



# Nanogeoscience: From Origins to Cutting-Edge Applications

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**A**t first glance, nano and Earth seem about as far apart as one can imagine. Nanogeoscience seems to be a word connecting opposites. But to a growing number of Earth scientists, this term makes sense. Although relatively difficult to detect and study, natural nanomaterials are ubiquitous in nature. Their properties are often different (sometimes dramatically different) from those of the same material at a larger size. In many cases, larger equivalents do not even exist. By understanding natural nanomaterials, we can acquire another perspective from which to view Earth's chemical and physical properties. Important insights into local, regional, and even global phenomena await our understanding of processes that are relevant at the smallest scales of Earth science research.

J DXV NQC R9 nanogeoscience, nanominerals, mineral nanoparticles, amorphous nanomaterials

## INTRODUCTION

Just a decade ago, the word “nanogeoscience” was not in general use. Today, the entire technical section of this issue of *Elements* magazine is devoted to it. How can this be? Where did nanogeoscience come from? Is it just a new name for colloid science, which has been around for nearly 200 years? If nanogeoscience is new, can it sustain the notoriety that it is receiving today, or is it just winning a short-term scientific popularity contest? Most importantly, is nanogeoscience telling us anything about our planet that we did not already know, and if so, what?

This issue of *Elements* seeks to at least begin to answer these questions and to explore several of the most important aspects of nanogeoscience as we currently understand them. However, a word of caution is in order. Nanogeoscience is a rapidly evolving field. The authors of the articles in this issue have done their best to present the existing state of several aspects of this quickly advancing and changing science, but we cannot cover all aspects. Further, we fully anticipate that there will be many more as-yet-undiscovered directions in the future, even in the near future. Nevertheless, to begin, it is essential to explore the foundations of nanogeoscience—the fields of nanoscience and nanotechnology themselves.

## THE RISE OF NANOSCIENCE AND NANOTECHNOLOGY

In English, “nano” is generally only used as a prefix (although this seems to be changing due to commercial use, for example, iPod Nano). “Nano” is derived from the Ancient Greek word *νᾶνος* and later the Latin word *nanus*,

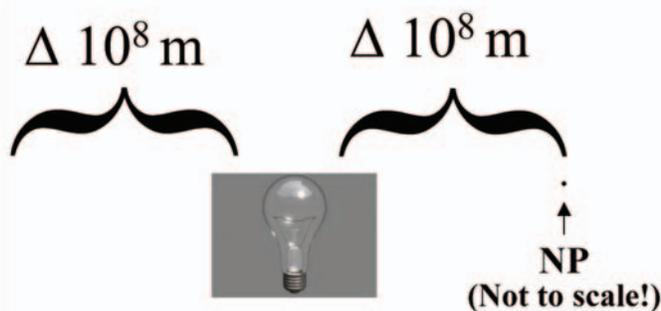
both meaning “dwarf.” According to its modern scientific definition, the prefix “nano” means one-billionth, or  $10^{-9}$ . For Earth scientists, where microns (the approximate size of a bacterial cell or the analytical resolution of an electron microprobe) and angstroms (the distance between atoms) are the microscopic units that are in greatest usage, it is convenient to remember that a nanometer (nm) is 10 angstroms or one-thousandth of a micron ( $\mu\text{m}$ ), and that 100 nanometers is one-tenth of a micron. For various scientific and engineering reasons and conventions, the word “nanoscale” signifies the

size range of approximately one nanometer to 100 nanometers. FIGURE 1 is a reminder of how small this size is (so that we do not take it for granted), and provides a foundation for understanding why it is so difficult to understand the behavior of nanoparticles in the incredibly complex Earth environment.

Nanoscience is the science of observing, measuring, and understanding the properties and behavior of nano-sized objects, which often turns out to be both enigmatic and exceptionally interesting. Nanotechnology takes advantage of many of the properties exhibited by nanomaterials and puts them to beneficial use in a great variety of commercial products and applications. The term “nanotechnology” was first defined and used in the 1970s, and this was followed by a good deal of scientific and engineering speculation in the 1980s. This activity coincided with, and was in large part driven by, the discovery of scanning tunneling microscopy (STM) in 1982, for which a Nobel Prize was awarded in 1986, and the development of the atomic force microscope in 1986. Also in the 1980s, fullerenes (pure carbon nanostructures such as “buckyballs,” named after Richard Buckminster Fuller who popularized the geodesic dome) and quantum dots (semiconducting spherical nanostructures) were developed. Carbon nanotubes were discovered just a few years later.

Some materials scientists, clay mineralogists, and heterogeneous catalysis experts would argue that nanoscience is nothing new and that they have been doing for decades what has now simply been given a modern name. Others may say that nanoscience is a true extension of existing fields into the nanoscale using theories and methods not available until recently. In fact, both arguments have strong merit. But one thing cannot be denied: although research funding for environmentally based nanoscience is growing but still relatively small and funding for nano-

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**FIGURE 1** The dimensional scale differences between the Earth and a lightbulb and between a lightbulb and a nanoparticle (NP) are the same. Another way to think of this is that, from the human frame of reference, observing and studying a single nanoparticle with a transmission electron microscope is comparable to probing the entire Earth down to the level of a single light bulb. Yet, because of their abundance and characteristics, nanominerals and mineral nanoparticles make a significant difference in Earth behavior.

geoscience is even less, state and private funding of the general fields of nanoscience and nanotechnology is booming. In the United States, federal funding from several agencies directed towards nanoscience and technology now exceeds \$1.5 billion annually, and similar amounts are invested within the European Union and in Japan. In 2006, corporate investment in nanotechnology exceeded \$4 billion worldwide. Thousands of nanotechnology-related patents are now filed each year, and thousands of products contain nanomaterials. Business projections over the last few years suggest that the global nanotechnology market, in manufacturing and materials, electronics and IT, and healthcare and life sciences, will be in the neighborhood of \$3 trillion by 2015, less than a decade from now.

With so little money going into nanogeoscience and environmental nanoscience and technology (in the United States, the investment is less than 5% of the total federal nanoscience and technology research budget), it is ironic that a major percentage of manufactured nanomaterials have naturally occurring analogs and that a significant portion of nanomaterials, used in everything from industrial processes to household products, will eventually end up in the environment. The fate and environmental impact of these nanomaterials is not clear. In the United States in 2008, the National Science Foundation, with smaller contributions from the Environmental Protection Agency, began funding two large university-based national centers for the study of the environmental implications of nanotechnology; nanogeoscience will play a key role in at least one of these centers. Parallel efforts are underway, or will be shortly, in several other countries.

## THE RISE OF NANOGEOSCIENCE

Stöber and Arnold (1961) and Langmuir (1971) developed scientific frameworks to understand mineral dissolution and stability, respectively, as a function of particle size. Besides these and a few other studies by Earth scientists, this kind of research was nearly nonexistent until about 15 years ago. Eventually, a few studies performed by Earth scientists appeared in the 1990s, and these studies rode the wave of nanoscience research that was building rapidly in other fields. These geoscience studies involved looking quantitatively at mineral nanoparticle properties and comparing them with the properties of larger grains of the same mineral. In this context, Banfield et al. (1993) and Gribb and Banfield (1997) investigated the transformation kinetics and phase stability of nanocrystalline  $\text{TiO}_2$ . Zhang

et al. (1999) observed a dramatic increase in the adsorption coefficient of a variety of organic acids onto  $\text{TiO}_2$  nanocrystals as the crystals became smaller. Rosso et al. (1999) were the first to show the formation of nanophases at the atomic level using STM and scanning tunneling spectroscopy (STS) (FIG. 2). All of these projects were early studies in what would eventually evolve into nanogeoscience as we know it today. Reviews of the field during its development include, but are not limited to, Banfield and Navrotsky (2001), Wigginton et al. (2007), Navrotsky et al. (2008), and Hochella et al. (2008).

A common misconception is that nanogeoscience is just colloid science renamed. This is not the case. Colloids are generally defined as being between one and 1000 nanometers in size; nominally, therefore, nanoparticles are only within the smallest 10% of that range. More importantly, however, one can think of nanoscience as being a critical offshoot of colloid science. In nanoscience, one studies the thermodynamic, mechanical, electrical, structural, optical, and/or chemical property *variations* as a function of the physical size and shape of the material. For minerals in the nano-size range studied to date, these variations are most pronounced below a few tens of nanometers, and can be dramatic below 10 nanometers. The reason for these changes is central to nanoscience, as mentioned above. These properties can deviate significantly (sometimes dramatically) from those of a larger particle of the same phase. There are also cases where bulk analogs to nanomaterials do not even exist. For minerals, these critically important aspects of nanoscience are described in the article by Waychunas and Zhang (2008 this issue).

Recently, we embarked on an electronic survey of the literature to try to quantify the articles and reviews dealing with some aspect of nanogeoscience—including terrestrial, ocean, and atmospheric research—that have appeared since the mid-1990s in the peer-reviewed literature. Spot-checking was done to make sure that the search was constructed properly and that the returns (the papers identified according to our target) were reasonable matches. The results showed that between 10 and 12 years ago, 60 to 70 articles per year were published on some aspect of nanoparticle science directly relevant to the Earth sciences. In the last five years, the average number of papers per year has been about 180, with a high of 220 in 2004. Two interesting insights come from this analysis. First, when the data are fitted to an exponential function, the average rate of increase in publication numbers is just over 10% per

year; this is approximately triple the average growth rate for all scientific fields according to Elsevier. Second, the great majority of papers and citations generated in the field of nanogeoscience have been in the atmospheric sciences, where nanoparticles and aerosols are central to the properties and chemical dynamics of the atmosphere (see Buseck and Adachi 2008 this issue). Nevertheless, we are learning that nanoparticles also have a major influence on the workings of the oceans and the rocky portion of our planet. Non-atmospheric nanogeoscience is expected to represent a much larger proportion of the total published output in nanogeoscience during the next decade.

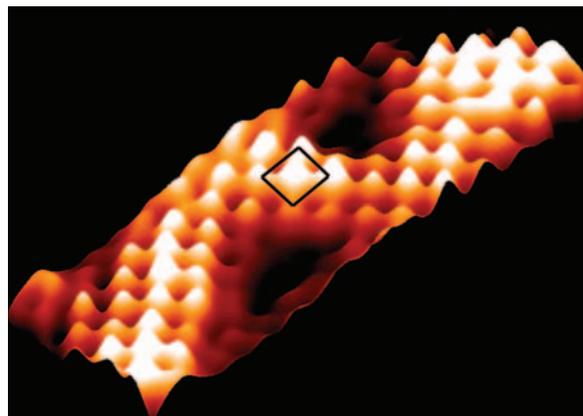
## CLASSIFICATION SCHEME FOR MINERAL NANOMATERIALS

We have developed a nanoscale mineral classification scheme (Hochella et al. 2008). This scheme is based on two nanoscale mineral types: nanominerals and mineral nanoparticles; and three nanoscale mineral habits: nanorods, nanosheets, and nanoparticles. Nanoscale minerals are defined as having at least one dimension in the nanorange, and, depending on the number of dimensions that are in that range, they can be further subdivided. Nanosheets, nanorods, and nanoparticles have one, two, and three dimensions in the nanorange, respectively (Fig. 3A, B, C). In addition, each of these three categories can be further divided into two types: nanominerals and mineral nanoparticles. Nanominerals exist only as one of the three types of nanoscale minerals; that is, there are no bulk equivalents of nanominerals. The type example of a nanomineral is ferrihydrite, an iron oxyhydroxide very common in soils and natural waters (fresh and ocean); it has never been observed larger than about 20 nm in diameter and is more typically 10 nm or less in diameter. Mineral nanoparticles are minerals that exist in the nanorange, but they can also exist in sizes that exceed the nanorange, up to the largest dimensions for minerals. Although it is likely that many nanominerals are yet to be discovered, presumably the great majority of minerals can exist as both mineral nanoparticles and the same mineral in the bulk state.

## GLOBAL OCCURRENCE, DISTRIBUTION, AND IMPORTANCE OF NANOMINERALS AND MINERAL NANOPARTICLES

Nanominerals and mineral nanoparticles are common and widely distributed throughout the atmosphere (Buseck and Adachi 2008 this issue), oceans, ground and surface waters (Hassellöv and von der Kammer 2008 this issue), and soils (Theng and Yuan 2008 this issue); in and/or on most living organisms (Bargar et al. 2008 this issue); and even within proteins like ferritin. Although the global mass distribution of naturally occurring nanominerals and mineral nanoparticles is not at present known, it is likely that the oceans hold the largest amount on Earth. River, glacial, and atmospheric (aeolian) inputs to the oceans are all major and continuous (Poulton and Raiswell 2005; Raiswell et al. 2006).

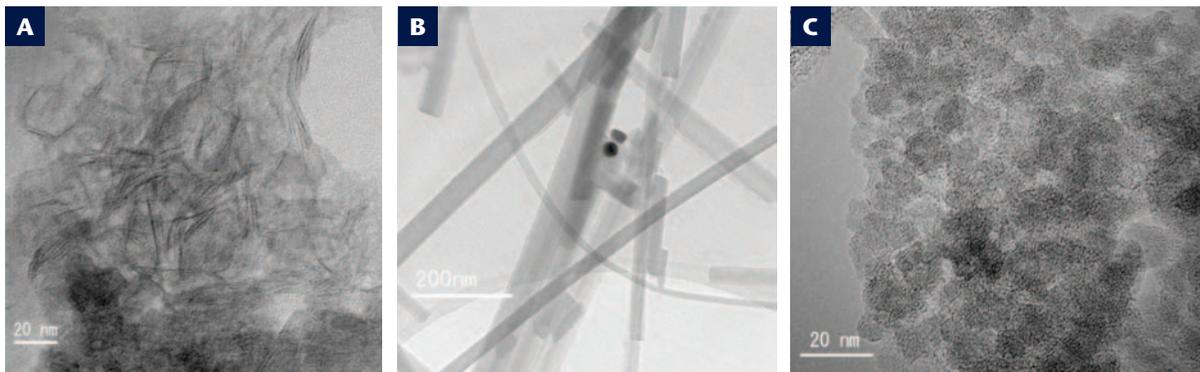
In terms of the relevance of nanogeoscience to the Earth sciences in general, the most important point is this: processes dealing with elemental distribution; biological-abiogenic Earth interaction; heterogeneous catalysis; reaction pathways; and mineral growth, transformation, and weathering are all related to phenomena at the nanoscale, often involving nano-sized geomaterials. What happens in this dimensional realm has no equivalent at either smaller or larger scales. Therein lies the essence and future scientific capital (and complexity) of nanogeoscience.



**FIGURE 2** STM image of a pyrite {100} surface undergoing controlled oxidation in a vacuum. The peaks correspond to individual iron atoms. Tunneling to sulfur dimers in the structure is not favored under these tunneling conditions, so they are “observed” as low points between the iron positions. A surface unit cell (0.54 nm on a side) is outlined. The dark triangular patches are where individual iron atoms have reacted with minute amounts of oxygen in the vacuum, resulting in an oxidation product in the range of 1 to 2 nm in size. See Rosso et al. (1999) and Becker et al. (2001) for details. HEFTQD 2 AX J DUHM QNRN

This situation can perhaps best be illustrated by the following example (just one of many that could be presented). Consider a transition metal in five states: as a hydrated ion; as the metal complexed in a small protein; as the metal adsorbed to the surface of a 1 nm mineral nanoparticle; as the metal adsorbed to the “same” mineral except 20 nm in size; and finally as the metal adsorbed to the “same” mineral except 200 nm in size. All of these entities carrying the metal will pass through a 0.22  $\mu\text{m}$  filter, the smallest filter size typically used in fieldwork and most laboratory work over the decades. What passes through such a filter has been typically operationally defined as “the dissolved fraction,” and the metal in our example would be chemically considered or formally modeled as a single dissolved species (typically as the hydrated ion). In fact, nanogeoscience research to date has taught us that the metal of interest will exhibit a significantly (potentially dramatically) different chemical behavior in *each* of the five states mentioned above. In this case, in a geoscience sense, chemical behavior includes everything from reaction affinities and kinetics to bioavailability. With nanogeoscience, we get a much more complex picture, but at the same time a much more realistic one.

The importance of nanogeoscience can be seen now in a rapidly growing literature containing many rich examples of new understanding of previously perplexing Earth observations. An example of global importance involves phytoplankton in the world’s oceans. Phytoplankton are responsible for more than half of the photosynthesis on Earth. They are therefore key to global ocean and atmospheric chemistry, ultimately and most importantly playing a crucial role in determining global atmospheric  $\text{CO}_2$  levels. Phytoplankton productivity in the world’s oceans depends largely on limiting nutrients, of which iron is one of the most important. Traditionally, it was thought that iron is made available through dissolved inorganic and organic complexes. However, now-classic studies have shown that a significant amount of iron in the oceans is tied up in nanoparticles in the 2 to 20 nm range (Wells and Goldberg 1991, 1994). In addition, it has been estimated that the input of iron to the oceans via Fe-containing nanoparticles far exceeds riverine input of dissolved iron (Poulton and



**FIGURE 3** Examples of the three nanoscale mineral habits. **(A)** Nanosheets, in this case vernadite, a layered manganese (4+) hydroxide similar to birnessite, except disordered in the layer-stacking direction and within layers. This specimen is from a ferromanganese crust on a seamount in the western Pacific Ocean. The sheets are as thin as 1 nm. **(B)** Nanorods, in this case the mineral palygorskite (also known as attapulgite), a Mg,Al modulated-layer phyllosilicate found in arid and semiarid soils and certain hydrothermal veins. **(C)** Nanoparticles, in this case ferrihydrite from Alabama, USA, in the <10 nm size range. @KK HL @F DR BNT OS DRX NE G- Wf + T MHUQDRHSX NE V HRBN MRHM

Raiswell 2002). Finally, it has been shown that iron in mineral nanoparticles is bioavailable to various species of marine phytoplankton and that these nanoparticles will become a more important source of iron in the oceans as Antarctic melting continues (Nodwell and Price 2001; Smith et al. 2007).

Nanogeoscience is coming to the fore in the understanding of toxic-metal transport in Earth's near-surface terrestrial environment. For example, it has been demonstrated, from field- and microscopy/spectroscopy-based measurements and observations, that radionuclides can be transported by groundwater over several kilometers in short periods of time, defying thermodynamically based predictions. An excellent example of this is associated with a nuclear waste processing plant near Mayak, Russia, where 70 to 90% of the plutonium transport in groundwater is by way of ferric oxides less than 15 nm in size, as well as via a few other nanophases (Novikov et al. 2006).

At the largest Superfund site in the United States, in western Montana, an area of 1600 km<sup>2</sup> is contaminated by Cu, Zn, As, Pb, and Cd, due to mining activities started one and a half centuries ago. Metals have moved many hundreds of kilometers down the hydrologic gradient and across floodplains in the Clark Fork River drainage. The primary carriers of these metals are nanominerals and mineral nanoparticles, chiefly manganese and iron oxyhydroxides (Hochella et al. 2005a, b).

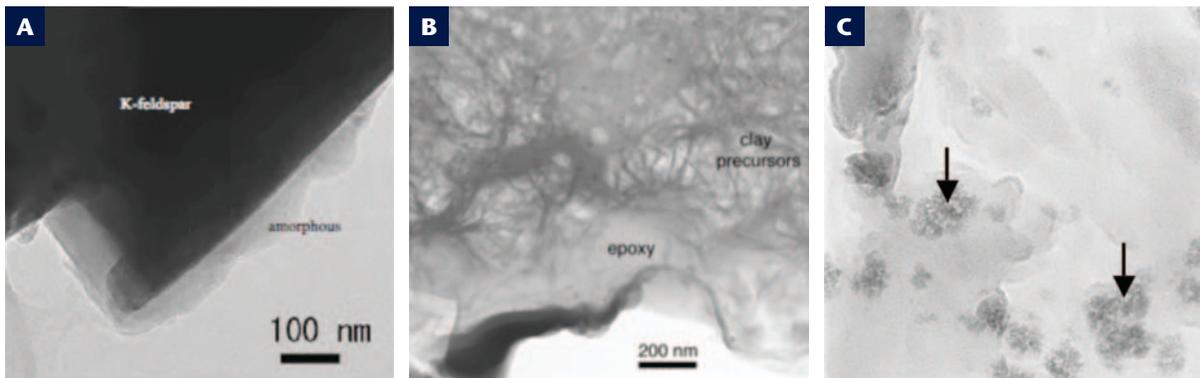
The mechanical properties of nanominerals and mineral nanoparticles, although much less studied at the present time, can also have a dramatic impact on the workings of Earth, and they remain one of the most exciting and important areas in the future of the science of mineralogy. Areas that have developed, or are currently developing, along these lines include the natural production of mineral nanoparticles by mechanical grinding associated with earthquake-generating faults in the shallow crust and at Earth's surface. Pulverized rock in fault zones up to 100 m wide contain large amounts of mineral fragments as small as 10–20 nm in size, and it has been suggested that in these cases mineral nanoparticles are important in fault mechanics (Wilson et al. 2005; Dor et al. 2006). It has also been suggested that nanoparticles of the high-pressure

silicates ringwoodite and wadsleyite play a central role in deep-focus earthquakes at 300–700 km depth in the Earth's mantle (Green and Burnley 1989 and pers. comm.). These mineral nanoparticles fill “anticracks”—planes of weakness that do not need to dilate to create empty space, in contrast to a normal crack. The nanoparticles can easily move past each other without mechanical shearing of individual grains (much like the slippery feel of talc when you rub it between your fingers); therefore, high pressure does not restrict this movement. New studies showing the importance of the mechanical properties of nanophases in the Earth include work on the variation of the compressibility of mineral phases as a function of size in the nanorange (Gilbert et al. 2006), as well as work on TiO<sub>2</sub> nanoparticles in garnet, which can be used to gain new information on metamorphic processes and exhumation rates (Hwang et al. 2007).

## NATURALLY OCCURRING AMORPHOUS NANOMATERIALS

It is ironic that even today, despite the fact that nanominerals and mineral nanoparticles are widely distributed, abundant, and important to how Earth functions, they remain difficult to study and understand. The same can be said, in fact to an even greater degree, for naturally occurring amorphous nanomaterials. Because of limited diffraction information, spectroscopic measurements that are harder to interpret, and highly variable chemistry and form, we know far less about naturally occurring amorphous nanomaterials than crystalline ones. However, we are starting to recognize these amorphous nanomaterials for their natural abundance and importance. Some specific examples follow.

Zhu et al. (2006) studied the amorphous nanofilms found on feldspar surfaces in the Jurassic Navajo Sandstone at Black Mesa, Arizona, USA (Fig. 4A). It is not clear whether the silica-rich, 10–50 nm thick amorphous layers are due to feldspar leaching or groundwater-precipitated silica. Whatever the origin, Zhu (2005) and Zhu et al. (2006) estimate that the weathering rate of these K-feldspars is 10<sup>5</sup> times slower under the present natural conditions of these rocks than under similar conditions in laboratory-based weathering experiments. The amorphous nanofilms provide an additional explanation as to why field-measured rates and laboratory-based dissolution rates using fresh, ground feldspar can be so different. Further, because the detection of these nanofilms requires transmission electron microscopy (TEM) and careful sample preparation—and this has never been “routine”—the Zhu studies raise the question as to how widespread amorphous nanofilms are in natural weathering environments. This question remains to be answered.



**FIGURE 4** (A) A K-feldspar grain from the Navajo Sandstone showing a continuous amorphous overlayer generally between 10 and 50 nm thick. (B) Weathered basalt surface in the vadose zone beneath the Hanford site, south-central Washington state, USA. These clay precursors take up contaminant uranium. (C) Nanoaggregates of amorphous Zn-sulfide nanoparticles (arrows point to examples) found in the reducing zone of the riverbed of the Clark Fork River, Montana, USA.

It has been clearly shown that amorphous nanofilms also form on uranium-containing pyrochlore (a calcium titanate that has been extensively considered for immobilizing fissile elements) during leaching experiments that have been allowed to proceed for several years (Xu et al. 2004). In this case, there is no question that the U-depleted amorphous nanofilms form due to incongruent dissolution and that the release of uranium is dramatically slowed as this protective layer forms.

In the extensively radionuclide-contaminated Hanford site in the state of Washington, USA, poorly crystalline and amorphous nanophases have recently been found to host uranium contamination (Stubbs et al. 2008). Weathered cavities within basalt clasts in the vadose zone contain glass and poorly crystalline clay precursors. A TEM image (Fig. 4B) of a typical ropey, platy silicate precursor to clay formation shows distinct features that go well below 10 nm in width. It is these poorly crystalline clay precursors, not the adjacent glass, that have taken up contaminant uranium. Exchange on and off these nanomaterials, or incorporation into them, may play an important role in dictating uranium's mobility through the vadose zone at this site.

Another example of amorphous natural nanomaterials comes from a study by Hochella et al. (2005a) concerning the heavy-metal association and transport in the Superfund-site portion of the Clark Fork River basin in western Montana, USA. There, secondary amorphous silica containing toxic heavy metals is relatively common in the Clark Fork riverbed and adjoining floodplains. Amorphous, aggregated Zn-sulfide nanoparticles have also been found in the reducing zone of Clark Fork riverbed sediments (Fig. 4C). TEM images suggest that these nanoparticles are on the order of 10 nm in size. The toxic metals that these amorphous silicates and sulfides contain must be considered much more bioavailable than those present in crystalline equivalents, due to their considerably higher solubilities.

At the Clark Fork and Hanford sites, the existence of amorphous, metal-bearing, naturally occurring nanomaterials has often gone undocumented, or they were completely unknown, until recently. The abundance of these nanomaterials, their chemical and physical properties, and the

environmental role that they play are almost completely unknown. Such materials, in these types of settings and in many other settings around the world, provide an extraordinary research opportunity for the future.

## NANOMATERIALS BEYOND EARTH

It is also interesting to note that nanominerals and mineral nanoparticles are present, perhaps not surprisingly, elsewhere in our solar system and in interplanetary and interstellar space. Data from spectral imagers onboard Mars Viking and Pathfinder landers, as well as ground-based observations (Bell et al. 2000; Morris et al. 2000), strongly suggest the presence of nanophase ferric oxides in the soils and atmosphere of Mars.

Some of the most intriguing mineral nanoparticles ever discovered are present in chondritic meteorites and interplanetary dust particles. Using a multistep acid digestion process that is aptly described as "burning down the haystack to find the needle," minute quantities of diamond nanoparticles can be recovered. It has often been suggested that these diamond nanoparticles represent presolar dust produced in supernovae. More recently, however, groups have argued that these diamonds could form directly in the solar nebula (Dai et al. 2002) and in conjunction with other star types (Verchovsky et al. 2006). Nanodiamonds average 2 to 3 nm in diameter (Fig. 5), and grains as small as 1 nm (<150 carbon atoms) have been observed (Dai et al. 2002). *Ab initio* calculations of the structure of such diamond nanoparticles (Raty et al. 2003) produce fascinating models, like that shown in Figure 5.

## WHAT LIES IN THE FUTURE?

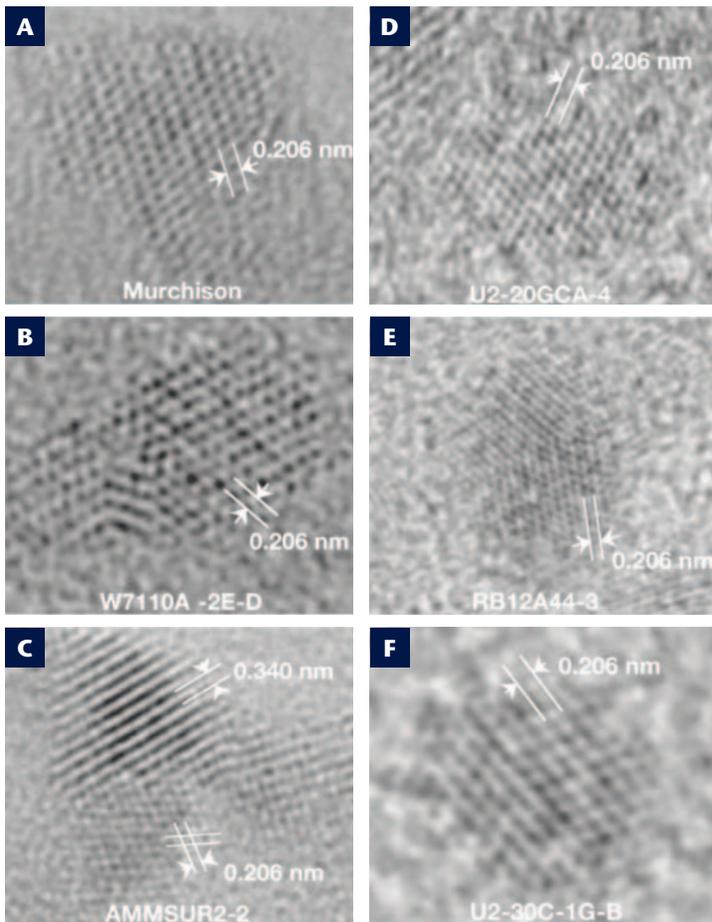
The following research areas in the field of nanogeoscience are among those that hold the most intriguing opportunities for the future.

### Nanogeo and Nanobio

Now that we are just beginning to understand inorganic nanosystems of all sorts, we have come to the realization that living things are also based on a vast array of structures and mechanisms that depend on the physics and chemistry only seen at the nanoscale. Striking examples of these are nanobiomachines, such as molecular motors. Much remains to be learned from the characteristics and behavior of natural nanoscale biological properties, both to help guide the understanding of inorganic systems and to better appreciate nanogeo and nanobio interactions.

### Nanopores and Mesopores

Nanopores (also called micropores), defined as pores with less than 2 nm of free diameter, and mesopores, defined as pores in the 2–50 nm range, often account for very large proportions of the total surface area available in rocks and



**Figure 5** (Left) High-resolution TEM images of 2–3 nm nanodiamonds recovered from the Murchison meteorite (A), interplanetary dust particles (B, D, E, F), and a micrometeorite (C). (Right) Ball-and-stick representations of two nanodiamonds based on *ab initio* calculations, the smaller with 147 C atoms (about 1.2 nm in diameter) and the larger with 275 C atoms (about 1.4 nm in diameter). The structures shown have diamond-structured cores (yellow) and fullerene-like reconstructed surfaces (red).

### Stability

The nominal size of the mineral kingdom currently stands at about 4500 species, and a large array of phase diagrams reflects their stability under a vast variety of conditions. Now, phase diagrams of a different nature—describing the phase space of nanominerals and mineral nanoparticles—are starting to appear (e.g. Chernyshova et al. 2007; Navrotsky et al. 2008). An important development is that mineral size and shape, as well as surface parameters (composition and structure), are now being added to phase-space variables. The mineral kingdom is more complex than previously thought. Nanogeoscience is at a relatively early stage of development, and large gaps in our knowledge exist. The next few years and decades will be an exciting time of new realizations, discovery, and change.

### ACKNOWLEDGMENTS

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soils, and within waterborne and airborne aggregates. Mineral–fluid interface reaction pathways and kinetics in these highly confined and/or tortuous spaces can be greatly altered compared to reactions at unconfined mineral–fluid interfaces (e.g. Hochella and Banfield 1995; Wang et al. 2003). These changes affect sorption, desorption, and diffusion, which in turn greatly affect precipitation, weathering, and transport phenomena.

### Aggregation

In nanogeoscience, a critical application of the previous point concerns the aggregation/disaggregation behavior of natural nanoparticles in air and water (e.g. Gilbert et al. 2007). Surface charge, cluster growth characteristics and stability, and fluid dynamics principles all come into play here. Clearly, it is imperative that the degree of aggregation also be taken into account when experimentally evaluating nanoparticle behavior as a function of particle size, solution chemistry, etc. (Cwiertny et al. 2008). A combination of experiments and modeling will help workers in this field understand the characteristics and behavior of the nano-aggregated state.

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