

# The Earth, Source of Health and Hazards: An Introduction to Medical Geology

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Annu. Rev. Earth Planet. Sci. 2007. 35:177–213

First published online as a Review in Advance on January 30, 2007

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

This article's doi:  
10.1146/annurev.earth.34.031405.125005

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0084-6597/07/0530-0177\$20.00

## Key Words

geomedicine/medical geology, chronic hazards, asbestos, trace elements

## Abstract

Insidious hazards that affect humans and other living creatures are addressed in this review. Debilitation and disease that may arise from naturally occurring gases, minerals, and elements create problems with characteristics that inhibit progress toward adequate and immediate solutions: (*a*) Human or animal reactions are delayed, not detected until long after the original exposure; (*b*) sporadic or continual low-level exposures to the minor or trace amounts of offending materials via the atmosphere, hydrosphere, and lithosphere are difficult to evaluate; (*c*) the air, water, and food consumed may contain hazardous substances that go unnoticed; and (*d*) health reactions depend on bioavailability of the hazard and susceptibility of the individual. The etiology of many chronic diseases from exposure to earth materials—*asbestos disease*, *As-* and *Se-induced cancers*, and other disabilities—are suspected, but precise mechanisms of induction are presently unknown. Stipulation of disease from Earth-based hazardous materials requires collaboration of Earth and biomedical scientists to avert, or at least ameliorate, future disease and debilitation.

## INTRODUCTION

Links between the natural environment and human health have been suggested for centuries. Greeks and Romans believed “ill winds” punished seafarers and knew that some vapors could kill. In the sixteenth century, Georgius Agricola depicted miners dying of inhalation problems. Cataclysmic upheavals such as volcanic explosions were part of ancient lore and implanted in our consciousness many times since the Mount Vesuvius (Herculaneum) disaster in 79 AD and Krakatoa in 1815. The Laki, Iceland, eruptions of 1783–1784, documented by Reverend Steingrímsson (1783–1784), darkened the European continent with particulates and gases that traveled great distances and led to many deaths within Europe. Mortality as a result of this disaster remains under investigation (Gratton et al. 2005).

Today we are very conscious of some natural hazards, no matter where they occur. Announcements by radio and television arrive within hours of an event, advising of the number of people affected. Early warning systems can be used to moderate such obvious public health impacts, provided detection systems are appropriately situated and monitored, and the population at risk alerted. There is no doubt that Hurricane Katrina, which hit the Gulf Coast of the United States and caused such devastation on August 26, 2005, has had a remarkable effect in the United States, while the recent earthquakes in Indonesia and Pakistan produced headlines across the world. People react to crises, and they are beginning to realize that there are global events about which we can do little except to anticipate, prepare for, and respond through supporting those people badly impacted. Public awareness and outcry have given way to the realization that we need a better understanding of the connections between the Earth and its inhabitants. Beyond recording the details of human suffering and deaths and economic impacts of disaster, it is now appropriate, indeed necessary, to consider geologic, geographic, and climatic contributions to public health. Earth materials, systems, cycles, and processes are publicly discussed and no longer novel.

The connection between Earth and its hazards is an active area of research with a variety of names; two that have been used in geology are geomedicine and medical geology (Berger 2003). There are many interesting aspects of such an interdisciplinary amalgamation, and this review selects a few examples where knowledge of Earth sciences has contributed to the understanding of specific health hazards. There are other approaches and many other examples that could be enumerated. It is exciting to consider the potential, and cross-disciplinary, research that can contribute to such personal and humane aspects of life and living in the twenty-first century. The opportunities for future scientific research to address health issues from the geosciences perspective are legion, but demand broad-based, multidisciplinary science, cooperation, and commitment.

## BACKGROUND

Each storm or earthquake is an event with a separate story. They are acute physical traumas with predictable surficial responses and humans demanding immediate medical attention. The relationships are obvious, the cause is Earth based, and the effect

is instantaneous, causing direct harm and immediate detriment to human health and well being.

There are other hazards that are much more difficult to detect and evaluate. They are hidden, in effect silent, chronic hazards with the time between exposure and the health response delayed. Symptoms or morbidity are through disruptions of normal physiologic pathways and metabolic events possibly expressed in several organ or body systems and these effects may remain unnoticed, perhaps for years. Furthermore, although exposure to some chronic hazards may have distinct and relatively obvious reactions, proof of the connection is elusive, as human responses will not only be delayed but variable, dictated by individual differences in habits, physiologies, and genetic or personal susceptibilities, as well as variable levels and durations of exposure to the potentially hazardous substances.

Infectious diseases are health impacts midway between acute and chronic hazards. Malaria—virtually eliminated from nontropical areas, especially in the Northern Hemisphere—remains rampant, causing up to 1,000,000 deaths per annum in the populations of Africa, Latin America, and Asia. A disease known for millennia, and fully described by the late 1870s, it is now easily diagnosed and confirmed through laboratory tests. Once any infectious disease is identified in a patient, the focus can turn to where the offending vector of the disease arose and how it was presented to the human recipient. For malaria, the female anopheline mosquito grows in local, still freshwaters. The insect transmits the plasmodium parasite generated in its gut, through its bite saliva, and into the blood stream and onto the liver where it proliferates and then invades red blood cells. By infecting the blood—the body's nutrient distribution system—the plasmodium has, in effect, circumvented the normal body's defense systems, and without treatment the outcome is often death. Strategies for prevention—such as eradication of mosquitoes by eliminating standing water, the use of sleeping nets, and pharmaceuticals such as quinine derivatives—are quite effective but not universally practiced. Malaria data are collected by the World Health Organization (WHO) Division of Control of Tropical Diseases, and insightful reviews of the present status across the world can be found at <http://www-micro.msb.le.ac.uk/224/Malaria.html>.

A parallel scenario exists for Lyme disease. The known vector is a tick seeking a blood meal. The bacterial pathogen in the tick passes to mice or deer. The exploding population of deer in the suburbs of the eastern United States has created a mini-epidemic that is advancing across the United States. Lyme disease symptoms usually alert individuals to seek medical care, and epidemiologists have studied the cases recorded by physicians and hospitals and reported to public health officials. The ability to define the disease and its geographic occurrence has mobilized researchers to seek methods of controlling exposure, if not eradication, as Lyme disease and related vector-borne diseases have now been detected across the world (Ginsberg 1993, Fish & Howard 1999).

The connection, cause and effect, appears straightforward. The identification of the carriers of infectious disease is like a successful detective story: The perpetrator has been sought and caught. It is prudent and effective for most infectious diseases that prevention seeks to eliminate the insect or animal vectors in spite of the fact that

the actual pathogen may have gestated in the soil or waters. Public health officials have learned where to expect the disease and to prevent the next outbreak by warning the population about how to avoid geographical areas where exposure is likely.

Noninfectious, chronic hazardous chemicals and biologic materials are everywhere in Earth environments but they are only beginning to be identified because they are not physically obvious, well defined, or isolated. They too require thoughtful detective work and, hopefully, happy endings akin to the brilliant deduction of John Snow isolating the source of cholera in a well in London (<http://www.ph.ucla.edu/epi/snow.html>). Prevention of chronic diseases from environmental exposures is proving to be more difficult to accomplish. Evaluating the possibilities, much less defining a specific culprit, requires integrated studies from macro- to micro- to submicro-evaluations of the physical and chemical characteristics of the dynamic Earth systems. The environment is constantly changing, as would be the exposures. The possibilities of defining the health hazard from multiple and diffuse sources that may impact a genetically varied but possibly predisposed and mobile population over time are staggering. The progress in defining chronic hazards, including those discussed in this review, is slow. Success was possible when disease occurrence and elevated exposures were collated. The problems of low-level exposures for these hazards remain under investigation.

Today, as we contemplate not only natural hazards but also contamination and bioterrorism, the focus must be on the ultimate sources that may harbor the hazards: air, water, and soils—research areas very much in the realm of Earth sciences. Sensitive techniques permit more precise detection and identification of potentially hazardous chemicals, biochemicals, and biologic agents, and geoscientists know a great deal about the processes and mechanisms of Earth materials distribution and can draw on information from many, possibly comparable, sites all over Earth.

There are, however, some other considerations, indeed problems beyond identification and mechanisms of distribution, of potentially harmful materials or agents. Today, unwanted health effects consistent among a group of individuals may reinforce the conclusion that the cause has been identified, usually through the efforts of pathologists and toxicologists employing optical and electron microscopic analysis and special histological techniques on excised tissues (Craighead 1995). Unfortunately, recovery of patients may be compromised if the sources of a toxin remain unknown or, if known, are not readily removed to expedite a cure or to mount effective treatment. Because of the plethora of bodily reactions that can now be monitored and the lack of sufficiently detailed personal exposure history, the cause or causes of most chronic hazards are suspected, not demonstrated. Similar reactions may not occur in what appear to be geographic areas with virtually identical hazards, suggesting that other and perhaps multiple factors in exposures and pathways need to be considered. As they may be intermittent, the cause(s) for most chronic hazards are unproven.

In attempts to confirm the medical effects of a chronic hazard, laboratory experiments on animal models or cell (in vitro) systems are sensible approaches, but do have drawbacks. Appropriate animal species with similar reactions to the hazard must be found, and projecting the experimental results, especially attempts to

relate the amount or dose level to humans, is not straightforward. The ethics of such experiments have come under question, and few humans volunteer as test cases. Furthermore, the animal test system usually employs high levels of a toxin over short periods of time and the lifespan of the animal is much shorter than the human. The more likely scenario in chronic human exposure is low doses over significantly longer times. Actions related to subacute levels in the environment have come about in large part with public awareness and through government intervention and regulation (e.g., OSHA and the Environmental Protection Agency) responding to suspected hazards. Unfortunately, at low exposure levels, the classic signals of disease may not appear, and in the meantime abnormalities such as cardiovascular effects or the accumulation of chemicals that alter cell functions, leading to cancers, for example, go unnoticed and undocumented.

Health impacts from chronic hazards with a likely environmental connection, though difficult to establish, may be identified by combining epidemiologic and geologic data. From such sets of data, models can be constructed to assay cause and effect possibilities (an example is presented under the section on As in the hydrosphere). Identification of the most likely hazards and situations is a precursor to prevention. To protect human populations, consistent monitoring of potentially harmful geological materials in living area sites should be integrated with the appearance of health problems. It is these collective data from a range of scientific disciplines—coordinated, exchanged, communicated, and analyzed—that are the purview of medical geology.

After a brief historical overview providing a perspective on the rise of research on human health relative to Earth materials, the discourse focuses on the chronic hazards found in the atmosphere, hydrosphere, and lithosphere experienced by some populations. The examples selected illustrate the types of impact and human physiological reactions in diverse global environments. Although reasonably well known and documented, if not totally deciphered, the causes and effects expressed by these examples are appreciated, if not conclusively demonstrated to everyone's satisfaction. All knowledge at this time must be tempered by the fact that studies at biomolecular levels continue to inform, adding new insights but also generating additional and different questions about exposure levels and pathways. With each explication of cellular processes, educated guesses of the most likely mechanisms force us to rethink the complicated reactions and inter-reactions between the health of individuals and the patterns we presently perceive with respect to Earth materials.

## **HISTORICAL PERSPECTIVE**

From the turn of the twentieth century, when vitamins were recognized as essential, food-focused biochemists have studied their roles in the complicated cascades required for normal metabolism. Over the intervening 100 years, the precise structures and functions of many biomolecular species, from DNA to enzymes, have firmly established the wide range of essential elements. The necessity of large amounts of C, N, O, H, P, Ca, Na, and K were expected, but other elements, cations and anions, proved to be cofactors in the metabolic events constantly taking place in the body. They were also deemed essential in lesser, often trace, amounts. These investigations

**Table 1 Elements, recommended daily adult allowances (RDA)\***

Element	RDA
Boron	(1.7–7.0 mg)**
Bromine	0.3–7.0 mg
Calcium	800–1300 mg
Cesium	0.1–17.5 µg
Chromium	130 µg
Cobalt	15–32 µg
Copper	1–2 mg
Fluoride	1.5–4.0 mg
Iodine	70–150 µg
Iron	10–18 mg
Lithium	730 µg
Magnesium	3.5 mg
Manganese	3.5 mg
Molybdenum	160 µg
Nickel	(35–700 µg)
Phosphorus	800–1300 mg
Potassium	3500 mg
Selenium	70 µg
Silicon	(21–46 µg)
Tin	0.13–12.69 µg
Vanadium	(12.4–30.0 µg)
Zinc	8–15 mg

\*Data from Food and Nutrition Board, 1989, National Research Council, National Academy Press, Washington, DC, 10th ed. Note: Many of the values are under discussion and differences have been suggested since this publication, especially for children and the elderly.

\*\*Values in parenthesis are from non-essential elements, those without accepted biologic function, detected in body tissues. Note: Al and Ti, in addition to Si, are in this category.

also demonstrated that there was discrimination between the host of elements present in an environment (**Tables 1 and 2**).

Some elements appeared to be biologically unnecessary and ignored or rejected, while others were not bioavailable. Alternatively, some bioavailable elements, especially if taken up in excess amounts, caused illness and sometimes death. The recognition of the several possible roles, especially the hazardous nature of some elements, fostered research that today encompasses virtually all of the naturally occurring elements from the ultimate source, Earth's rocks and minerals.

By the late 1960s, the proliferation of investigations connecting the environment and human health led to the establishment of the Environmental Protection Agency,

**Table 2** The most abundant chemical elements in the continental crust. Note the very small percent by weight of those beyond phosphorus (P)

Element	Ion	Percent by weight
Oxygen (O)	O <sup>2-</sup>	45.00
Silicon (Si)	Si <sup>4+</sup>	27.20
Aluminum (Al)	Al <sup>3+</sup>	8.00
Iron (Fe)	Fe <sup>2+</sup> and Fe <sup>3+</sup>	5.80
Calcium (Ca)	Ca <sup>2+</sup>	5.06
Magnesium (Mg)	Mg <sup>2+</sup>	2.77
Sodium (Na)	Na <sup>+</sup>	2.32
Potassium (K)	K <sup>+</sup>	1.68
Titanium (Ti)	Ti <sup>4+</sup>	0.68
Hydrogen (H)	H <sup>+</sup>	0.86
Manganese (Mn)	Mn <sup>2+</sup> , Mn <sup>3+</sup> , Mn <sup>4+</sup>	0.14
Phosphorous (P)	P <sup>3+</sup>	0.10
All other elements		0.77
Total		100.00

a federal agency with remarkable scope. It was to “have the capacity to do research on important pollutants irrespective of the media in which they appear and on the impact of these pollutants on the total environment” (Barth 1971). Several acts aided the establishment of national programs for the prevention and control of air pollution, e.g., the Clean Air Act of 1971. Together with other state or national groups, investigations commenced on the quality of U.S. waters and the adverse effects of solid waste, radiation, pesticides, etc. In effect, the thrust of the endeavors was to study the physical, chemical, and biological effects of pollutants, including the social and economical aspects of the problems, with an obvious aim to promote technological innovation that would permit accurate assays.

Field laboratories whose purpose was to ensure integrative, interdisciplinary approaches for economical use of resources were organized. With such a broad mandate and sufficient funding for all manner of investigations, publications appeared that addressed many parts of Earth that might harbor potentially hazardous substances.

Annual symposia at the University of Missouri resulted in a series of publications entitled, “Trace Substances in Environmental Health,” that has provided a remarkable record of these activities. Edited by Hemphill, they commenced in 1967 and there are 25 volumes in this series (Hemphill 1967–1991). The purpose of the meetings, interdisciplinary from the outset and increasingly international over the years, explored the health significance of numerous inorganic and organic substances in trace amounts in our bodies and in the air, food, and water. The papers focused on the multiplicity of reactions, noting that many public health issues were responses to human redistribution of natural materials. If the research reported was laboratory based—on animals, on cells, or on excised tissues (in vitro)—the results often contained caveats

on extrapolation to humans. It is clear in perusing the tables of contents that over time there was increased attention and reporting of site-specific diseases, epidemiologic studies, and reinforcement of the geographic association between some hazardous substances.

Originally supported by the Division of Health Sciences and Public Health Service, the University of Missouri publications document the commitment of the government toward establishing the relationships between the quality of the surficial environment and the health of people, plants, and animals. Geographic or areal associations collated with the health status of a population reinforced the supposition that a cause and effect between the environment and human health could be determined. Studies ranged from rural to urban and from botanical to agricultural. Other investigations focused on possible mechanisms of transport as well as analytical techniques for evaluation of the potential environmental source(s) and possible impacts. Early volumes decried that health data were sparse and difficult to obtain, but noted that the analyses recorded on live individuals might have a preventative application (Lenihan 1971). The impetus for the gatherings and the publications was to be broadly informative and to benefit public health. However, for some trace element hazards, the impacts on the population were questioned and it was agreed that direct connection, a cause with an effect, had rarely been unambiguously demonstrated (Enterline 1979).

This interdisciplinary research relied on pattern recognition and spatial analyses, making maps, a basic coordination technique. Constructed at scales appropriate to the resolution of available data, the superposition of the results of geochemical and of epidemiological investigations could identify overlaps and possible links. However, there were problems (Hopps 1971). For example, in some cases, amalgamations of data sets from diverse disciplines were frustrated because of the use of different spatial scales. Furthermore, there was insufficient accurate and reproducible data to enable a baseline amount for a chemical in the environment, much less a trend or superfluity within an area. To gain such information, the costs would likely be prohibitive and the results only of local significance, with limited predictability to other sites. Similar data limitations were present in epidemiological investigations in which identification of disease, or its likelihood of occurrence, was often the result of calculations from populations that were not fixed in time or in space.

These difficulties remain: very few sites on Earth's surface have been sufficiently well sampled to confidently establish the many, or any unique, factors that could create health problems in our multichemical dynamic environment. It has taken years of research to understand, much less to predict, bioavailability of potentially hazardous elements and compounds. Compendiums, some addressing only one element or factor, bespeak the forward motion of activities in the biogeochemical spectrum (Sigel 1973; Prasad 1988; Sigel & Sigel 1990, 2003).

Conferences on health issues continue around the world, especially in countries concerned with degraded environments and socialized medicine. Publications mark an increased understanding of the complexities and status of at-risk populations (Grupe & Herrmann 1988, Skinner & Berger 2003, Selinus 2005). Information on environmental issues is available in the twenty-first century through computer searches of a plethora of databases. Descriptions of many Earth materials hazards are



now more likely to describe pollution at special geographic and industrial sites and to include hypotheses on potential mechanisms of disease induction (Thornton 1983, Naidu & Nadebaum 2003, Fuge 2005). Research is likely to involve collaborations between geochemists, geologists, or hydrologists, together with plant physiologists, pathologists, or toxicologists that minimize the divisions between geobioscientists and rely on the reporting of medical practitioners, public health researchers, and epidemiologic researchers. The collaborations employ the widest range of analytical techniques and statistics from these many areas of expertise and apply them to specific health issues.

The most probable research scenario in medical geology today commences from a scientific consortium. The questions framed address a particular hazard, or potential for disease, affecting a local or selected population. The hazardous source(s), vectors, or etiologic agents and Earth-based transmission mechanisms are postulated, and the results confirm that the funding provided justified the interdisciplinary research effort, with benefits to public health.

The global interdisciplinary aspects of many cooperative research efforts, e.g., those on SARS or avian flu, illustrate the advantages of such undertakings. Data collected and recorded by national health authorities [e.g., the Centers for Disease Control (CDC)] and exchanged internationally identified the infectious agents at the molecular level. Immediate preventive action minimized exposure and has so far been successful at avoiding epidemics. International sharing of data on the known or potential hazards that could induce chronic diseases, especially the relationships to geologic sources and processes, is slowly being accumulated through the efforts of individuals and small groups. The exchange has benefited from rapid communication networks and publications predominantly in English, despite the country of origin of the authors (Chamley 2003, Komatina 2004). Today, alert geobiomedical researchers across the globe can share ideas and make opportunities for collaborative research. By capitalizing on personal insights from geographic locales with similar rock types, drainage systems, or other topographic features that have constituted hazardous health environments for indigenous populations elsewhere in the past, our perspectives have broadened as we seek amelioration, if not prevention, of some chronic diseases.

## THE ATMOSPHERE AND THE AIR

### Atmosphere

Humans require oxygen, but the atmosphere is a heterogeneous mixture that contains other gases, aerosols, and particulates. The present concentration in the atmosphere, 21% oxygen (**Supplemental Table 1**, follow the Supplemental Material link from the Annual Reviews home page at <http://www.annualreviews.org>), is appropriate for normal human metabolic activity. However, oxygen concentration varies with elevation, so some physiologic adaptation is possible. However, reduction or a total restriction of oxygen, even of short duration, can result in death. There are instances in which geologic events or materials reduce availability of oxygen and are identified as

the cause of death or debilitating diseases. Naturally occurring processes and mineral particulates can directly impact health. Continual availability of appropriate amounts of oxygen is the most important human need. Proper lung function depends on the exchange of oxygen and CO<sub>2</sub>, but too much CO<sub>2</sub> is lethal.

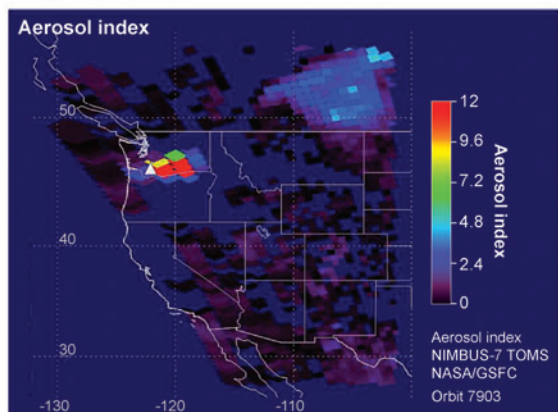
One of the most dramatic demonstrations of the suffocating effect of CO<sub>2</sub> was the explosion of Lake Nyos in Cameroon on August 12, 1986. More than 1700 people were killed by the flow of ground-hugging CO<sub>2</sub> gas emitted as a result of convective turnover of a stratified lake in a crater of a defunct volcano (Evans et al. 1993). The virtually instantaneous demise of the population from an acute geologic event affected an unsuspecting community. To avoid future disaster, a monitoring system has been put in place (Myers 2004).

Volcanic eruptions contribute particulates and gases such as SO<sub>2</sub> into the atmosphere (Horwell et al. 2005). The spread of dust and gas clouds through Europe during the late eighteenth-century eruption of Laki in Iceland, resulted in many deaths in the following months (Gratton et al. 2003). The blast from Mount Saint Helen's in 1980 not only flattened trees in the surrounding forest, but showered the landscape with particles of volcanic debris and fine-grained dust as the prevailing winds moved these materials eastward. Tracking the SO<sub>2</sub> and aerosols is now possible through satellite imagery (**Figure 1**), and some particles and aerosols of small radius (<1 μm) will reach the stratosphere and may stay airborne for several years (Wilson & Spengler 1996).

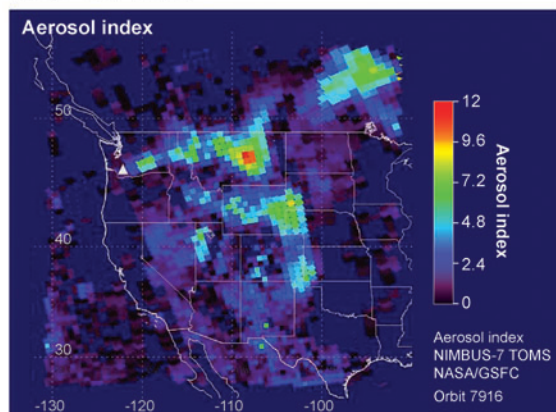
Chronic atmospheric pollution, the generation of aerosols and dust, is typical of modern everyday living. Airborne particles and soils from unpaved roadways and agricultural lands affect human health by interfering with respiratory functions. Loess, sediments resulting from glacial action, blown into towns in China on prevailing winds, a natural event described by Derbyshire (2003), show health effects affecting the lungs of the population, similar to the effect of particulates generated by motor vehicles in cities. Indoor air quality, a separate area of investigation today, reflects personal choices as well as cultural and other factors. Organic industrial compounds emanate from chemicals applied to rugs, walls, household cleaning agents, smoke, and so on—all contaminants that are probably detrimental to human health. In many public environments where levels have been measured, such as buildings and schools, the total amount of particulate (aerosol) exposure is comparable to outdoor air. To predict the level of human exposures on a time-weighted average, a model was generated after sampling in six American cities. It was partially successful in discriminating between pollutants. That is, SO<sub>2</sub>, although primarily from outdoor sources, was a good predictor of personal exposure, particulate matter, ≥5 (PM<sub>5</sub> μm) from both indoor (predominantly smoking) and outdoor sources showed a great deal more scatter (Dockery & Spengler 1981). Using principal component analysis to examine the pollutant composition and seasonal-dependent pollutant sources, Santanam et al. (1990) showed that mean values for PM<sub>2.5</sub> (maximum-diameter) in nonsmoking homes were very close to outdoor mean values. For air quality, the composition and size of the potential hazardous materials are critical (**Figure 2**).

Chronic exposure can be evaluated in occupational environments. Continual elevated exposure to silica and other silicates is hazardous in some workplaces.

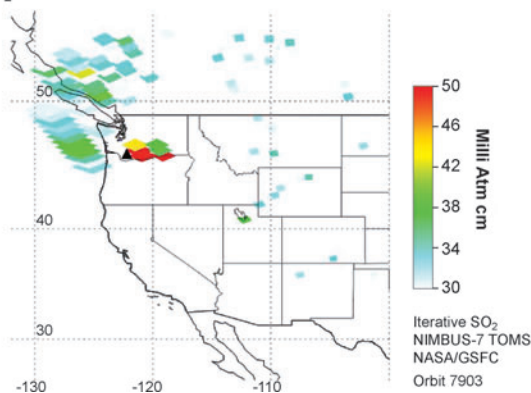
May 18, 1980



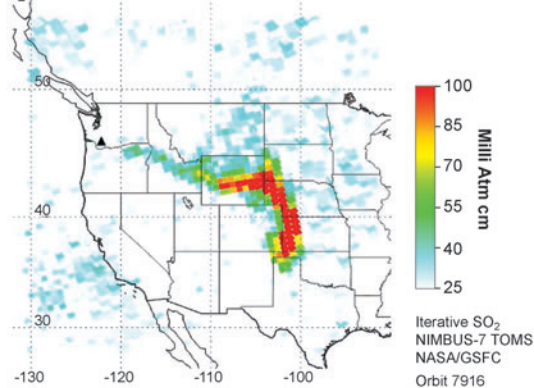
May 19, 1980



SO<sub>2</sub> concentrations



SO<sub>2</sub> concentrations



**Figure 1**

Satellite images of the Mt. St. Helens eruption May 18 and May 19, 1980, showing eastward trend of aerosols and SO<sub>2</sub> over the two days. Courtesy of Roland Geerken, Center for Earth Observation, Yale University.

Construction and mine workers are exposed to rock dust, with dire health results (Gee et al. 1984). Cherniak (1986) documents a frightful experience for laborers digging a tunnel through sandstone across the Delaware Water Gap. Acknowledgment of the workplace hazards resulted in regulations, and exposures are now monitored (Doll & Peto 1981, 1985). It was the obvious relationship of occupational hazards to health that eventually led to the banning of asbestos, the industrially important, naturally occurring mineral materials used worldwide for insulation. Its potentially hazardous nature has been known and documented for more than 100 years (Michaels & Chissick 1979, Skinner et al. 1988). By the 1960s, the possibility that nonoccupational exposure to asbestos may be hazardous created such fear in the general populace that the very mention of asbestos received a single response: This material

Particle diameter →										
Meters	10 <sup>-10</sup> (1Å)	10 <sup>-9</sup>	10 <sup>-8</sup>	10 <sup>-7</sup>	10 <sup>-6</sup>	10 <sup>-5</sup>	10 <sup>-4</sup>	10 <sup>-3</sup>	10 <sup>-2</sup>	
Microns (μ, 10 <sup>-6</sup> meter)	0.0001	1 μm, 1 nm 0.001	0.01	0.1	1	10	100	1 mm 1,000	1 cm 10,000	
Solids	Clay		Silt		Fine sand	Coarse sand		Gravel		
	Volcanic and industrial ash									
	Lung-damaging dusts Combustion nuclei, fly ash, colloidal silica, coal dust									
Water-related	H <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> O	Smog		Clouds and fog		Mist	Drizzle	Rain
Biological	CO <sub>2</sub>		Proteins	Viruses	Bacteria, spores, and pollen		Cells	Hair		
Sampling and analysis methods								Visible to the eye		
						Impinger		Sieving		
	Election microscocpe . . . light microscope									
	Spectroscopy			X-ray diffraction						

**Figure 2**

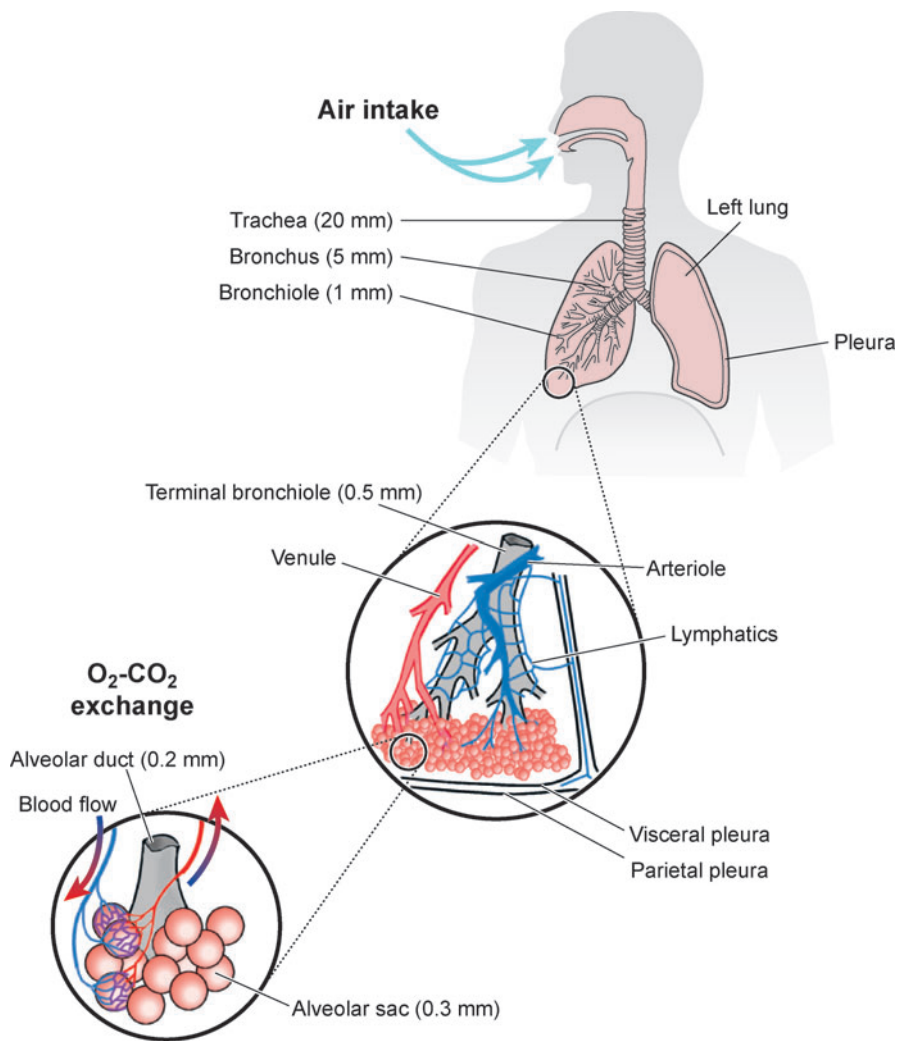
Diameters of airborne particles: solids, liquids, gases, inorganic, and biologic Earth materials and the techniques usually employed in detection and analysis.

is dangerous and should be totally avoided, as it causes lung disease. Today, discussion continues in scientific and popular literature, including newspapers (Nolan et al. 2005).

### Air and the Human Lung

Human adults breathe tens of thousands of liters of air daily (Bates 1989). The heterogeneous, mostly gaseous, mixture enters the lung and passes through a series of passages lined with cells and cilia to prevent inhalation or aid expulsion: the hairs in the nose, the bronchial tubes lined with mucous, and the ciliated cells that beat upward serve to expel any foreign materials through expectoration, a cough or sneeze. These are normal bodily reactions, the mechanisms that prevent particles from reaching the alveolar sacs where gas exchange, the transfer of O<sub>2</sub> and CO<sub>2</sub>, takes place with the pulmonary blood (**Figure 3**).

The surface area for gas exchange, approximately 90 m<sup>2</sup>, and the exchange through the capillary bed take place in 0.75 s for a person at rest with a blood flow of approximately 4.5 liters min<sup>-1</sup>. Normal breathing requires respiratory muscles, but expiration is largely passive, the lung being essentially a self-deflating balloon with elastic recoil. If small-sized particles (<10 μm) reach the sacs, there is a body defense mechanism, scarring or fibrosis, that isolates these foreign bodies. The cellular response through recruitment of other cells, macrophages and fibroblasts, seeks to encapsulate the offending material, but unfortunately scar formation also decreases the elasticity



**Figure 3**

Schematic diagram of the human respiratory system. The gross anatomy and sizes of the airways in the air flow system. After Skinner et al. 1988, figure 3.1, p. 110.

of the tissues. The fibrosis effectively obliterates a portion of the sacs and the more foreign materials entering the lung the greater proportion affected by scarring. The result is reduced gas transfer to or from the blood and defective oxygenation of the red blood cells that carry oxygen to other tissues and organs. Ferruginous bodies, encapsulated inorganic asbestos fibers, detected in lung tissues are a telltale sign of exposure to asbestos (Skinner et al. 1988).

Some individuals, especially those who smoke, compromise the protective mechanisms of the lung (Gee et al. 1984). Oxygen levels are lowered throughout the body

with persistent exposure and scarring. For example, researchers have proposed that increased particulate exposure may be responsible for cardiovascular disease.

Size, shape, density, and reactivity of particles all influence how far they will be transported and where they will be deposited (Wilson & Spengler 1996, table 3.2, p. 45). Deposition of all foreign substances—chemical, inorganic or organic, and mineral, as well as biological (pollen, bacteria, fungi, viri)—in the respiratory tract can initiate inflammatory responses and incite local proliferative fibrosis.

## Asbestos and the Lung

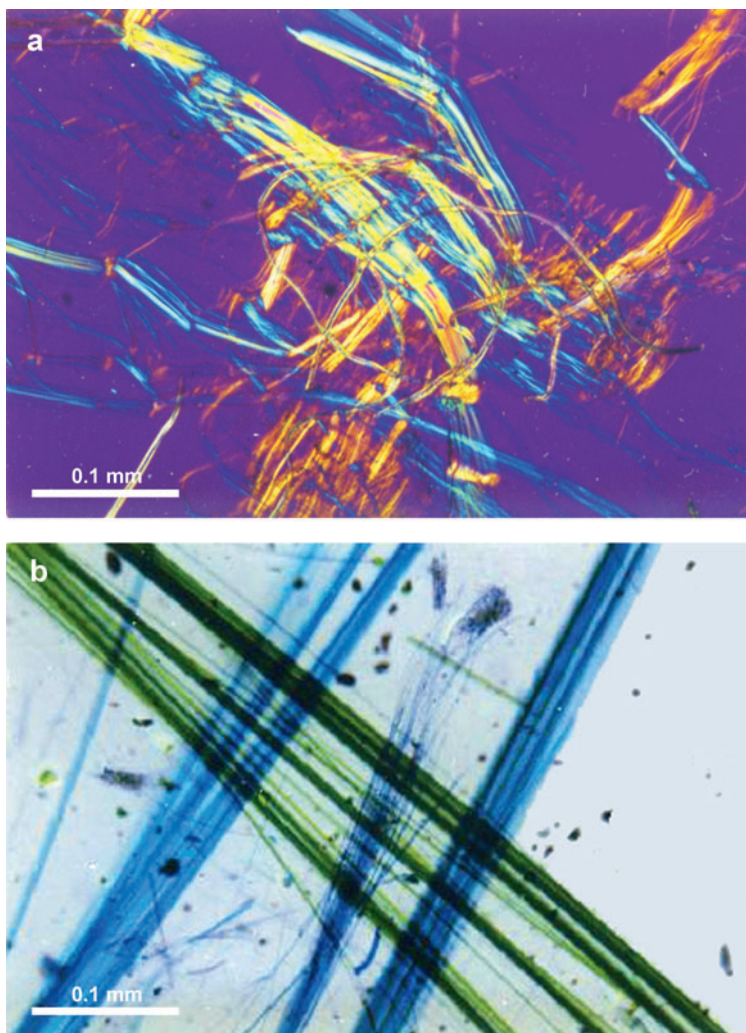
Asbestos is a classic example of a chronic inhalation hazard. Dusts containing fibrous materials are in the atmosphere, especially where building materials containing asbestos have been installed (for example, the wrappings on heating pipes, or on floor, ceiling, and roofing tiles). These particles are usually present in exceedingly small quantities and so tiny that they go undetected because they are not visible to the naked eye.

Workers exposed for years to large quantities of asbestos develop asbestosis, a fibrosing disease easily detected in chest X rays and by measurement of the volume of expired air—the forced expiratory volume in 1 s (FEV<sub>1</sub>)—that estimates the elasticity of the lung (Bates 1989). Asbestosis is a chronic disease characterized by declining ability to breathe properly and reduced lung capacity. The lowering oxygen supply, which is at first transient and then affects other body systems, is similar to other lung impairment diseases, e.g., silicosis and asthma.

Some asbestos workers, especially those who were smokers, contracted lung cancers. The personal choice of smoking confounded the etiology, as some workers were not susceptible to cancer an expression of differences in human physiologic responses or exposure levels (Ross 1984). However, cause and effect, asbestos and lung disease, was easily diagnosed. Another group of cancers affect the mesothelial tissues that surround the lung (**Figure 3**). Mesothelioma, although initially identified in the miners and their families in South Africa (Wagner et al. 1980), is also present in Cappadocia, Turkey. The diagnosis in this latter environment is domestic exposure on a restricted population. The responsible mineral was not any of the six asbestos species (**Supplemental Table 2**) but rather a fibrous zeolite, erionite (Baris et al. 1978, Mumpton 1979, Dogan et al. 2006).

All diseases of the lung take years, even decades, to manifest. Mesothelioma may go undiagnosed for up to 40 years, but workplace disease studies over the past 35 years established that some asbestos minerals as well as erionite may cause this cancer. An examination of tissues from mesothelioma cases in South Africa demonstrated that one of the amphibole asbestos minerals, crocidolite, or blue asbestos, was the most likely cause (**Figure 4a,b**).

White asbestos, the serpentine mineral chrysotile, by far the most usual insulation material in buildings and homes, does not show a connection to mesothelioma. However, determination of the mechanisms and identifying potential offending mineral materials are continuing, as other locales (Libby, Montana) and other minerals



**Figure 4**

(a) Bundles of flexible fibers of chrysotile or “white asbestos.” Optical photomicrograph under crossed polarization. The different colors are related to the thickness of the fiber bundles.

(b) Fibrous crocidolite, the asbestos form of the mineral riebeckite also known as “blue asbestos.” Optical photomicrograph under crossed polarization. Straight parallel fiber bundles are typical of the amphibole mineral group. Courtesy of Malcolm Ross, USGS.

or biological agents are implicated in causing mesothelioma (Ross & Nolan 2003, Gunter et al. 2003, Meeker et al. 2003, Dogan et al. 2006).

Whether and which airborne particulates— aerosols, pollens, bacterial spores, or gases such as radon—are the responsible offenders causing lung disease depends upon the exposure possibilities for particular individuals, i.e., the environment in which

they may have been, or are, exposed. For example, radon gas caused lung cancer in uranium miners in Europe and was thought to be a hazard for people living on granite rocks in parts of New England. Measurements of the radon level in homes showed such low levels ( $<4 \mu\text{Ci}$ ) that other sources, including smoking, were considered to be more likely hazards for populations in this area (Cothren & Smith 1987). The identification and levels of potential hazards per unit volume of air can be measured, and regulations (such as forbidding smoking in public buildings) can minimize the risks to the general public for several, but certainly not all, airborne hazards.

## THE HYDROSPHERE AND WATER

Earth scientists are well aware that ocean waters cover more than 70% of the surface of our planet and only 3% of water is freshwater. Of that very small percentage, 79% of freshwater is in ice caps and glaciers, almost 30% is groundwater, and  $<1\%$  is more accessible in lakes and rivers (Figure 5).

Potable waters, the waters we depend on for drinking, are a miniscule amount of waters on the surface, and have been through the water cycle many times (Hornberger et al. 1998; Dingman 2002; Natl. Res. Council. 2004a,b,c). The scarcity of water, such as in portions of the southwestern United States, is a major concern as expanding populations increase usage for personal and agricultural needs (Gleick 1993). Geological information on aquifers, estimating distribution and drawdown, and ground-based water storage possibilities are now and will continue to be the important areas in which geology and hydrology can provide major contributions to human health and well being.

The issue is not only quantity but quality of available waters. The composition of all freshwater is an interplay between the waters and geologic materials. The usual water cycle diagram does not acknowledge the addition of natural materials complicated by anthropogenic input such as fertilizer applications, effluent from mines, and industries, as well as sewage and storm water—the wastes from our built environment. These are the potential sources of pollutants that actually determine water composition, and they are of considerable volume. For example, industrial waste may be

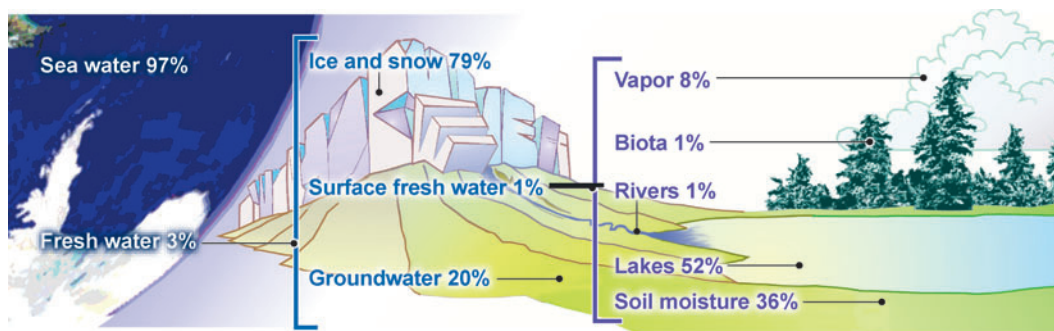


Figure 5

The sources of water on Earth. Percentages from Dingman 2002.



continually dumped onto the land surface or into waters and contribute potentially hazardous materials. The pollution is not only predominantly anthropogenically contributed, but also comes from point sources with heterogeneous compositions. The effluent in variable amounts produced from disparate sources also may arrive at irregular time intervals. Purification schemes required for human use, and their absence in third-world countries, often horrifyingly depicted, are an obvious common local problem. The mechanisms of transfer of possible water-borne disease, as well as chemical hazards, can be relatively easily determined in surface waters. However, with increased demand for water, not only supply but replenishment to secure quantity, ground water from aquifers is more likely to be utilized. Ground waters may contain unsuspected hazards, as in Bangladesh (discussed below), and the water composition may alter over time. These hazards are exacerbated as humans change the course of rivers by building dams at the same time that the demand for ground water for agriculture, mining, and personal uses explodes. All living forms depend on water, a limited resource that is now a precious commodity (WHO 2003).

A vast literature gathered over many years from all over the world, especially for arid areas of the United States and Middle East, cite the inorganic, organic, and biological content and contaminants found in freshwaters (Nat. Res. Council. 1987, 2004a,b,c; World Health Organ. 2004, 2006; U.S. Geol. Surv. 2006). To highlight some of the geomedical issues related to water consumption, two recognized potential contaminants, arsenic and fluorine, are discussed. These naturally occurring elements and their distribution illustrate how critical geological and hydrological knowledge are and the necessity for sharing data for global applications.

### **Arsenic (As)**

As is a common, widely distributed element in Earth's crust, with the highest concentrations found in some coals, but also in sediments such as mudstones and their metamorphic equivalents. The mobilization of As is increased by mining (Vaughan 2006). China's economic boom, requiring large energy resources, predominately from coal, is anticipated to vastly increase dust in the atmosphere from coal-fired utilities. The dusts generated, air pollutants, contain As and, if not controlled, are expected to affect the composition of surface waters compositions far beyond the borders of the country.

Long recognized as a poison, As is also a contaminant of groundwater supplies. As concentrations can be easily detected and quantitatively evaluated, and similar analytic techniques are applied to assay samples of the blood, urine, hair, and nails of exposed populations. There is no presently known animal model for estimating toxicity or dose response, but there is considerable accumulated data on human ingestion that shows a wide range of susceptibilities and toxicities (Przygoda et al. 2001).

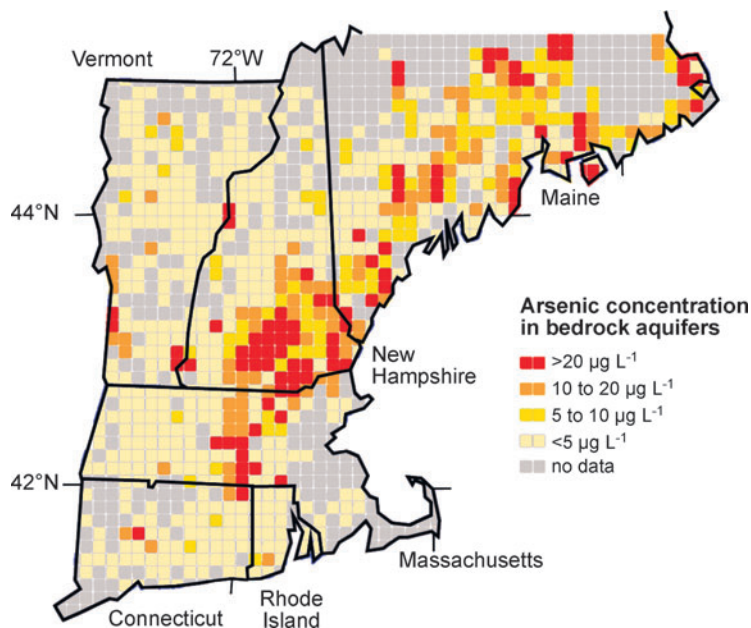
The nondeliberate health hazards of geogenic As are known through descriptions beginning in the 1920s, with black foot disease in Taiwan and skin disorders derived from well waters in Argentina. Unfortunately, the use of As-contaminated waters continued. In Antofagasta, Chile, where the Toconce River, with an average As

concentration of  $800 \mu\text{g L}^{-1}$ , became the local water source in 1958, horrible diseases affecting the unsuspecting public ensued (Hopenhayn-Rich et al. 1996, Hopenhayn 2006). A more recent public health crisis is the water problems in Bangladesh and West Bengal, India. Chronic exposures to As-containing waters was a result of a switch from surface waters contaminated with human waste and cholera bacteria to groundwater extracted through shallow tube wells. The groundwater source, the deltaic sediments, contained pyrite and arsenopyrite, minerals that incorporate As within their crystal structures (Naidu & Nadebaum 2003). Dissolution freeing As from the minerals, the ultimate source of the As, was enhanced at depth as a result of organic components and associated bacterial activity in the sediments. A range of As compounds were transferred through pumping groundwater, which in some locations had total As concentrations that exceeded  $200 \mu\text{g L}^{-1}$  (Charlet & Polya 2006).

Inorganic As is rapidly absorbed in the intestinal tract, and although approximately 70% may be eliminated in the urine, a portion of the initial  $\text{As}^{+5}$  form in the minerals may have changed in part to  $\text{As}^{+3}$ , the more toxic form, and been further altered in the body into organic metabolites. Methylated  $\text{As}^{+3}$  complexes are now considered the bad actors in causing disease (Vahter 2002). The inorganic and organic compounds find their way into a range of body tissues, causing some obvious symptoms such as keratoses of the skin, particularly in the calloused areas of the hands and feet. With continued exposure, skin cancer and other disorders develop within the vascular system and the bladder and possibly induce diabetes. This scenario played out in Bangladesh. Skin lesions appeared, and widespread sickness and death from cancers followed. It is estimated that more than 80 million citizens have been and are exposed to As-contaminated waters, and more than 300,000 have skin problems and cancer (Chowdhury et al. 2000). The identification of As as a waterborne silent hazard in the past somehow did not register with those who could have prevented the Bangladesh disaster. One of the groups most concerned with worldwide public health, the United Nations Scientific and Cultural Organization (NESCO), urged the Indian communities to dig the wells with the presumption, and good intentions, that higher-quality water would become available and benefit the local population. The ability to correct the present situation is not easy and very expensive. The lack of communication of the waterborne hazard posed by As is unforgivable and surely will no longer be tolerated.

Although high levels of As are clearly a health hazard, low-level exposure and the possibility that As may accumulate over time in the human body to become a lethal contaminant is under study. Waters in many parts of the world contain much lower levels than those encountered in Bangladesh. In eastern New England, 20%–30% of private wells exceed the present As drinking water standard of  $10 \mu\text{g L}^{-1}$ , and elevated bladder cancer was noted in the area (**Figure 6**).

A model developed to evaluate potential sources of As in the area included geologic and hydrologic variables such as rock types, areas where there had been Pleistocene marine inundation, and the landscape and topography. Geochemical measurements of As in stream sediments and well waters have led to the suggestion that the groundwater As concentration may be, at least partially, the result of past applications of arsenical pesticides (Ayotte et al. 2006).



**Figure 6**

The As concentration in Bedrock Aquifers. After Ayotte 2006.

The ability to predict the possible sources of As in waters used, or contemplated for use, and possibly causing disease, is not a trivial undertaking, as shown by the multiple possibilities in the modeling study. Health effects from any potential carcinogen are now only beginning to be evaluated and many other factors, diet or genetic predispositions that increase individual susceptibilities, will have to be added to future evaluations of the geological and hydrological hazard possibilities. Determining that the primary source in New England was not necessarily mineral materials is only part of the uncertainty identified in such a study. The model was limited by incomplete knowledge of the aquifers, including the bedrock fracture patterns and precise well depths. More detailed and accurate geological information—with three-dimensional knowledge of the catchment basin, transfer rates of the waters from the sites of rocks, or sediments, in addition to local compositional variation of the waters over time—would make any assay more precise. These data are not usually available. Unfortunately, it is only when disease strikes that the potential offending material and its sources are questioned and an environmental context is investigated, and that may be too late to assess the possible hazards. As illustrated here, there may be dual or multiple geogenic, industrial, or agricultural sources to consider. An interesting insight to another side of hazards of As possibilities is a paper that shows that Se, occurring in the same areas as As, may mitigate the initiation and the degree of disease (Wuyi et al. 2003).

Bair (2001) undertook another slightly different application of detailed hydrological studies on waterborne toxins. He studied contamination of groundwater in

the town of Woburn, west of Boston, where a number of children died of leukemia. Bair's project followed on a book, "A Civil Action," by Jonathan Haar (which is also a movie in which the persistence of a lawyer concerned for the families exposed to chemicals thrown into streams by factories has a justifying if not happy ending). Hydrologic investigations were undertaken to determine flow patterns of contaminants from the streams into the groundwater that permeated local wells with lethal results (Bair 2001). In these studies, the organic chemicals transferred into well waters could be tracked because of their chemical persistence in the aquifer. Chronic exposure of the populace to a wide range of potentially hazardous substances through drinking water illustrates the crossover from geological information and contributions that have proved invaluable to tracking and evaluating silent health hazards.

### Fluorine (F)

Fluorine (F) has long been considered a beneficial addition to waters to aid dental and bone health (Sognnaes 1960, Schamschula & Barmes 1981, Am. Diet. Assoc. 2005). Approximately 60 countries have taken the opportunity to put roughly 1 ppm ( $1 \text{ mg L}^{-1}$ ) F into their reservoirs, so water fluoridation is a worldwide phenomenon. However, higher concentrations of F in some freshwaters have created health problems, and the fact that HF, a highly acidic compound, can be volatilized by factories producing steel, bricks, glass, and ceramics has in the past scorched surrounding plant life and caused harm to animals in areas in North America and England (Bowen 1966). One occupational health hazard related to F was documented in Al factory workers, where bauxite ( $\text{Al}_2\text{O}_3$ ) submitted to electrolysis in a bath of cryolite ( $\text{Na}_3\text{AlF}_6$ ) was the early method used to free the Al; today  $\text{AlF}_3$  is used. F detected in the bones of workers was cited as the cause of increased bone mineral density (amount of mineral per unit area), bone spurs, and deformities, expressions of a disease known as fluorosis (Vischer et al. 1970).

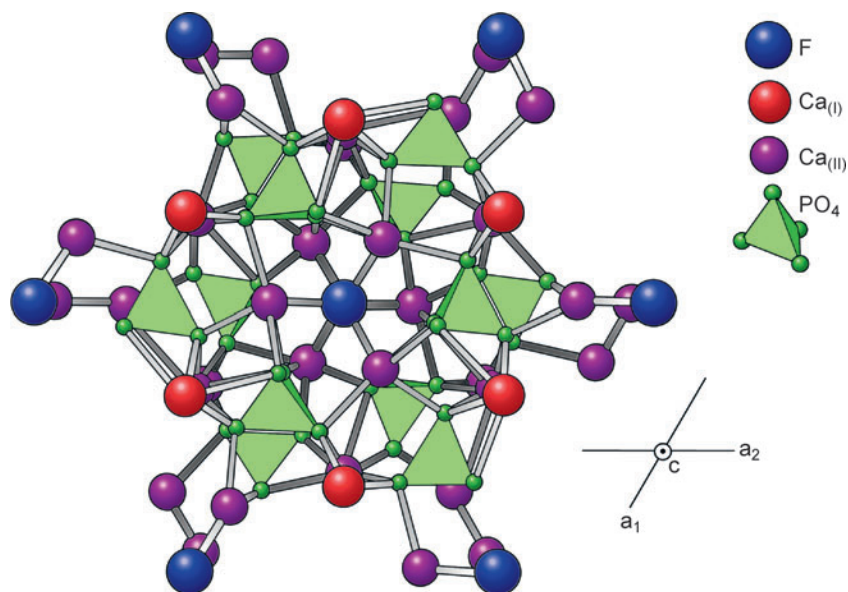
As early as 1937 in Madras, India, brown mottling and white spots on teeth prone to pitting and chipping (dental fluorosis) was described in people consuming water with F concentrations  $>2$  ppm. In other regions of India (Punjab) where individuals had been ingesting and cooking with waters averaging higher F levels, as well as growing vegetables in fluorotic soils, crippling deformities were common. Kyphosis and mineral overgrowths of vertebrae cemented the spine and restricted movement; analyses of these patients' bones showed up to 700 ppm F (Jolly 1970). An epidemiological study confirmed that water concentrations  $>2.5$  ppm F, some as high as 16 ppm, caused chronic F intoxication and skeletal fluorosis and, secondarily, affected the nervous system, as hypermineralization led to compression of the spinal cord and other unfortunate outcomes such as difficulty in breathing.

Hypomineralization (reduced mineral content) and interrupted calcification was detected by microradiography (X-ray transmission examination) of mineralized tissues from Morroccans exposed to high F levels from well waters arriving from rock phosphates in the area, probably exacerbated by the consistent drinking of green tea (the national drink). Poor calcification was characteristic of the enamel but not the

dentine of their teeth, and alveolar bone (bone that surrounds the teeth) had abnormal porous structure. Similar findings were experimentally produced in guinea pigs ingesting pellets of the phosphate rock (predominantly apatite) containing from 1.5% to 3.25% F. These analyses indicated that cellular activities were distinct for the different mineralizing tissues in humans (Baud & Alami 1970). Clearly, bone and dental tissues that normally mineralize with apatite were the focus of F uptake, and elevated amounts disturbed their formation. Animals as well as humans could be affected.

One of the most reactive of elements, F became a pharmacologic agent. The conspicuous finding that F ingestion correlates with an increase in mineralized tissue formation in bone suggested that it may be used to treat osteoporosis, a group of diseases typically developed with age in which bone tissues become less mineralized and less dense. Early trials on osteoporotic patients who ingested NaF tablets, 30–60 mg per day for 5–9 months, relieved bone pain with no obvious side effects. Histological examinations (microscopic techniques used to identify tissue characteristics (Jee 1981) of bone biopsies of the participants showed increased bone formation, with analyses of the bulk mineral containing approximately 3% F. In other clinical investigations with longer NaF ingestion, the two cells involved in the dynamic deposition and resorption typical of bone, osteoblasts (deposit bone substance) and osteoclasts (resorb bone and mineral substance), were evaluated. After more than 80 weeks of treatment, a doubling of the volumetric density of cancellous bone marked by an increase in the number of osteoblasts and osteoid (organic matrix) formation was noted (Schenk et al. 1970). However, mineralization of the newly formed osteoid was delayed, in spite of vitamin D supplementation. Reduction or stopping NaF ingestion restored mineralization. Researchers concluded that F may be useful as a stimulant for bone tissue formation, but continued high doses are not a cure for bone disorders such as senile osteoporosis. The tissue reactions observed suggested that cells are distinctive to their specialized tissues and functions and will probably respond independently to a new chemical environment (Canalis 1996) although high doses of F interfered, perhaps as an inhibitor of specific enzymes, with the mineralization process in all of the mineralized tissue systems.

With such information, F appears to be expressing the Aristotelian adage, a little of a good thing may be advantageous, but excess is likely to be dangerous. F occurs, geologically substituting for OH, in biotites and amphiboles, which, upon weathering form F-containing clays in soils that are likely to have wide surficial geographic distribution as well as variable compositional ranges. An overview of the F cycle includes several geologic and anthropogenic sources and sinks (Edmunds & Smedley 2005). For example, HF emitted during the refinement of  $\text{Al}_2\text{O}_3$  into Al metal and the HF emitted from volcanic eruptions may deposit on flora and fauna, lakes, and soils, with eventual incorporation into groundwater. An ultrahigh average F concentration,  $1281 \text{ mg L}^{-1}$ , of Lake Magadi in Tanzania has been reported, whereas the streams bordering and presumably flowing into the lake averaged only  $0.6 \text{ mg L}^{-1}$  (Jones et al. 1977). The high lake amounts are the result of degassing and multiple sediments that produce brines below the Lake. Concentration of F in any surface waters, although generally much higher than in rainfall, reflects the local geologic



**Figure 7**

Crystal structure of fluorapatite projection down the  $c$  axis.

environment, especially in areas where F-containing minerals and alternate F sources may be located.

F as fluorapatite is a well-known member of the calcium phosphate mineral group (**Figure 7**). A hydroxylfluorapatite is the usual phosphate species found highly dispersed in ocean sediments, probably where biological activity aids precipitation and localization. Highly concentrated phosphate precipitates become ores mined for fertilizer (Cook 1976). The Phosphoria Formation in the western United States contains high concentrations of F in a mineral known as francolite, a carbonate- and F-containing apatitic species that is very fine grained (McKelvey et al. 1959, Gulbrandson 1966, McConnell 1973). The crystal chemical location of carbonate in the bioapatitic structure has been a topic of investigation for many years, as this is the usual chemical formulation in biological apatites (Glimcher 1998; Skinner 1989, 2003, 2005). Because F can be incorporated in the mineral of mineralized tissues, and has the potential for aiding dental health, but causing medical problems, especially when continually ingested at high concentrations, dose levels for this element are important. The potential for dual roles has generated much discussion about the risks versus the benefits of fluorine ingestion.

The 2004 WHO guideline for F in drinking water is  $1.5 \text{ mg L}^{-1}$ , although China has adopted a lower value of  $1.0 \text{ mg L}^{-1}$ , and Tanzania has a national standard of  $8 \text{ mg L}^{-1}$ , reflecting the costs of extracting F from waters for a poor country. In the United States, where many additional sources of F, such as toothpaste and tea, augment the level ingested, the necessity to fluoridate waters has generated considerable

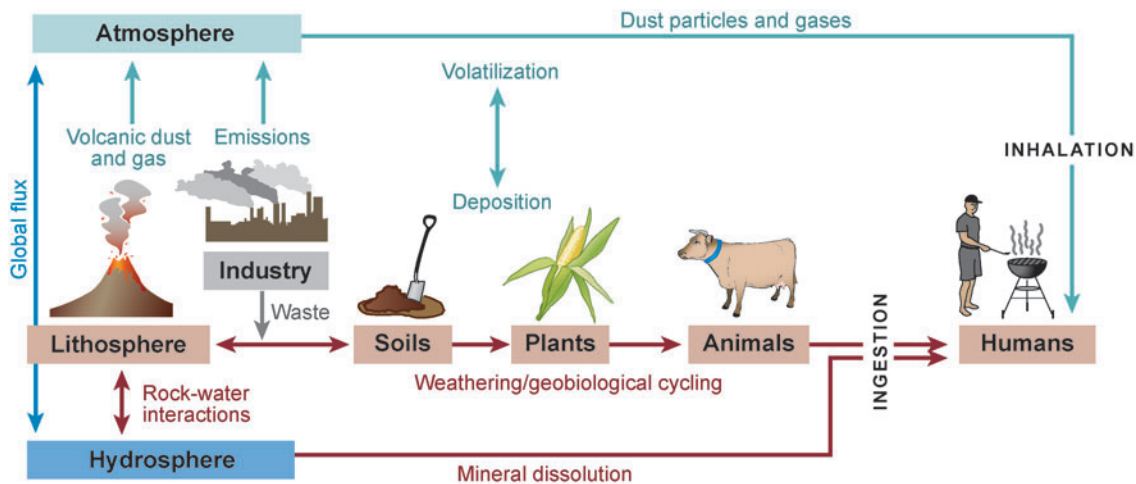
debate with diametrically opposed views (Waldbott 1978), and the debate continues (Am. Diet. Assoc. 2006). There are those in the population who question whether some locales need to fluoridate water if the groundwater sources are adequate, but often water assays are not available. Communities throughout the world could become aware of the amount of F in their waters and take the responsible path to check for variations from time to time. Water chemistry will respond to drawdown as different rock masses may be sampled over time. It seems prudent to follow the lead set by the British Geological Survey that permits the concentrations of F in wells and accessible surface waters to be documented and available for review (Edmunds et al. 1989).

## LITHOSPHERE AND SOILS

A complex of inorganic and biologic particles, soils are the transition zone between the atmosphere and the lithosphere, providing the environment that allows plants, which become the food for animals and humans, to grow. Like air and water, soils and sediments contain chemical, biochemical, mineral and microbial components that have major impacts on health. The heterogeneous distribution of these components, such as the presence of As-containing minerals in the sediments in Bangladesh mentioned above that created a waterborne hazard, is but one of many examples that have come to the attention of our environmentally aware populations.

Soils generated over some rock types in some climatic regions can be thin, whereas enormously thick sediment accumulations form in still freshwaters and in deltas on the edges of continents. The range of soil types is extremely variable and patchy and reflects different source rocks and the weathering and transport processes typical of the climate. Some soils are alkaline and highly oxidized—these are characteristic of dry environments—whereas others are acidic and with low Eh (the redox value, an estimate of the oxygen potential); where rain fosters high plant growth and accumulation of organic detritus in some low-lying areas, soils may remain saturated (marshes). Overwhelmingly composed of inorganic (mineral) materials (>95%) with particle size of sand (0.05 mm to 2 mm) to clay (<0.02 mm to 2  $\mu$ m) (see **Figure 2**), soils are a dynamic membrane inhabited by many living forms: bacteria, fungi, an enormous range of invertebrate species, and the roots of plants. The solubility of the predominant mineral materials responds to the geobiohydrological ecosystems providing solutions containing the elemental components that may be nutrients and any chemical species including contaminants that can become hazards (Alloway 1995, 2005). The complex interactive mechanisms and activities of the living forms show continual change, and aside from humans directly ingesting potentially contaminated soils, geophagy (Abrahams 2003), exposure to any contaminant is most likely through the plants and animals that become part of the human food chain.

Every element has a cycle that is today vastly influenced by human needs and activities (Sigel & Sigel 1990, Sigel et al. 2005). The trace elements necessary for the growth and maintenance of normal human physiology, as well as those indicted as



**Figure 8**

The continuum of Earth materials between the atmosphere, hydrosphere, and lithosphere and the pathways for uptake of particles, gases, and elements into plants, animals, and humans. After Fordyce 2005, figure 1, p. 378.

potential human carcinogens, have to be bioavailable, that is, be ingested by humans, usually via the plant kingdom (**Figure 8, Table 2**).

Foodstuffs usually contain relatively large quantities of Ca, Mg, or Fe, as well as elements that may be chronic hazards such as Se, Cd, Mo, Pb, and Zn. The quantity depends on the substrate, the mineralogy of the soils, and the release, transport to, and uptake by the plant materials whose degeneration in place completes the cycle back to the soil. Agriculture and soil dynamics are beyond this discussion, but we are all familiar with the fact that many soils have been altered by the use of fertilizers, pesticides, and irrigation practices that inadvertently, at least in the past, have brought several potential hazards into the human diet. Every trace element, as well as organic chemical or biological additives, is potentially hazardous, especially if consumed in large quantities. Body systems and protective mechanisms may be overwhelmed and unable to effect elimination or adequate sequestrations of a hazardous substance. Two elements with known medical effects are discussed below.

### **Cadmium (Cd)**

One of the elements considered extremely hazardous by the United Nations Environmental Program is Cd, which is usually incorporated in minor or trace amounts in Zn minerals, e.g., sphalerite, ZnS in sulfide deposits, and separated as a by-product of mining operations. Its important early use, to prevent corrosion by plating of steel, especially of ships and automobiles, has been phased out because of health issues. However, Ni-Cd batteries, because they can be recharged and are lightweight, are a likely means of exposure. Luckily, the expense of mining and refining Cd has encouraged recycling, which results in several tons of Cd metal recovered each year.



Widespread but in miniscule quantities in primary as well as secondary rocks and water, Cd cannot be entirely excluded from the diet, as it is readily taken up by many plants, e.g., lettuce and spinach, and has been detected in tobacco leaves and smoke (Emsley 2001). This is because the element also associates with sulfur-containing biochemicals such as the amino acid cysteine. For example, a group of cysteine-rich enzymes, the metallothiones, bind heavy metals and contribute to the regulation of the essential intracellular elements Zn and Cu (Chiu et al. 1989). Metallothione molecules can assist in the body's defenses by taking up circulating Cd, and aiding its elimination by passing it to the kidneys. However, any Cd that accumulates in body tissues may remain for 30 years, an attribute typical of silent chronic hazards. At body levels >200 ppm Cd, there is interference with normal kidney activities, such as the processing and resorption of proteins, amino acids, and glucose, and kidney failure may result (Seiler et al. 1994).

Attention was drawn to Cd as a chronic elemental hazard with the identification of the disease known as itai-itai, or ouch-ouch. The name reflects the problem as the disease weakens bones and joints, making movements painful. It was discovered in Fuchu, a city 200 miles north of Tokyo, Japan. The affected populace consumed rice containing elevated amounts of Cd grown in paddies irrigated by waters downstream from sulfide deposits mined for Zn and Cu. The disease was found in other areas in Japan with high Cd in the food, and the potential for bone disorders and disturbed kidney function have been confirmed epidemiologically (Nakagawa et al. 1990; <http://www.kanazawa-med.ac.jp/~pubhealt/cadmium2/itaiitai-e/itai01.html>).

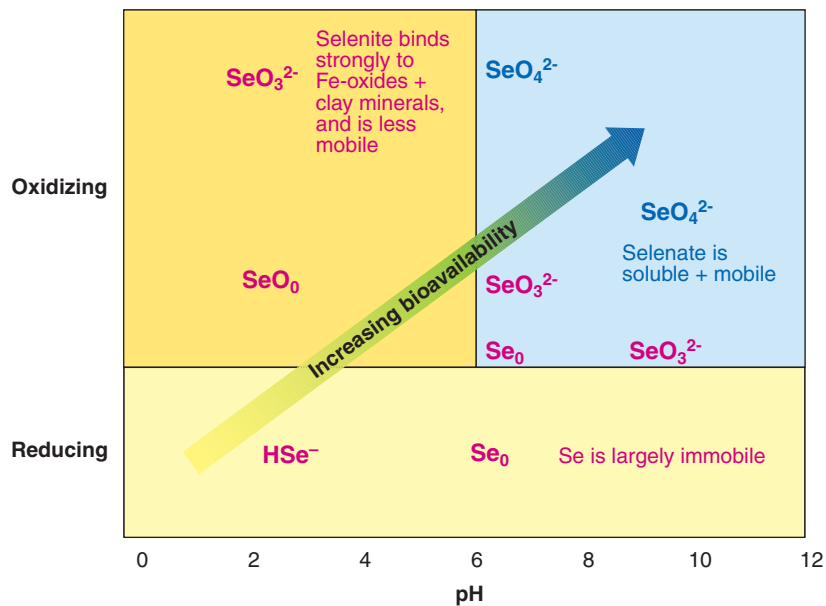
## Selenium (Se)

Similar to Cd, Se is also available from the smelting products of Cu mines, as it too is geochemically associated with sulfur minerals that may predominantly contain Cu, Zn, and Pb. Se metal may occur naturally, as do many uncommon Se-containing minerals (Fordyce 2005, table 8, p. 379). As a result of its ease of extraction, but mostly because Se is a remarkable metal, it conducts electricity 1000 times faster when light falls onto its surface, providing a metal with multiple industrial uses, e.g., in photoelectric cells and photocopiers. Although chemical analysis of the very minor concentrations of Se in the environment was not performed on a regular basis until the past few decades, the chemical form and speciation of Se can be predicted from knowledge of the pH and redox conditions of the soils. Selenite ( $\text{Se}^{4+}$ ), the predominant inorganic species, is absorbed more readily onto soil particles than selenate ( $\text{Se}^{6+}$ ) and increases with decreasing pH. At acidic conditions, selenites may form insoluble complexes, with iron oxides lowering the bioavailability of Se.

The remarkable range of speciation of Se (**Figure 9**) allows the element to move from water and soil to the atmosphere. Methyl derivatives of Se are released during the burning of coal and from soils, lakes, and sewage through methylation by anaerobic bacteria. Respiration of dissolved Se in the oceans during phytoplankton blooms is also a source of Se (Haygarth 1995, Amouroux et al. 2001). In addition, plants with Se in their tissues, mostly substituting for S in the amino acids methionine and cysteine, can sometimes also reduce the element to selenide ( $\text{Se}^{2-}$ ), forming dimethylselenide,

**Figure 9**

Schematic diagram showing the bioavailability of Se and selenium complexes in soils under varying conditions, pH and Eh. After Fordyce 2005, figure 4, p. 382.



the garlic odor in the air adjacent to accumulator plant species growing on soils rich in Se (Neal 1995).

“Every cell of the body contains more than a million atoms of selenium” (Emsley 2001, p. 379). With such a statement and the knowledge that Se is essential for good health, with recommended ingestion at 60–75  $\mu\text{g day}^{-1}$ , it is peculiar that Se has a reputation as a hazardous element (Fordyce 2005). Like most trace elements, Se needs to be present in just the right amounts to assure appropriate availability for body metabolic requirements, but for Se the amount is less than 450  $\mu\text{g day}^{-1}$ .

As far back as the thirteenth century, Marco Polo noted animals that behaved peculiarly and were affected by staggers. They had consumed a plant of the vetch family (*Astragalus*), also known as loco weed in the United States. *Astragalus* concentrates Se up to 1.4% of its dry weight. Selenosis, or Se overload disease, also causes hoof loss in animals and hair and nail loss in humans ingesting elevated Se. However, other geographic areas were noted by reduced productivity and ameliorated by including Se in fertilizers spread on grass plots to elevate the plant and dietary level.

Low Se availability leading to a deficiency disease is the more likely scenario and has been identified in Keshan, a county in northeast China. The local grains contained  $<0.04 \text{ mg kg}^{-1}$  Se, and analyses of hair (a convenient assay of diet level)  $<0.12 \text{ mg kg}^{-1}$ , implicating low Se levels. Children and females showed congestive heart disease, and in the Linxian province there was a high incidence of stomach cancer. Sodium selenite supplements (0.5–1.0 mg per week) relieved the symptoms and reduced the incidence of deaths over the 4 years of study (Tan 1989). Keshan-Beck, an

osteoarthritis disease with stunted growth of the skeleton and joint degeneration, has also been related to low Se intake, although iodine deficiency and fungal infections known to compromise thyroid hormones and therefore bone development may be possible cofactors. Intake of Se supplements did prove to be a helpful treatment (Peng et al. 1999). In a study in Inner Mongolia, a different benefit from Se ingestion was demonstrated. People exposed to high levels of As in their drinking water with classic skin and other symptoms were fed yeast tablets containing 100  $\mu\text{g}$  of Se. After 14 months, there was a reduction in symptoms and lower levels of As in their hair and nails. Wuyi et al. (2003) suggested that Se was an antidote, an antagonist of As, and helpful in removing the offending As from body tissues. As an essential element from dietary sources, the roles Se plays in human disease and health are not yet fully evaluated nor completely understood.

The many roles associated with bacterial, fungal, and other invertebrate inhabitants that aid the bioavailability of the elements discussed in this section cannot be underestimated (Natl. Acad. Press 2005). Their direct and indirect contributions to the cycles required to present both nutrients and hazardous contaminants to humans and animals offer tremendous opportunities for future research. Connecting the geological with biological sciences to investigate health issues from the soil perspective has begun, but needs considerably more collaborative attention (Bennett et al. 2000, 2001; Rodgers & Bennett 2004).

## SUMMARY

Exposure to natural Earth materials is at least partially through choice, but is undoubtedly increased by anthropogenic activities that have altered Earth's surface environments. An expanding world population now inhabits many areas where the exposure to potential hazards may be high and result in unwanted health effects. Investigations of potential hazards take into account the fact that humans are the largest force changing the surficial natural environment. Humans are also responsible for the explosive production of synthetics, a remarkable chemical smorgasbord that can impact health as they become distributed via Earth processes (e.g., Plant & Davis 2003). There are huge opportunities for research to draw on knowledge of natural processes, Earth materials, and synthetics in relation to public health.

This review discusses the transfer of a few hazardous Earth materials, some known for many years, into our bodies through limited routes of access: via air, water, or what we eat. A surfeit of any, even natural, materials can interfere with normal body functions and produce telltale signatures in or on our body. Chronic exposure to natural materials, the focus of this discussion, was chosen because low-level exposures are more likely today. To address chronic hazards is more challenging because the symptoms and diseases are often delayed so only when large numbers of the population are affected is an overt public health response generated. The recording and reporting of disease has made everyone more likely to consider the possibilities of contributions from the environment. As Earth scientists, we can be part of the prevention of disease.

Sensitive techniques are available to detect, identify, and measure the exceedingly small amounts of potentially hazardous materials in the atmosphere, hydrosphere, and lithosphere. Geographical Information Systems (GIS) has become the technique with which geochemical and surficial topographic and any other geologic data can be linked to epidemiological data on disease and its distribution. Physicians and medical scientists detect and estimate the quantity of foreign substances, or their products, in patients' blood, urine, organs, tissues, and cells, separating normal from pathological reactions. Accumulated medical histories are needed to pinpoint possible causes from their assessments of the tissue analyses.

The variable responses of individuals to chronic hazards must be reiterated because statements on particular health hazards are usually the result of epidemiologic studies that must evaluate limited data on human populations and focus on a few variables. What has become clear is that although the appearance of a disease or disability can be determined, the complete etiology, identification of an offending environmentally based source, and rate and amount or levels of exposure involve complex interactions that often cannot be measured or reconstructed. Furthermore, there are likely multifactorial considerations in attempting to find a cause and effect for all exposed or all diseased individuals, which requires comparison with well-chosen control group studies and requires large amounts of research funds. Epidemiological analyses provide statistical probabilities from accumulated data. When similar results are detected from many locales, they serve to reinforce the connection. Estimating the burden of disease is a nontrivial undertaking (Browne & Wagner 2001, Pruss et al. 2002)

Asbestos was discussed as an example of a chronic airborne hazard. These fibrous mineral particulates remain under investigation as confounding factors (smoking), and projecting the risk to low-level situations from studies on occupational exposure cannot yet be predicted (Pan et al. 2006). Although it is possible to discriminate among particulates and measure their size relative to human lung physiology, the biomechanisms inducing a range of cancers related to specific mineral exposures is not known (IOM 2006). There is an increase in asthma in the U.S. population, which suggests that other natural and anthropogenically created aerosols, and gases, and individual sensitivities will continue to keep chronic airborne hazards an active area of research.

Hazards arising from polluted waters were outlined through the discussion of As and F. As, a known poison and the cause of widespread disease in India and China, is an unfortunate illustration of problems not yet preventable nor remediable, although there are successful filter systems that have been engineered for ultrahigh concentrations on wells. The best response to As as a chronic hazard is prevention through awareness and through analyses of domestic/agricultural waters. F is an element with a checkered career in human health. Known to cause skeletal fluorosis when present in high amounts, F has been added to domestic waters as a benefit to dental health. Ongoing studies phrase a question of whether fluoridated toothpaste and prophylactic dental treatments are obviating the need for water fluoridation. There is the possibility, at least for some individuals, that expanding F intake from the very small augmentation in drinking water may turn the dental advantage into a potentially

chronic skeletal problem. The answer will not be forthcoming in the near future, as evaluation of dental and skeletal health from large populations over time will need to be matched with water data from diverse geographic locales to secure the necessary accuracy or determinations of thresholds for very low levels of F exposure.

The lithosphere, rocks, minerals, and soils comprise the ultimate sources of all nutrients and a wide range of potential hazards, some, as discussed herein, the most insidious. Most contacts with hazardous materials come via ingestion for both animals and humans. Luckily, the foodstuffs in the United States are monitored by government agencies, such as the Food and Drug Agency. The detection and avoidance of high concentrations of known hazardous chemicals may be supervised, but could be compromised by importation from international sources, reinforcing the importance of monitoring and maintaining an overview critical to public health. Two cations with important worldwide industrial applications are Cd and Se. Se, an essential element for human health, has a surface distribution dictated by element speciation in response to pH, Eh, and microbial activity. It has been known for quite some time that some plants can accumulate Se, a clear example of bioavailability of this element that underscores the necessity to integrate biochemical with geochemical data and knowledge when determining health effects. The discussion of Cd shows that ingestion, although inadvertent, is probable. The element's health effects show a relationship with sulfur-containing biochemicals, specifically the amino acid cysteine. An enzyme, a metallothione, may sequester Cd and prevent normal elimination of Cd. Skeletal disease itai-itai developed when the populace in western Japan inadvertently consumed rice with high Cd levels grown in paddies downstream from Cu and Zn mining sites.

It is important to go beyond measurements of the total trace element content in the geologic environment. Bioavailability and bioaccumulations in plants and animals of several potentially hazardous elements (Hg and Mo, for example, have already been identified) are also important, as are the modes of transmission through the human food chain.

Climate was and is impacting humans and their well being. Although the actual long-term changes are debated, there is no doubt that humans will have little opportunity to change natural events or influence the global results on waters and soils, especially elemental distributions. The concern with the future and specific environmental impacts has created a sea change in public perceptions. It has been acknowledged that Earth processes and materials are intimately involved with humans and their well being.

Over the past 50 years, fueled by increasingly sensitive analytical techniques and the rapid and global exchange of data and expertise, several health issues associated with exposures to Earth materials have been identified and continue to be investigated. Proceeding through coordination among a wide spectrum of biogeoscientists, coupled with economic and sociological considerations, communities throughout the world are contemplating the importance of the environment on the health and well being of their populace. Meaningful crossovers of basic information and collective knowledge on the detection and amelioration of acute and chronic diseases have

appeared (Skinner & Berger 2003, Selinus et al. 2005). These compendiums will be upgraded with the remarkable explosion of collaborative research on new topics and areas that increase understandings of cause and effect. The purview of medical geology and environmental health will expand in the decades to come.

### SUMMARY POINTS

1. Medical geology/geomedicine is the area of scientific research that focuses on the materials and processes in the environment that have impacted human health. It encompasses collaborative investigations between geosciences and health sciences.
2. Acute hazards such as earthquakes and volcanic eruptions have obvious and immediate health impacts.
3. Chronic health effects are hidden, effectively silent hazards that appear as debilitations and disease in populations only after lengthy exposures to potentially lethal chemicals and agents.
4. Health impacts depend on bioavailability of hazardous materials or agents and their transfer to or into the human body. Gases, minerals, chemicals, and bacteria have all been implicated as potentially hazardous materials in the air, water, and soil.
5. Susceptibility to particular hazards is variable for individuals and may change with age or with a change in habitat or diet. Some populations, the very young or the aged, are likely to be more susceptible to chronic hazards.
6. The continuum of potential hazards from Earth sources offers many opportunities for collaborative investigations, as new hazards are being generated through human activities and especially as an increased world population occupies many different environments.
7. Collaboration between Earth and medical/health scientists is essential to establishing cause-and-effect relationships: Geologists can identify and locate possible hazards in the environment and their modes of distribution, while physicians, pathologists, toxicologists, epidemiologists, and public health personnel can identify and record diseases and sites of occurrence in the population. By superposing the spatial patterns of the two data sets using GIS, the opportunity to correlate induction of disease with patterns of exposure to particular hazardous materials or agents is optimized.
8. The many and diverse human responses to different levels of chronic hazards plus patchy reporting of disease occurrences for individuals, communities, and countries limit the data available for constructing models capable of predicting thresholds or exposure levels to chronic hazards for an at-risk group of individuals or populations.

## FUTURE ISSUES

1. Each potential hazard from earthquakes and volcanic eruptions to geographic locales with high levels of dust that may carry bacterial or fungal toxins can now be detected and monitored by satellites.
2. Satellite monitoring needs to be more selective for specific hazards in order to detect some of the potential chronic hazards, e.g., As and Cd. However, there will always be a need for “ground truthing” the sources and obtaining accurate analytical levels at the locales where humans may be exposed. An expanding population requires that more areas be scrutinized and monitored.
3. Discrimination levels of all analytical techniques must be continually upgraded as new scientific information and instrumentation become available.
4. Detailed mapping and periodic upgrading of air and waterborne hazards as well as soil compositions will be most useful in discriminating among potential chronic hazards, chemical or biochemical. The potential for optimizing worldwide health and practicing preventive medicine, an expensive undertaking to be sure, is real, and when the data become available for a range of geographic locales, it will markedly aid scientific research and understanding.
5. Worldwide integration of hazard detection and data sharing are essential to evaluating chronic as well as acute health issues. Detection of potential geographic hazard areas is possible. The global communications network linking responsible parties or agencies transmitting data on disease, as well as the geographic/geologic data, is important. The standardization of disease reporting as well as information on treatment modalities are requirements not yet in place. The WHO data on specific infectious diseases, e.g., Asian flu, should be emulated for chronic-induced diseases that are more difficult to detect and monitor, and could benefit prevention in the future.

## ACKNOWLEDGMENTS

I acknowledge the personal opportunity and satisfaction I was afforded as chairman of the committee charged by the National Research Council and Institute of Medicine to produce a report on research priorities for Earth sciences and public health. The discussions drawing scientists from many disciplines was a remarkably stimulating experience. I also thank Dr. William Straight, my colleague who kindly produced the figures for this review and the thoughtful reviewers who markedly improved the manuscript.

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## Errata

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