfortunately, the issues of conversion to electronic publishing, electronic bookstores, centralized mailing, etc. combined with impending financial difficulties required immediate action in order for MAC to function in the best interests of the Association and its membership. The new Quebec location for the business office allows for more efficient running of many MAC functions. All the publishing, ordering, mailing, and coordination activities now reside in one place, which is also proximal to the new treasurer, Martine Savard.

Please note that our offices moved on July 1 to Quebec City. Our new address is:

MINERALOGICAL ASSOCIATION OF CANADA/ASSOCIATION MINÉRALOGIQUE DU CANADA

490, rue de la Couronne
Québec (QC) G1K 9A9
Canada

Tel.: 418-653-0333

Fax: 418-653-0777

E-mail: office@mineralogical
association.ca

Next Council Meeting

The next council meeting will be in Cambridge, England, during the Frontiers meeting in July 2007. This will be the first time council has ventured from traditional meeting grounds—the site of the annual GAC-MAC conference. However, we emphasize that MAC remains fully supportive of the long and very successful collaboration in the running of the annual GAC-MAC meetings and will be helping out at the very unique venue of Yellowknife. As in the past, MAC will be assisting the Yellowknife organizing committee in whatever way it can, providing funding for sessions, sponsoring a short course ("Geology of Gems," by Lee Groat of UBC), and assisting with student participation. The departure from the normal procedure is merely a reflection of MAC maturing and interacting with other societies, while at the same time retaining its traditional ways.

Daniel J. Kontak
Past President

MONTREAL 2006: A SUCCESS

Montreal 2006 was a highly successful meeting in all respects—even the rains could not dampen the enthusiasm that permeated the halls and rooms of the refurbished venue at Université du Québec à Montréal. The sessions were varied and provided interesting information to just about any Earth scientist. MAC contributed financially to several sessions, in particular the session on alkaline igneous systems, organized by D. Lentz, A. Lalonde, S. Salvi, and J. Paquette, which went on for the three days of the meeting. This session was an excellent example of the merging and application of a wide spectrum of disciplines and techniques in the Earth sciences to resolve the nature and origin of alkaline systems and associated hydrothermal processes. Congratulations to the organizers of this and other MAC-sponsored sessions (Advances in Micro- and Nano-Scale Characterization and Analysis of Earth Materials; Metamorphism, Crustal Fluids and Experimental Petrology: G. Skippen Tribute; Kimberlites and Other Diamondiferous Rocks; Earth's Mantle: New Insights from Diamonds and Xenoliths). We will publish a summary of these special sessions in the next issue of *Elements*. Our heartfelt thanks to the local organizing committee chaired by Normand Goulet for all the hard work in planning this meeting.

MAC Awards Luncheon

The MAC awards luncheon was held at the McGill Faculty Club, and Jeanne Paquette of McGill University is to be thanked for helping to arrange this truly inspirational venue, where members dined in elaborate and stylish surroundings. As always, the awardees were delightful and entertained us with the stories of their educational and vocational journeys.

SEEKING PROPOSALS FOR BERRY SUMMER SCHOOLS

You would like to invite a world-leading specialist to run an in-depth workshop on a topic in mineralogy, geochemistry, crystallography, ore deposits geology, or petrology?

**MAC CAN PROVIDE UP TO \$2500
TO HELP MAKE IT HAPPEN.**

Berry Summer Schools are typically run in a university setting, with one or two invited instructors.

They can last from two to five days.

They provide a hands-on component, either in the lab or in the field.

They can be run anywhere in the world.

The number of attendees is small (30 to 60).

They are stand-alone events, decoupled from scientific meetings.

They are geared to meet the needs of students, but also attract industry representatives and academics.

You can read reports on the first three Berry Schools in MAC Newsletters 68 (p. 9), 71 (p. 8), and 73 (p. 11) at www.mineralogicalassociation.ca/

INTERESTED?

FOR MORE INFORMATION, CONTACT THE CHAIR OF THE TECHNICAL PROGRAM COMMITTEE, PETER BURNS, AT PBURNS@ND.EDU



Traditional photograph of the 2006 award winners at the MAC luncheon. From left to right, Ron Peterson and Alan Grant (Hawley Medal), Joel Grice (Past Presidents' Medal), Michael Schindler (Young Scientist Award), Mati Raudsepp (Berry Medal), Dan Kontak (MAC past president), Jason Mackenzie (Mac Foundation Scholarship), Peter Burns (MAC vice president), and Kurt Kyser (MAC president). You can read citations and responses for the MAC awards on MAC's website as well as in a future issue of *The Canadian Mineralogist*.

The Geology of Gem Deposits

MINERALOGICAL ASSOCIATION OF CANADA SHORT COURSE

21–22 MAY 2007, YELLOWKNIFE, CANADA

SHORT COURSE ORGANIZER: Lee Groat, University of British Columbia

This two-day short course will look at gemstones from a geological perspective. Gem deposits are rare because in general the conditions that promote their formation are unusual and thus worthy of scientific study. Modern geological and analytical techniques have recently been applied to gem occurrences in Canada and elsewhere, and our models and understanding of their formation is being radically altered. This short course will review our current understanding of diamond, ruby, sapphire, and emerald deposits but will also examine the lesser-known coloured gem deposits.

This short course will precede Yellowknife 2007—the joint annual meeting of the Geological Association of Canada and the Mineralogical Association of Canada, in Yellowknife, Northwest Territories, Canada. It will be a unique opportunity to experience a change of climate and a meeting north of 60°.

1. INTRODUCTION
2. DIAMOND DEPOSITS (THOMAS STACHEL)
3. GEM CORUNDUM (RUBY AND SAPPHIRE) DEPOSITS (GASTON GIULIANI)
4. GEM BERYL (EMERALD, AQUAMARINE, ETC.) DEPOSITS (LEE GROAT ET AL.)
5. OTHER GEMS (TSAVORITE, TANZANITE, TOPAZ, ETC.) (TASHIA DZIKOWSKI ET AL.)
6. GEM-BEARING PEGMATITES (SKIP SIMMONS)
7. EXPLORATION FOR GEM DEPOSITS

For more information, e-mail Lee Groat at lgroat@eos.ubc.ca or visit the conference website at www.nwtgeoscience.ca/Yellowknife2007



CANADA'S NORTH...
ITS CLIMATE, ITS CULTURE,
ITS MINING HERITAGE, AND ITS FUTURE!

LE NORD CANADIEN...
SON CLIMAT, SA CULTURE,
SON HÉRITAGE MINIER ET SON FUTURE!

VISIT OUR WEBSITE - VISITEZ NOTRE SITE INTERNET
www.nwtgeoscience.ca/yellowknife2007





www.sfmc-fr.org

Société Française de Minéralogie et de Cristallographie



A TRIBUTE TO PROFESSOR HUBERT CURIEN

Organized by the Institut de Minéralogie et de Physique des Milieux Condensés (IMPMC), the Association Française de Cristallographie (AFC) and the Société Française de Minéralogie et de Cristallographie (SFMC)

On June 19, over eighty persons gathered at IMPMC in Paris to remember the outstanding contribution of Hubert Curien to mineralogy and crystallography. Professor Hubert Curien, who died on February 6, 2005 at the age of 80, exercised countless responsibilities in the French and European research administrations, including the C.E.R.N. and the European Space Agency (of which he was the first president). In addition, he acted as Minister of Research and Technology in France. He was president of the SFMC in 1967 and of AFC in 1969. During this meeting, we commemorated Hubert Curien as an outstanding professor (he never stopped teaching) and a distinguished mineralogist and crystallographer. In the presence of Ms Curien, many of his former students and colleagues testified as to how Hubert Curien has influenced their lives, by his example, by his care, by his advice, etc. His scientific contribution was illustrated by a few selected examples: defects in solids like LiF, inelastic scattering of X-rays in bcc iron, the formation of twins, and so on. In many cases, the work of Hubert Curien was precursory, and several current fields in solid-state physics and geophysics bear the imprint of this generous man.

A NEW RAMAN DATABASE ONLINE ON THE SFMC WEBSITE

Raman spectroscopy is a very powerful tool to rapidly characterize minerals. However, databases on Raman spectra are relatively scarce. The SFMC is happy to contribute to the international dataset by presenting a new Raman database, collected primarily by Claire Bény (BRGM), together with Jean-Michel Bény (BRGM, University of Orléans and CNRS) and Bernard Lasnier (Nantes University).

Visit the new Raman database at <http://www.sfmc-fr.org/main/raman.htm> and send all remarks to sfmc@ccr.jussieu.fr

You are also invited to contribute by providing new spectra. The following information is associated with each spectrum: analytical conditions of acquisition, characteristic wavenumbers, and structure of minerals.

PRIX HAÛY-LACROIX 2006



Héléne Gailhanou

Each year the SFMC awards the Prix Haüy-Lacroix to recognize a young scientist for the quality of his PhD research in the fields of mineralogy, geochemistry, petrology, or material science. In 2006, it was awarded to Héléne Gailhanou. She completed her PhD at the Laboratoire TECSN – Université d'Aix-Marseille III, with J. Olives and J. Rogez as advisors. Dr Gailhanou is now a postdoctoral fellow at the BRGM in Orléans (contact: H.Gailhanou@brgm.fr). The following is a summary of her study entitled "Experimental Determination of Thermodynamic Properties and Study of Nanostructures of Clay Minerals."

Clay minerals such as smectite and interstratified illite-smectite are particularly well-adapted for natural or engineered barriers in waste confinement. Nevertheless, data concerning their thermodynamic properties, essential for understanding their chemical behavior over long time periods, are rare and of questionable value.

For the first time, all the thermodynamic functions of internationally referred clay minerals—illite IMt-2, smectite MX-80, interstratified illite-smectite ISCz-1—and the mixed-layer illite-smectite series of Shinzan (Japan) have been determined. The study of nanostructures by HRTEM-EDX has provided very original results (e.g. presence of tri-octahedral illite) and has led to an accurate redefinition of these minerals.

The minerals were studied in the anhydrous and hydrous states. A preliminary study of hydration was carried out on smectite MX-80 and interstratified ISCz-1. For the first time, water vapor adsorption isotherms have been obtained at various temperatures, from 25°C to 105°C.

The enthalpies of formation of minerals were determined from the enthalpies of dissolution in an HF-HNO₃ solution at 25°C of (1) the sample (mineral + impurities) and (2) the mixed oxide or hydroxide constituents (of the mineral) + impurities.

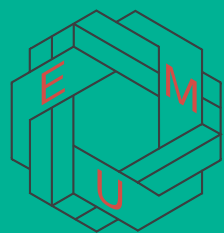
The enthalpies of mixing of illite and smectite layers were obtained by calorimetry of dissolution on Shinzan mixed-layer series. They are slightly negative, with a minimum value of 3.7 kJ/mol O₁₀(OH)₂ for 50% illite–50% smectite. Mixed-layer minerals are therefore slightly more stable than the assemblage of the two end-members, illite and montmorillonite.

Heat capacities were obtained by adiabatic calorimetry, from 5K to 380K, and by differential scanning calorimetry, from 300K to 500K. The values were corrected by subtracting the contribution of impurities. Water in hydrous clay minerals undergoes one or two continuous glass transitions between 150 and 270K. They may correspond to different types of adsorbed water. From C_p values, entropies and enthalpies of heating were calculated.

Gibbs free energies of formation were obtained from enthalpies and entropies of formation at various temperatures. In particular, Gibbs free energies of formation from oxides are negative, which shows that clay minerals are more stable than the association of the corresponding oxides.

By comparing the values obtained for anhydrous and hydrous minerals, enthalpies of hydration and Gibbs free energies of hydration were calculated.

At the same time, equilibrium experiments of clays in aqueous solutions were carried out. The values of ionic activity products obtained after two years, for various clay-solution systems, were compared with calorimetric results.



www.univie.ac.at/Mineralogie/EMU

European Mineralogical Union

The EMU, an association of all mineralogical societies in European countries, continues to organise sessions at major conferences, to award a medal for research excellence, and to support such ventures as the *European Journal of Mineralogy*. A particularly important activity of EMU is the organisation of short courses ('schools') dealing with forefront aspects of the mineral sciences. These short courses are taught by international experts and attended by research students, younger researchers, and more experienced scientists. The courses are accompanied by the publication of volumes in the series known as the *EMU Notes in Mineralogy*.

EMU NOTES IN MINERALOGY

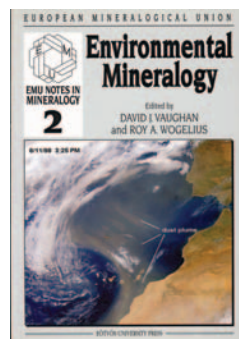
The first six volumes in this series are as follows:

Modular Aspects of Minerals, Volume 1 (1997)

S. Merlino (Pisa, Italy), editor, 448 pages, ISBN 963 463 1320, 20€ (excl. postage)

Beginning with fundamental aspects, in particular with applications of OD theory, the crystal chemistry of silicates, sulphides, sulphosalts, oxides and oxyalsalts is discussed from the standpoint of their modularity. The reader is introduced to terms such as building block, polytypism, polysomatic families and homologous series, and to procedures to investigate the concepts which underly them. The widespread availability of high-resolution electron microscopes allows the investigation of the microstructural aspects of materials of geological importance, emphasising the relevance of knowledge of modularity.

Environmental Mineralogy, Volume 2 (2000)



D.J. Vaughan and R.A. Wogelius (Manchester, UK), editors, 434 pages, ISBN 963 463 1333, 20€ (excl. postage)

Environmental mineralogy is a field that calls on both core mineralogical skills and interdisciplinary understanding across the chemical, biological and geological fields. It is an area ideally suited to development of advanced teaching that redefines the boundaries of mineralogy. Analytical, experimental, and computational methods are discussed, and overviews are presented on the mineralogy of soils, marine sediments, atmospheric particles (aerosols), and different kinds of wastes. Also the role of microbial controls and aspects of cultural heritage are discussed.

Solid Solution in Silicate and Oxide Systems of Geological Importance, Volume 3 (2001)

C. Geiger (Kiel, Germany), editor, 466 pages, ISBN 963 463 1347, 20€ (excl. postage)

The solid Earth and extraterrestrial samples from sources such as meteorites consist of materials that include many examples of mineral solid solutions. Research on such solid solutions is broadly based, encompassing work undertaken in physics, chemistry, and materials sciences as

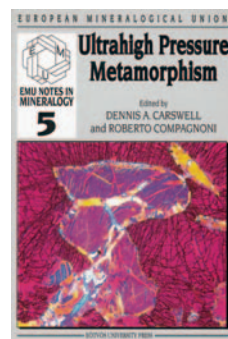
well as in mineralogy. The chapters in this volume reflect this diversity. The volume begins with an extensive coverage of the thermodynamic approach. The rapid development of enhanced computer power also allows atomistic simulation techniques, and details of the methodology and applications of such techniques are discussed with examples.

Energy Modelling in Minerals, Volume 4 (2002)

C.M. Gramaccioli (Milan, Italy), editor, 425 pages, ISBN 963 463 5660, 20€ (excl. postage)

Accurate quantum-mechanical simulations have significantly extended our understanding of Earth materials and hold great promise for the future development of the Earth and planetary sciences. Phase transitions, equations of state, elasticity and thermoelastic properties of minerals – topics essential for geophysics – can be studied in this way. The reader is introduced to the energy modelling and computer simulation of crystal structures and properties of minerals. Monte Carlo methods and *ab initio* theories are presented. Individual chapters focus on theoretical aspects and the experimental techniques required to investigate the thermodynamic properties of minerals and the kinetics of mineral systems.

Ultrahigh Pressure Metamorphism, Volume 5 (2003)



D.A. Carswell (Sheffield, UK) and R. Compagnoni (Torino, Italy), editors, 508 pages, ISBN 963 463 6462, 24€ (excl. postage)

Ultrahigh pressure metamorphism (UHPM) is a normal feature of continental plate collisional orogens and is found worldwide. This textbook volume contributes to our understanding of the UHPM terranes in the Western Alps, Norway, the Kokchetav massif, the Dabie Shan-Suli orogen, the Bohemian Massif and the NW Himalaya. In the context of these examples, one of the main questions to be answered is how deep the upper part of the continental lithosphere can subduct. Mineralogical and geochemical aspects are discussed, along with tectonometamorphic evolution paths. A CD-ROM with additional colour images compiled by F. Rolfo (Torino, Italy) is included with the volume.

Spectroscopic Methods in Mineralogy, Volume 6 (2004)

A. Beran and E. Libowitzky (Vienna, Austria), editors, 659 pages, ISBN 963 463 6624, 24€ (excl. postage)

Spectroscopic methods are particularly valuable in providing information about the local structure of minerals, in contrast to diffraction methods which give information about the long-range order. Theory and application of luminescence techniques, optical absorption, IR, Raman, Mössbauer, NMR, and X-ray absorption (XANES and EXAFS) spectroscopies are discussed. This textbook includes numerous examples to demonstrate the power, and also the limits, of these methods.

A detailed report on just-published volume 7, *Mineral Behaviour at Extreme Conditions*, will be given in the next issue of *Elements*.

R. Miletich (Heidelberg, Germany) editor, 488 pages, ISBN 963 463 8676, 24€ (excl. postage)

The publication of the EMU Notes has been made possible through the generous support of several organisations, in particular the European Commission, and through the considerable efforts of the contributors, editors and series editor Tamás G. Weiszbürg.

Copies of the EMU Notes can be obtained via the EMU home page: www.univie.ac.at/Mineralogie/EMU/school.htm#Notes, and also via the publication order lists of several mineralogical societies (e.g. Mineralogical Society of America, Mineralogical Society of Great Britain and Ireland). Please contact the EMU secretary if difficulties are encountered in obtaining any of these (or future) volumes (herta.silvia.effenberger@univie.ac.at).

Peter Ulmer, President
David Vaughan, Past President
Herta Effenberger, Secretary

Micro- and Mesoporous Mineral Phases¹

For those working in a lab, one of the “petits plaisirs” enlightening everyday life is when the librarian proclaims “I have just received and shelved a new white book.” You realize immediately that a brand new volume of the prestigious book series *Reviews in Mineralogy and Geochemistry* (RiMG) has arrived from the States. Needless to say, you break off what you are doing, you open it, and you go through it rapidly, even if the title is far from your current topic of interest. A quick flip through the pages usually suffices to give you a good idea of what and who is in the forefront of the subject. If you are in the field, or eagerly want to learn about it, the white brick immediately becomes a reference book for your ongoing work or training. After some months or years of use, the book may eventually turn to grey and lose more and more bundles of pages—that is, it may show evidence of how much it has been useful!

Micro- and Mesoporous Mineral Phases is volume 57 in the RiMG series. It was launched in 2005 and edited by Giovanni Ferraris and Stefano Merlino for the Mineralogical Society of America (MSA) and the Geochemical Society, in partnership with the Italian Accademia Nazionale dei Lincei. The 448 pages of text and figures are organized into 12 chapters, themselves corresponding to the 12 invited lectures delivered at the 2004 meeting on micro- and mesoporous mineral phases, held on December 6 and 7, in Rome, Italy.

The book starts with two chapters dealing with the definition of micro- and mesoporous phases (chapter 1, by L.B. McCusker) and the topology of their framework host (chapter 2, by S. Krivovichev). Then, the polysomatic aspects of microporous minerals related mostly to layer silicates are developed (chapter 3, by G. Ferraris and A. Gula), as are heterosilicates involving coordination polyhedra other than tetrahedra in the framework (chapter 4, by N.V. Chukanov and I.V. Pekov; chapter 5, by I.V. Pekov and N.V. Chukanov; chapter 6, by J. Rocha and Z. Lin). Treatment of the structural and crystal chemical features of sodalite-type structures (chapter 7, by W. Depmeier) precedes the presentations of the modular aspect of the cancrinite-davyne group and C-S-H phases (chapter 8, by E. Bonaccorsi and S. Merlino). More casual examples encompass the versatility of the tunnel structures of manganese oxides (chapter 9, by M. Pasero) and that of apatite (chapter 10, by T. White, C. Ferraris, J. Kim and S. Madhavi). Porous

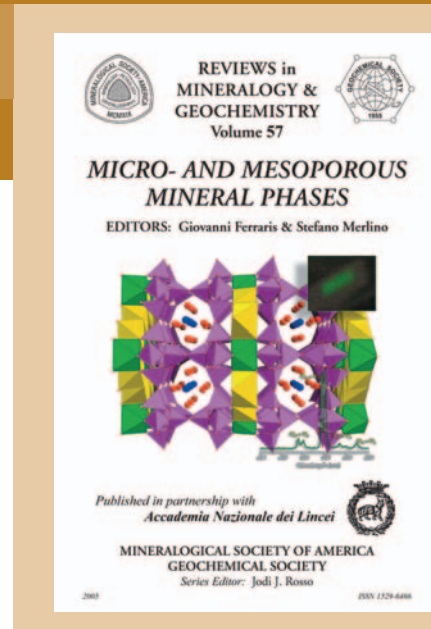
sulfide and selenide structures are then discussed (chapter 11, by E. Makovicky). Finally, mesopores arising from microstructures based on non-porous, crystalline or not, atomic structures of carbon, serpentine, and clathrates are addressed (chapter 12, by M. Mellini) and placed in an Earth science and materials science context. Zeolites are not covered in this volume because they were the subject of the RiMG volume number 45, published in 2001.

This book is a most valuable hymn to the crystallography and crystal chemistry of more or less open mineral structures. A neophyte going through the book may have the strange feeling that many structures seemingly violate the usual rule of thumb: that crystals should have a compact atomic structure. Well, we have long known, from the description of silicate structures based on progressive polymerization of silicate tetrahedra, that channel-bearing frameworks are present among ring silicates and among some chain and layer silicates, i.e. well before the well-known framework silicates including zeolites are mentioned. But to realize that so many other structure types and even sulfides or selenides may display open structure is amazing and quite informative.

This book allows ample space for the presentation of crystallographic data on these chemically and structurally diverse crystalline compounds. Many unit-cell data and structural formulae are available, and anyone who wants to figure out those 3-D crystal structures on his computer may import fractional co-ordinates from current mineralogical data banks. It is also a gold mine for anyone interested in testing new materials for the countless, present and future applications of porous mineral phases. Among the possible applications, such structures may act as molecular sieves, catalysts or catalyst supports, gas absorbers and sources, glue for hardening of cement, biocompatible materials, battery elements, traps for remediation of nuclear wastes, and fuel cell electrolytes, to mention a few.

Thus, this book reinforces existing bridges between materials science and crystallography. It is also rewarding to see how classical structure resolution of minerals by X-ray diffraction can feed the present needs of industrial and environmental applications.

But as you close this RiMG volume, you may wonder if all these mineral structures are really porous structures. A reader not aware of the wide definition of porous minerals may wonder about the very existence of pores in many of the structures presented here. Thus, the “polyhedral” representation or the “small ball and stick” diagrams used everywhere in the figures overemphasize holes and tunnels that a “space filling” diagram might not have



shown so clearly. Also the systematic separation of a “guest” atom or group of atoms from a “host” framework reinforces this feeling. Discussing only the host may lead to the wrong conclusion that pores do exist in the structure. Intuitively, pores are related to open spaces in the structure, which may or may not be interconnected. In practice, such open spaces may be either empty or loosely occupied by molecules or low-charge ions. This means that you can remove such guests without disturbing too much the charge balance and the rigidity of the host framework. Many structures in the book depart from this intuitive view.

This book may also be inspiring for the mineralogist or materials physicist interested in working out the types of defects involved in those averaged, supposed-to-be-perfect structures (polysomes, twins, stacking faults, intergrowths, etc.). The editorial quality of the text is quite good, while the computer-assisted drawings are clear and informative.

In conclusion, I recommend this volume not only to libraries in Earth sciences but also to libraries specializing in solid-state chemistry. An annual subscription to *American Mineralogist* provides you with free RiMGs published during the current year. Additional copies may be ordered at moderate cost from the MSA business office.

Oh! I guess that another new “petit plaisir” experienced in many labs right now is when the colorful *Elements* magazine appears in the mail box. Again, our ongoing activities come to a halt, as we cannot resist going through it greedily!

Alain Baronnet

Université Paul Cézanne and Centre de Recherche en Matière Condensée et Nanosciences (CRMCN-CNRS)
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¹ Giovanni Ferraris and Stefano Merlino, editors (2005) *Reviews in Mineralogy and Geochemistry* 57, Mineralogical Society of America, 3635 Concorde Pkwy Ste 500, Chantilly, VA 20151-1125, United States. US\$40; 25% discount for MSA members

Mineral Deposits and Earth Evolution¹

This book contains papers that were part of the Geological Society of London's 2003 Fermor flagship meeting "World-Class Mineral Deposits and Earth Evolution." The objective of the meeting was to investigate how mineral deposits have changed during Earth's evolution over the last 3.8 Ga and what they can tell us about this evolution.

With these objectives in mind, Groves et al. point to the change in the nature of the subcontinental lithospheric mantle (SCLM) with time. In the Archean, the high degree of plume-related partial melting led to the formation of thick, highly depleted, buoyant SCLM, while the lower degrees of melting characteristic of the Phanerozoic gave rise to thinner and denser, easily delaminated and subducted mantle. They argue that it is only Ni-Cu deposits that show a variation directly attributable to a cooling Earth. The style of deposition of U, Fe and Mn is related to the development of an oxygenated marine environment in the interval 2.6 to 2.0 Ga. Porphyry Cu, orogenic Au, and VHMS deposits likely accumulated throughout time, and their existence is rather a question of preservation than of deposition or non-deposition.

Harcouet et al. report on their thermal evolution model during the period of structural deformation in the Ashanti gold belt of Ghana between 2.130 and 2.095 Ga (just prior to Au mineralization in the belt at 2.063 Ga). They suggest that the thermal perturbations shown by their modelling could be related to periodic "mantle overturning," but stress that the increase in heat flow indicated by their model is not of catastrophic proportions. An interesting aspect of the model is that it indicates significant lateral heat flow, which is caused by differences in thermal conductivity of different rock units and is concentrated close to the boundaries between these units. This may have been important in promoting local circulation of mineralizing fluids.

A very different, global approach to the origin of gold mineralization is taken by Leahy et al. They argue that an essential requirement is the presence of gold-enriched source rocks occurring in a tectonic environment and at a metamorphic grade that would have permitted the existence of fluids to dissolve and transport the gold. They recognize seven distinctive tectonic settings and analyze the 181 currently active, large (>100 t Au) gold mines in terms of these settings. They find that 46% of the deposits fall within large

ocean closure orogens, 32% within continental arcs and 10% within large accretionary arc complexes. They conclude by relating Au mineralization strictly to tectonism and decay theories that have postulated "golden epochs" as either spurious or coincident with periods of enhanced crustal growth.

Hayward et al. show how the chemical and morphological heterogeneity of Witwatersrand gold can be used to approach the question of whether the gold is the result of hydrothermal modifications of early placer deposits or was initially introduced hydrothermally. While most of the observed gold grains had morphologies indicative of hydrothermal deposition, wide variations in the Ag and Hg content in gold throughout the Witwatersrand are likely related to variations in the provenance of the detrital gold in the various "reefs." They attribute the morphologies of the gold grains to very localized (mm- to cm-scale) remobilization by low volumes of fluid.

De Wit and Theart present a statistical analysis of the number of different types of deposits related to different Archean cratons, and also of differences between deposits in Archean cratons and in younger crust. There is a wide variation in the frequency of occurrence of many deposit types among different Archean cratons, with the Zimbabwean craton being particularly rich in many of the groups of elements that they consider. Archean cratons are much better mineralized than areas underlain by younger rocks except for the element group U-Th-REE. Their analysis suffers in that they are unable to factor in the effectiveness of the exploration that has been applied in different areas (which they acknowledge) and that they use number of deposits per unit area rather than the integrated amount of metal contained within all of the deposits per unit area as the yardstick for comparison. Nevertheless their analysis points to certain areas that contain less than the expected number of discoveries. After reflection on possible reasons for this, the explorationist might be able to use this fact as an indication of where the chances of grass-roots success would be the greatest.

A number of papers depart from the strict discussion of ore deposits and tackle the question of how the Earth's atmosphere may have evolved with time. Traditionally, it has always been maintained that biogenic fractionation of sulfur isotopes started after the close of the Archean, although some data obtained over the last 15–20 years have cast doubt on this hypothesis. In order to provide a better understanding of the development of isotopic fractionation processes during the Archean, Grassineau et al. chose to study the



isotopic composition of S and C in the 3.8 Ga Isua and 2.7 Ga Belingwe greenstone belts, and compare their results with their own and literature data on the 3.24 Ga Barberton belt. Their overall conclusions are that a biological sulfur cycle may have been operational at 3.8 Ga and 3.2 Ga but was flourishing by 2.7 Ga, and that the biological carbon cycle was operational by 3.2 Ga and may have operated at 3.8 Ga.

Farquhar and Wang start with a very coherent explanation of mass-independent sulfur isotope fractionation that will be welcomed by anyone (this writer included!) who wants an accessible summary of the field. Such fractionation is strong in rocks older than 2.45 Ga, minor but present in rocks with ages between 2.45 and 2.0 Ga and apparently rare to absent in rocks younger than this. They point out that when oxygen in the atmosphere is 10^{-5} PAL and less (PAL = present atmospheric oxygen), photolysis of SO_2 and the mass-independent production of ^{33}S is most efficient, with transfer to the surface occurring as both H_2SO_4 and S_8 aerosols. Photolysis can still occur at $>10^{-5}$ PAL with less efficiency and is likely to cease at $>10^{-1.5}$ PAL. This may be the reason for the variation in mass-independent ^{33}S in rocks of different ages, and thus may place constraints on the change in the oxygen content of the atmosphere with time. They stress, however, that the lack of mass-independent ^{33}S in younger rocks could have causes other than the oxygen content of the atmosphere, including changes in the ozone content of the atmosphere which could have screened out the radiation causing S photolysis.

Lowry et al. show that there is a relationship between the isotopic composition of sulfur in sulfides related to granitoid intrusions in different terranes of Scotland and northern England and the sulfur that occurs in the surrounding sediments or underlying basement. They observed that in the Lakesman-Leinster and Grampian terranes, intrusions contain sulfur whose isotopic values vary from typical

¹ McDonald I et al., editors (2006) Mineral Deposits and Earth Evolution, Geological Society Special Publication 248, 280 pp, ISBN 1862391823

mantle values to mantle values enriched in heavy sulfur, but in the Southern Uplands, intrusions are enriched in light sulfur. These variations suggest that contamination by local sediments has been important in controlling the sulfur isotope composition of the intrusions and their related mineralization. The isotopic composition of sulfur in intrusions of the Northern Highlands is more varied and is thought to reflect the thick cratonic basement underlying this area.

Raiswell and Anderson have developed a model to account for at least part of the iron enrichment observed in deep-basin sediments. Anoxic environments that develop on oceanic shelves containing a high proportion of organic matter serve as traps for Fe, taking it into solution as sulfide or causing it to precipitate as pyrite. In either case it remains trapped within the pores of sediments on the shelves. Once the supply of iron oxide ceases, the Fe content of pore waters builds up, and dissolved Fe can escape into the overlying more oxidized water, where part is re-precipitated as Fe oxide, but part escapes and is transported into deeper water where it precipitates as iron sulfide and becomes concentrated in the deep basinal sediments.

Grieve provides a useful summary of the characteristics of impact structures and associated metamorphism. He divides impact-related deposits into three classes. Progenetic deposits are pre-existing deposits that have been brought to accessible depths by the impact; major examples include the Witwatersrand and uranium in the Carswell structure of the Athabaska district of Canada. Syngenetic deposits form as a direct result of shock pressure or heat (including subsequent

hydrothermal activity) related to the impact; Sudbury is the prime example, although Witwatersrand gold has been affected by impact-related hydrothermal activity. Epigenetic deposits occur in and are younger than the structures produced by impact; oil and gas accumulations are the prime examples.

Other papers focus on specific tectonic settings or specific ore deposit types. Herrington et al. present a reinterpretation of the structure of the Urals, simplifying this into two magmatic arcs: a western, immature, Late Ordovician volcanic arc (the Tagil-Magnetogorsk arc) that developed as a result of eastward subduction and a continental arc (the Valerianovka arc) located at the leading edge of the Kazakh plate. These collided in the late Paleozoic and at the same time were thrust westward over the East European craton. The arcs were welded by syn-collisional granitoids and subsequently offset along a series of post-collisional, sinistral strike-slip faults, which accounts for the lens-like distribution of the terranes.

Heinrich et al. summarize the implications of their results from laser-ablation-ICPMS analysis of fluid inclusions for the genesis of porphyry copper systems. They comment that the fluid/rock ratios required to produce a deposit need not be much greater than 1, that the size of a deposit depends more on the efficiency of the transfer of Cu from magma to fluid phase (they suggest that immiscible Cu-rich sulfides may play a role in this transfer) than on the overall size of the magma system, and that the grade of the deposit depends on how much fluid is cooled over the required temperature range within a restricted body of rock before the ambient temperature rises too high. They suggest that circulating meteoric

water may play a role in cooling the environment of ore deposition, although they have found no evidence that the mixing of meteoric and magmatic water has played a role in sulfide deposition.

Far more attention has been paid in the geologic literature to diamonds found in kimberlites and lamproites than to alluvial diamonds. Bluck et al. seek to redress the imbalance by discussing factors that are important in the formation of placer deposits along the coast of Southwestern Africa. They conclude that the development of mega-placer deposits ($>50 \times 10^6$ carats at $>95\%$ gem quality) depends on the craton size and its diamond fertility; the efficiency of the drainage (not preceded by earlier systems and focussed on a limited terminal area); and the energy prevailing in the terminal area, which should be sufficient to remove the less dense components transported by the drainage system.

While this book could be criticized in that not all papers relate to the theme of Earth evolution, many of the papers relate directly to the topic and provide a useful update to explanations for the change of styles of mineralization with time and to isotopic constraints on the nature of the early atmosphere. The other papers are most certainly not to be decried in that they also provide good summaries of the state of our understanding of the formation of major ore deposit types. This book belongs on the shelf of any student of ore deposits. Preparing this review has certainly taught me a lot!

Tony Naldrett
University of Toronto

UNIVERSITY OF NEW BRUNSWICK - TENURE TRACK POSITION

The Department of Geology at the University of New Brunswick (Fredericton) invites applications for a **tenure track position as Assistant Professor** in fields related to **Metamorphic Petrology and/or Earth and Planetary Materials**, effective January 1, 2007.

This new position will complement expanding research and teaching activities in Petrology and Earth/Planetary Science and build upon the recent appointment of a Tier 1 Canada Research Chair in Planetary Materials, and allied Research Scientist and Research Engineer appointments in the Planetary and Space Science Centre housed in the Geology Department. The Department of Geology maintains undergraduate programs in Geology, Environmental Geochemistry and Geological Engineering to which the successful candidate is expected to contribute. The teaching responsibilities of the successful candidate will include undergraduate courses in metamorphic petrology and mineralogy, as well as contributing to the overall undergraduate program. Department research facilities include cathodoluminescence and

fluid inclusion microscopes, high-T controlled-atmosphere furnace, hydrothermal apparatus, piston-cylinder apparatus for high-P/high-T phase equilibrium studies, rocking autoclaves and an excellent thin sectioning workshop. Analytical equipment includes ICP-OES, XRD and a micro-Raman spectrometer. Excellent analytical electron microscopy capabilities at UNB's Microscopy and Microanalysis Facility, including EPMA, analytical SEM and analytical STEM, provide fundamental research support. Further details can be obtained from www.unb.ca/fredericton/science/geology.

The successful candidate will be expected to develop and manage an externally funded program of independent research. Candidates must have a Ph.D. in research areas that should include one or more of the following: metamorphic petrology, mineralogy, mineral physics, planetary materials/planetary evolution. Experience in the field study of metamorphic rocks will be considered an asset.

Interested persons should submit a letter of application, current curriculum vitae with a list

of publications and the names, addresses (including email) and telephone numbers of three (3) references to:

Chair
Department of Geology
University of New Brunswick
2 Bailey Drive
Fredericton, NB E3B 5A3
Canada

Email submissions to the Chair in care of Christine Lodge <lodge@unb.ca> are encouraged, and must be followed by hard copies of the required information.

Review of applications will begin September 1, 2006 and continue until a suitable candidate is found.

All qualified candidates are encouraged to apply; however, Canadians and permanent residents will be given priority. Applicants must indicate current citizenship status.

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timothy.bunning@wpafb.af.mil;
Web page: www.mrs.org/s_mrs/sec.asp?CID=4750&DID=164575

May 6–10 10th European Workshop on Modern Developments and Applications in Microbeam Analysis (EMAS 2007), Antwerp, Belgium. Details: EMAS Secretariat, c/o University of Antwerp, Dept. of Chemistry, Campus Drie Eiken, Universiteitsplein 1, BE-2610 Antwerp-Wilrijk, Belgium. Tel.: 32 3 820 23 43; fax: 32 3 820 23 43; e-mail: Luc.Vantdack@ua.ac.be

May 21–25 AGU Joint Assembly, Acapulco, Mexico. Details: AGU Meetings Department, 2000 Florida Avenue NW, Washington, DC, 20009 USA. Tel.: 800-966-2481, ext. 333 or 202-777-7330; fax: +1-202-328-0566; E-mail: ja-help@agu.org; web page: <http://www.agu.org/meetings/ja07/>

May 23–25 Geological Association of Canada and Mineralogical Association of Canada Joint Meeting (GAC–MAC): Yellowknife 2007 – For a Change in Climate, Yellowknife, Canada. Web page: www.nwtgeoscience.ca/Yellowknife2007

June 2–7 44th Annual Meeting of the Clay Minerals Society, Santa Fe, New Mexico, USA. Details: Louise J. Criscenti, Sandia National Laboratories. E-mail: ljcrisc@sandia.gov; web page: <http://www.sandia.gov/clay>

June 17–20 10th International Conference and Exhibition of the European Ceramic Society, Berlin, Germany. Details: Deutsche Keramische Gesellschaft e.V., Am Grott 7, D-51147 Köln. Tel.: +49-2203-96648-0; fax: +49-2203-69301; e-mail: ecers2007@dkg.de; website: www.ecers2007berlin.de

June 25–30 Combined Societies' Meeting: MinSoc, MSA and MAC: Frontiers in Mineral Sciences 2007, Cambridge UK. Details: M.A. Carpenter, e-mail: mc43@esc.cam.ac.uk; web page: www.minersoc.org/pages/meetings/frontiers/index.html

July 2–6 Sixth Hutton Symposium on the Origin of Granites and Related Rocks, Stellenbosch University, South Africa. E-mail: Hutton@sun.ac.za; web page: <http://academic.sun.ac.za/geology/hutton/hutton2007.htm>

July 2–13 International Union of Geodesy and Geophysics (IUGG) 2007 General Assembly, Perugia, Italy. E-mail: secretary@IUGG2007perugia.it; website: www.iugg2007perugia.it

July 9–13 11th Congress of the International Society of Rock Mechanics, Lisbon, Portugal. Contact: Sociedade Portuguesa de Geotecnia, LNEC, Av. do Brasil, 101, 1700-066 Lisboa, Portugal. Tel.: +351 218443321; fax: +351 218443021; e-mail: spg@inec.pt; website: www.isrm2007.org

July 21–26 American Crystallographic Association 2007 Meeting, Salt Lake City, Utah, USA. Details: Jill Trehwella, Dept of Mol & Micro BioSciences, Australian Federation Fellow, Univ. of Sydney NSW 2006 Australia. Tel.: 61 2 935 187; fax: 61 2 935 147 26; e-mail: 82jtrehwella@usyd.edu.au; web page: www.hwi.buffalo.edu/ACA/meetingspg_list/futuremeetings.html

July 22–27 Euroclay 2007, Aveiro, Portugal. Details: Prof. Fernando Rocha or Prof. Celso Gomes; e-mail: cgomes@geo.ua.pt; web page: www.ing.pan.pl/ecga_js/confer1.htm

August 12–17 15th International Zeolite Conference (15th IZC), Beijing, China. Contact: Prof. Shilum Qiu, Organizing Secretary, 15th IZC, State Key Laboratory of Inorganic Synthesis and Preparative Chemistry, Jilin University, Linyuan Road 1788, Changchun 130012, China. Tel.: +86-431-5168590; fax: +86-431-5168614; e-mail: izc@jlu.edu.cn; website: www.15izc.org.cn

August 13–17 2007 Meteoritical Society Annual Meeting, Tucson, Arizona, USA. Details: Dr. Tim Jull, e-mail: jull@u.arizona.edu; web page: <http://metsoc2007.org>

August 13–18 Twelfth International Symposium on Water-Rock Interaction (WRI-12), Kunming, China. Details: Secretary General, Yanxin Wang, School of Environmental Studies, China University of Geosciences, 430074 Wuhan, P. R. China. Tel.: +86-027-67885040; fax: +86-027-87481365; e-mail: wri12@cug.edu.cn; website: www.wri12.org

August 19–23 American Chemical Society 234th National Meeting, Boston, Massachusetts, USA. Details: ACS Meetings, 1155-16th St., N.W., Washington, DC 20036-4899. Tel.: (202) 872-4396; fax (202) 872-6128; e-mail: natlmtgs@acs.org; web page: www.chemistry.org/portal/a/c/s/1/acsdisplay.html?DOC=meetings%5cfuture.html

August 19–24 Goldschmidt 2007, Cologne, Germany. Details: Dr. Herbert Palme, e-mail: herbert.palme@uni-koeln.de; website: www.the-conference.com/gold2007/index.php

August 22–27 24th European Crystallographic Meeting (ECM24), Marrakech, Morocco. E-mail: thalal@marrana.ma; website: www.ecm24.org

September 1–15 Modular Course in Structure, Tectonics, and Mineral Exploration (Field-Based), Sudbury, Ontario, Canada. Information: Bruno Lafrance, Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Willet Green Miller Centre, 933 Ramsey Lake Road, Sudbury, Ontario, Canada, P3E 6B5. Tel.: 705-675-1151, ext. 2264; fax: 705-675-4898; e-mail: blafrance@laurentian.ca; website: <http://earthsciences.laurentian.ca>

September 6–7 AGREE II – Arctic Geology, Resources and Environment Conference, Tromsø, Norway. Details: Geological Society of Norway (NGF). Web page: <http://www.geologi.no/cgi-bin/geologi/imaker?id=8529>

September 10–12 Geological Society of London Bicentennial Conference – Earth Science in the Service of Society, the next 200 years, London, UK. Web page: <http://www.geolsoc.org.uk/template.cfm?name=Bicentenary>

September 10–14 23rd International Organic Geochemistry Meeting (IMOG07), Torquay, Devon, UK. Details: Sally Cornford, IGI Ltd, Hallsannery, Bideford, Devon EX39 5HE, UK. Tel.: +44 (0) 1237 471749; fax: +44 (0) 1237 421700; e-mail: sa@igilt.com; web page: www.eaog.org/meetings/meetings.html

September 13–17 Geological Society of London: Hutton, Horne and Barrow: Classic Field Localities near Edinburgh and in the Eastern Scottish Highlands. Details: Alys Johnson, Burlington House, Piccadilly, London, W1J 0BG. Tel.: 020 7434 9944; fax: 020 7 439 8975; e-mail: alys.johnson@geolsoc.org.uk; web page: www.geolsoc.org.uk/template.cfm?name=Bicentenary_Field_Excursion_Hutton_Horne_and_Barrow

September 14–19 Geological Society of London Mineral Deposits of South-West England, Venue TBA. Details: Alys Johnson, Burlington House, Piccadilly, London, W1J 0BG. Tel.: 020 7434 9944; fax: 020 7 439 8975; e-mail: alys.johnson@

geolsoc.org.uk; web page: www.geolsoc.org.uk/template.cfm?name=Bicentenary_Field_Excursion_Mineral_deposits

September 16–19 Material Science & Technology 2007 Conference and Exhibition – MS&T '07, Detroit, Michigan, USA. Details: TMS, 184 Thorn Hill Rd, Warrendale, PA, USA 15086. Tel.: 724-776-9000, e-mail: mtgserv@tms.org; web page: www.matscitech.org/2007/2007_mst.htm

September 23–28 SEG International Exposition & 77th Annual Meeting, San Antonio, Texas, USA. E-mail: meetings@seg.org

September 25–29 WIRMS 2007: International Workshop on Infrared Microscopy and Spectroscopy with Accelerator Based Sources, Awaji Island, Japan. Details: Takao Nanba, Hiroaki Kimura, or Shin-ichi Kimura, Kobe University, Spring-8, UVSOR Facility. E-mail: nanba@phys.sci.kobe-u.ac.jp, or kimura@spring8.or.jp or kimura@ims.ac.jp; web page: www.uvsor.ims.ac.jp/WIRMS2007/

October 2007 AMPHIBOLES, Accademia Nazionale dei Lincei (Rome, Italy). Details: TBA. Contact G. Della Ventura, F. Hawthorne, A. Mottana and R. Oberli. Contact for North America: frank_hawthorne@umanitoba.ca

October 28–November 1 Geological Society of America Annual Meeting, Denver Colorado, USA. Details: GSA Meetings Dept., P.O. Box 9140, Boulder, CO 80301-9140, USA; tel.: 303-447-2020; fax: 303-447-1133; e-mail: meetings@geosociety.org; web page: www.geosociety.org/meetings/index.htm

November 26–30 Materials Research Society Fall Meeting, Boston, MA USA. Details: Duane Dimos. E-mail: dbdimos@sandia.gov; web page: www.mrs.org/s_mrs/sec.asp?CID=4749&DID=164574

December 10–14 AGU Fall Meeting, San Francisco, California, USA. Details: AGU Meetings Department, 2000 Florida Avenue NW, Washington, DC 20009, USA. Tel.: 202-777-7335; fax: 202-328-0566; e-mail: meetinginfo@agu.org; web page: www.agu.org/meetings

The meetings convened by the societies participating in *Elements* are highlighted in yellow. This meetings calendar was compiled by Andrea Koziol. To get meeting information listed, please contact Andrea at Andrea.Koziol@notes.udayton.edu



Prints of Don Dixon's painting of the ancient Earth can be purchased at www.cosmographica.com

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THE TUCSON SHOW

The largest mineralogical event of any type in the world (bar none) is the annual phenomenon commonly referred to as the Tucson Show, or among regular participants, simply Tucson. It is actually an amalgam of numerous (in recent years over 30) mineral, rock, meteorite, gem, fossil, jewelry, etc. shows, which grew out of a single mineral show that started in 1955. This is an international event extraordinaire. During the last week of January and first two weeks of February of each year, tens of thousands (estimated 100,000 in 2002) of mineral and gem collectors, curators, scientists, and natural history enthusiasts, from every corner of the globe, descend on Tucson. Shows are held in giant tents, at hotels and resorts, and in exhibit halls all over the city, with the majority located in the city center.

The show that began it all—the Tucson Gem & Mineral Show organized by the Tucson Gem and Mineral Society (TGMS) (www.tgms.org/tgms.htm)—occupies the Tucson Convention Center over the last four days of the event. There are several hundred dealers at this show along with displays from major mineral museums and private collections from around the world. Numerous talks, symposia, and meetings are held in conjunction with the show, including a symposium cosponsored by the TGMS, the Friends of Mineralogy (FM), and the Mineralogical Society of America (MSA). The symposium theme coincides with the theme of the TGMS show and is usually a mineral or mineral group. In 2006 the show and symposium theme was “Minerals of Canada” (see photographs in this article). All are welcome to participate in this symposium (see this year’s call for abstracts on page 216 of this issue).

For a comprehensive guide of each year’s shows, covering almost all aspects of the Tucson phenomenon, see the print and online show guide (www.tucsonshowguide.com/tsg) published by *Color Stone* magazine.

John Rakovan



“Minerals of Canada” was the theme of the 2006 edition of the Tucson Gem and Mineral Show. The presence of the main Canadian museums as exhibitors, including the Royal Ontario Museum and the Canadian Museum of Nature, ensured that exceptional samples of the main mineral locations of Canada were on display. It was possible to admire some of the best specimens of carletonite, catapleite, elpidite, eudidymite, epididymite, leifite, and serandite ever retrieved from Mont Saint-Hilaire; a selection of magnificent phosphates from Rapid Creek and Big Fish River, including augelite, gormanite, lazulite, ludlamite, wardite, and whiteite; and some outstanding specimens of grossular and vesuvianite from Asbestos. PHOTOS JULIAN GRAY

Alessandro Guastoni



David Vaughan of Outback Mining proudly displays their find of tiger eye from the Hamersley Range of the Pilbara region, Australia. PHOTO J. GRAY

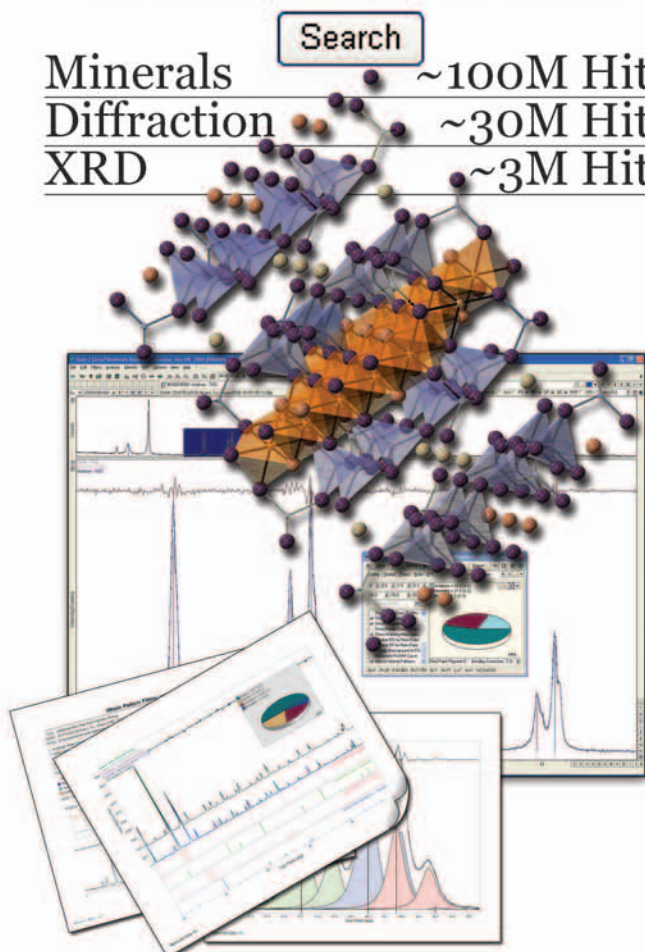


This year, among the best specimens that deserve to be mentioned, were some samples of dark pink elbaite from Paprok in Afghanistan, including a large specimen on matrix displaying a group of well-formed crystals more than 20 cm long. WAYNE THOMPSON FINE MINERALS, PHOTO A. GUASTONI

Next year the theme of the show will be
“Australia – Minerals from Down Under”
 (February 8–11, 2007).

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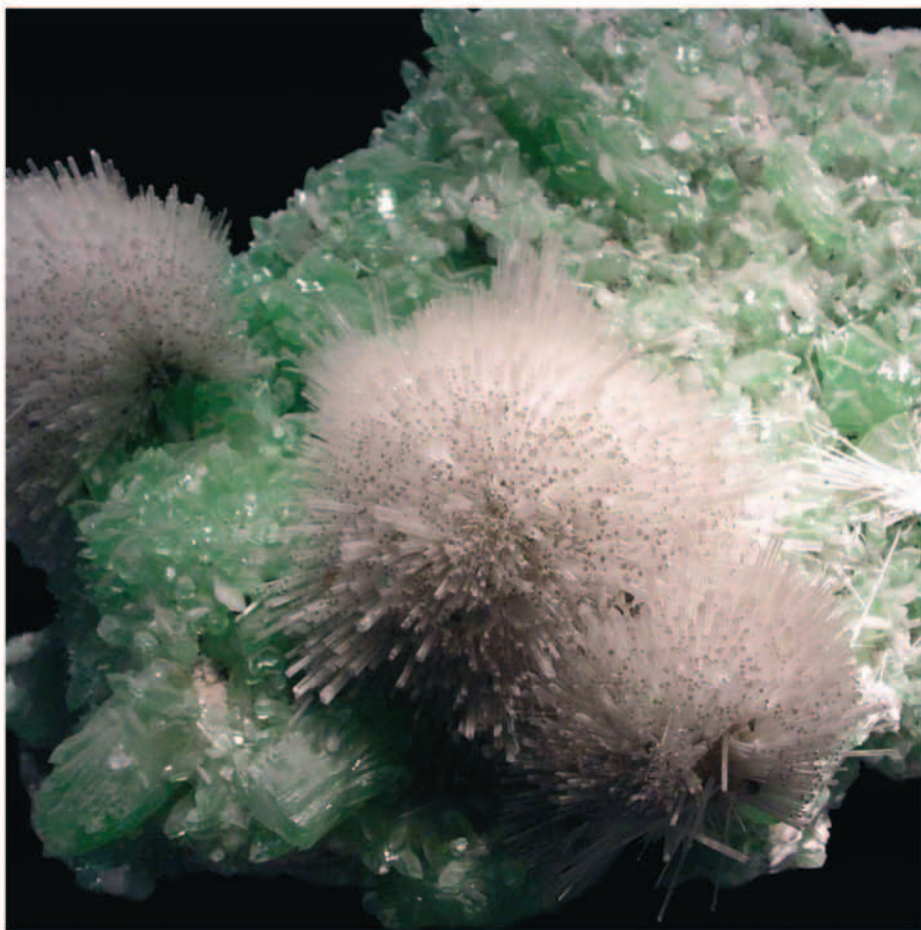
Applicants should submit a resume, statement of teaching and research interests, reprints or preprints of three representative scholarly publications, and the names and complete contact information (including phone, fax and e-mail) of three references to: **Mineral Deposit Search, Department of Earth & Ocean Sciences, The University of British Columbia, 6339 Stores Road, Vancouver, BC, Canada, V6T 1Z4. E-mail: MineralDeposits@eos.ubc.ca. The deadline for applications is October 2, 2006.**



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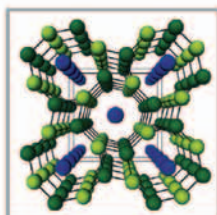
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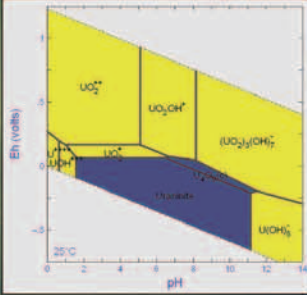
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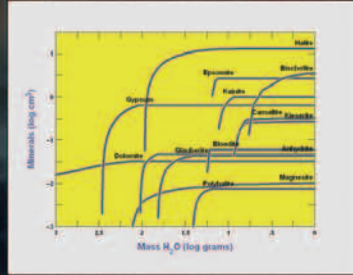
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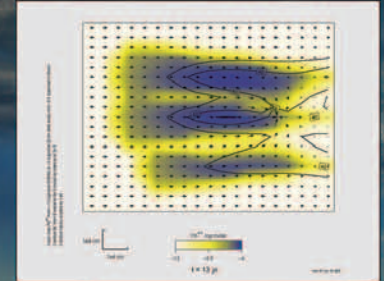


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