1 Medical Geology: Perspectives and Prospects

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This chapter is a brief history of medical geology—the study of health problems related to "place." This overview is not exhaustive; instead, it highlights some important cases that have arisen during the development of the science of medical geology. An excess, deficiency or imbalance of inorganic elements originating from geological sources can affect human and animal well-being either directly (e.g., a lack of dietary iodine leading to goiter) or indirectly (e.g., effect on metabolic processes such as the supposed protective effect of selenium in cardiovascular disease). Such links have long been known but were unexplained until alchemy evolved into chemistry in the seventeenth century, when medicine ceased to be the art of monks versed in homeopathic remedies and experimental explanations of disease was sought rather than relying on the writings of the Classical Greek philosophers, and modern geology was forged by Lyell and Hutton. In addition, the exploitation of mineral resources gathered pace in the seventeenth century and brought in its train the widespread release of toxic elements to the environment. New sciences of public health and industrial hygiene emerged and their studies have helped inform our understanding of the health implications of the natural occurrence of these elements.

1.1 The Foundations of Medical Geology

1.1.1 Ancient Reports

Many ancient cultures made reference to the relationship between environment and health. Often health problems were linked to occupational environments but close links to the natural environment were also noted. Chinese medical texts dating back to the third century BC contain several references to relationships between environment and health. During both the Song Dynasty (1000 BC) and the Ming Dynasty (Fourteenth to Seventeenth century AD), lung problems related to rock crushing and symptoms of occupational lead poisoning were recognized. Similarly, the Tang

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Dynasty alchemist Chen Shao-Wei stated that lead, silver, copper, antimony, gold and iron were poisonous (see discussion in Nriagu, 1983).

Contemporary archaeologists and medical historians have provided us with evidence that the poor health often revealed by the tissues of prehistoric cadavers and mummies can commonly be linked to detrimental environmental conditions of the time. Goiter, for example, which is the result of severe iodine deficiency, was widely prevalent in ancient China, Greece, and Egypt, as well as in the Inca state of Peru. The fact that this condition was often treated with seaweed, a good source of iodine, indicates that these ancient civilizations had some degree of knowledge with regard to the treatment of dietary deficiencies with natural supplements.

As early as 1,500 years ago, certain relationships between water quality and health were known:

> Whoever wishes to investigate medicine properly, should proceed thus....We must also consider the qualities of the waters, for as they differ from one another in taste and weight, so also do they differ much in their quality (Hippocrates 460–377 BC).

Hippocrates, a Greek physician of the Classical period, recognized that health and place are causally related and that environmental factors affected the distribution of disease (Låg 1990; Foster 2002). Hippocrates noted in his treatise *On Airs, Waters, and Places* (Part 7) that, under certain circumstances, water "comes from soil which produces thermal waters, such as those having iron, copper, silver, gold, sulphur, alum, bitumen, or nitre," and such water is "bad for every purpose." Vitruvius, a Roman architect in the last century BC, noted the potential health dangers related to mining when he observed that water and pollution near mines posed health threats (cited in Nriagu 1983). Later, in the first century AD, the Greek physician Galen reaffirmed the potential danger of mining activities when he noticed that acid mists were often associated with the extraction of copper (cited in Lindberg 1992).

An early description linking geology and health is recounted in the travels of Marco Polo and his Uncle Niccoló. Journeying from Italy to the court of the Great Khan in China in the 1270s they passed to the south and east of the Great Desert of Lop:

> At the end of the ten days he reaches a province called Su-chau....Travelers passing this way do not venture to go among these mountains with any beast except those of the country, because a poisonous herb grows here, which makes beasts that feed on it lose their hoofs; but beasts born in the country recognize this herb and avoid it (Latham 1958).

The animal pathology observed by Marco Polo that resulted from horses eating certain plants was similar to a condition that today we know is caused by the consumption of plants in which selenium has accumulated; this explorer's account may be the earliest report of selenium toxicity. Marco Polo also described goiter in the area around the oasis city of Yarkand (Shache) and ascribed it to a peculiarity of the local water. Earlier, near Kerman on the Iranian eastern frontier, he commented on a lack of bellicosity in the tribesmen that he attributed to the nature of the soil. In what could be considered the first public health experiment, Marco Polo imported soil to place around the tribe's tents in an effort to restore their bellicosity. His approach proved to be effective (see also Chap. 16).

Health problems resulting from the production of metal have been identified in many parts of the world. The common use of metals in ancient societies suggested their toxicity. Although the relationship between lead and a variety of health risks is now well documented in modern society, the relationship was less well known in the past. Lead has been exploited for over six millennia, with significant production beginning about 5,000 years ago, increasing proportionately through the Copper, Bronze, and Iron Ages, and finally peaking about 2,000 years ago (Hong et al. 1994; Nriagu 1998). Several descriptions of lead poisoning found in texts from past civilizations further corroborate the heavy uses of lead. Clay tablets from the middle and late Assyrian periods (1550–600 BC) provide accounts of lead-poisoning symptoms, as do ancient Egyptian medical papyri and Sanskrit texts dating from over 3,000 years ago (Nriagu 1983). About 24% of discovered lead reserves were mined in ancient times (Nriagu 1998).

It has been estimated that during the time of the Roman Empire the annual production of lead approached 80,000 tonnes (Hong et al. 1994; Nriagu 1998), and copper, zinc and mercury were also mined extensively (Nriagu 1998). Lead usage exceeded 550 g per person per year, with the primary applications being plumbing, architecture, and shipbuilding. Lead salts were used to preserve fruits and vegetables, and lead was also added to wine to stop further fermentation and to add color or bouquet (Nriagu 1983). The use of large amounts of lead in the daily life of Roman aristocracy had a significant impact on their health, including epidemics of plumbism, high incidence of sterility and stillbirths and mental incompetence. Physiological profiles of Roman emperors who lived between 50 and 250 BC suggest that the majority of these individuals suffered from lead poisoning (Nriagu 1983)., It has been claimed that a contributing factor to the fall of the Roman Empire, in AD 476, may have been the excessive use of lead in pottery, water pipes and other sources (Hernberg 2000).

Mercury was used during the Roman Empire to ease the pain of teething infants, as well as to aid in the recovery of gold and silver. Such applications were also widely found in Egypt in the twelfth century and in Central and South America in the sixteenth century (Eaton and Robertson 1994; Silver and Rothman 1995). Mercury was used to treat syphilis during the sixteenth century and in the felting process in the 1800s (Fergusson 1990).

Copper was first used in its native form approximately 7,000 years ago, with significant production beginning some

2,000 years later and eventually peaking at a production rate of about 15,000 tonnes annually during the Roman Empire, when it was used for both military and civilian purposes, especially coinage. A significant drop in the production of copper followed the fall of the Roman Empire, and production remained low until about 900 years ago when a dramatic increase in production occurred in China, reaching a maximum of 13,000 tonnes annually and causing a number health problems (Hong et al. 1994).

Arsenic was used for therapeutic purposes by the ancient Greeks, Romans, Arabs, and Peruvians, because small doses were thought to improve the complexion; however, it has also long been used as a poison (Fergusson 1990). In the sixteenth century, Georgius Agricola (Agricola 1556) described the symptoms of "Schneeberger" disease among miners working in the Erzgebirge of Germany to mine silver in association with uranium. That disease has since been identified as lung cancer deriving from metal dust and radon inhalation.

1.1.2 More Recent Reports

The industrial revolution in Europe and North America encouraged people to quit the poverty of subsistence agriculture in the countryside to live in increasingly crowded cities where they found work in factories, chemical plants and foundries; however, such occupations exposed the workers to higher levels of chemical elements and compounds that, as rural dwellers, they would rarely have encountered. Friedrich Engels wrote graphic descriptions of the ill health of the new English proletariat in his politically seminal book, *The Conditions of the Working Class in England*, published in 1845. He described the plight of children forced to work in the potteries of Staffordshire: "By far the most injurious is the work of those who dip. . .into a fluid containing great quantities of lead, and often of arsenic.... The consequence is violent pain, and serious diseases of the stomach and intestines. . .partial paralysis of the hand muscles. . .convulsions" (Engels 1845). Engels further characterized the conditions of workers in mid-nineteenth century industrial England as "want and disease, permanent or temporary."

The sciences of toxicology and industrial medicine arose in response to the health problems caused by unregulated industrialization. These sciences have provided the clinical data that allow us to understand the consequences of excess exposure to elements in the natural environment, whether it be due to simple exposure to particular rocks or the exploitation of mineral resources. The emergence of modern geological sciences coupled with increasingly powerful analytical techniques laid the foundation for determining the nature and occurrence of trace elements in rocks and sediments. Scientific agriculture has focused attention on inorganic element deficiencies in plants and animals. Modern medicine has provided reliable descriptions of diseases and more accurate diagnoses through internationally recognized nomenclatures.

Rural people have always recognized that the health of domesticated animals is influenced by drinking water or diet and, therefore, soil properties. These observations could not be explained until the advent of scientific agriculture in the nineteenth century, when it required only a small step to suggest that humans may also be caught up in similar relationships. Diseases now known to be caused by a lack or excess of elements in soil and plants were given names that reflected where they occurred, such as Derbyshire neck in the iodine-deficient areas of the English Midlands or Bodmin Moor sickness over the granites of southwest England where cobalt deficiency is endemic in sheep unless treated. It is interesting to note that in Japan, before the 1868 Meiji Restoration, meat was rarely eaten so there was no tradition of animal husbandry. Japanese authors have suggested that this lack of animal indicators largely contributed to the failure to recognize the significance of metal pollution until it became catastrophic.

Archaeologists have also noted links between health and environmental factors. Analysis of bone material has provided an excellent tool for studying the diet and nutritional status of prehistoric humans and animals (Krzysztof and Glab 2001). For example, the transition from a hunter–gatherer society to an agriculturally based economy resulted in a major dietary change and an accompanying iron deficiency. Iron in plants is more difficult to absorb than iron from a meat source; hence, it has been proposed that this new reliance on a crop diet may have resulted in iron deficiency and anemia among the general population (Roberts and Manchester 2007).

Skeletal remains found in Kentucky have provided prime examples of the relationship between geology and ancient human health. Native Americans established permanent settlements in the area and began normal crop cultivation practices. As a result of soil micronutrient deficiencies, their maize contained extremely low levels of zinc and manganese. These deficiencies led to a range of diet-related health effects that have been clearly documented through the study of dental and skeletal pathology in human remains (Moynahan 1979).

Several landmark discoveries in medical geology have been made in Norway. For a long time, Norwegian farmers have been aware of the unusually frequent occurrence of osteomalacia among domestic animals in certain districts, and to combat the disease they initiated the practice of adding crushed bones to the feed of the animals. Some farmers suspected that a particular pasture plant caused osteomalacia, and a Norwegian official named Jens Bjelke (1580–1659), who had an interest in botany and a knowledge of foreign languages, gave the suspected plant the Latin name *Gramen ossifragum* ("the grass that breaks bones"). The name has also been *written Gramen Norwagicum ossifragum*.

One hundred years ago, the geologist J. H. L. Vogt learned of the practice of adding crushed bones to the diets of farm animals and investigated a region where osteomalacia was common. When he found very small amounts of the mineral apatite in the rocks, he drew the logical and correct conclusion that a deficiency of phosphorus was the cause of the osteomalacia. Another Norwegian geologist (Esmark 1823) had previously pointed out that vegetation was extraordinarily sparse over the bedrock which was found by Vogt to be very poor in apatite. Once the cause of the osteomalacia was determined, it became a relatively simple matter to prevent the damage by adding phosphorus fertilizer to the soil (Låg 1990) (see also Chap. 15, this volume).

A significant publication was André Voisin's book, *Soil, Grass and Cancer* (1959), especially in light of today's interest in the dangers of free radicals in cells and the protective effects of antioxidant substances and enzymes. Over 40 years ago, Voisin stressed the protective role of catalase and observed that copper deficiency was accompanied by low cytochrome oxidase activity.

Oddur Eiriksson and Benedikt Pjetursson provided detailed descriptions of the damage to teeth of domestic animals that resulted from the eruption of the Icelandic volcano Hekla in 1693. At that time it was not known that the cause was fluorosis. The relationship between the incidence of fluorine deficiency and dental caries has been carefully studied in Scandinavia since World War II, with attention being particularly centered around the need for fluoridation of water. Analyses of the fluoride content of natural waters from various sources and their relationships to the frequency of caries have been reported from several districts (see also Chap. 10, this volume).

1.2 Geochemical Classification of the Elements

The principles of geochemistry and, hence, medical geology were established at a time when modern analytical techniques were in their infancy and most scientists relied on the very laborious classical chemical approaches. Despite the limitations imposed by a lack of rapid analysis of rocks and soils, the basic principles of geochemistry were known by the start of the twentieth century. In 1908, Frank W. Clarke, of the U.S. Geological Survey, published the original edition of *The Data of Geochemistry*, in which he adopted a systems approach to present his information. Clarke's book was the forerunner of several texts published during the first half of the twentieth century that have helped us understand how geochemistry is linked to health. Arguably the most important text of the period was V. Goldschmidt's *Geochemistry* (1954), which was based on work by Linus Pauling; it was completed by Alex Muir in Scotland and published after Goldschmidt's death in 1947. Two of Goldschmidt's ideas are of special relevance to medical geology: his geochemical classification of the elements and his recognition of the importance of ionic radii in explaining "impurities" in natural crystals.

Table 1.1 Geochemical classification of elements

Group	Elements
Siderophile	Fe, Co, Ni, Pt, Au, Mo, Ge, Sn, C, P
Atmophile	H, N, O
Chalcophile	Cu, Ag, Zn, Cd, Hg, Pb, As, S, Te
Lithophile	Li, Na, K, Rb, Cs, Mg, Ca, Sr, Ba, Al, rare earths (REE)

Goldschmidt's geochemical classification groups elements into four empirical categories (Table 1.1). The *siderophilic* elements are those primarily associated with the iron–nickel (Fe–Ni) core of the Earth; these elements may be found elsewhere to some extent, but this classification explains why, for example, platinum and associated metals are normally rare and dispersed in crustal rocks. This fundamental geochemical observation allowed Alvarez et al. (1980) to recognize the significance of the high iridium contents of clays found at the Cretaceous/Tertiary (K/T) boundary. They proposed the persuasive idea that the impact of an asteroid (Fe–Ni type) on the surface of the Earth could explain the massive species extinctions that define the K/T boundary, including the demise of the dinosaurs. Was this an example of medical geology on a global scale?

The *atmophilic* elements are those dominating the air around us, and *lithophilic* elements are common in crustal silicates (Alvarez et al. 1980). Of special interest are the *chalcophilic* elements, which derive their name from a geochemical grouping of these elements with copper (Greek *χαλκός*). These elements are encountered locally in high concentrations where recent or ancient reducing conditions (and hydrothermal conditions) have led to the reduction of sulfate to sulfide, resulting in the formation of sulfide minerals such as pyrite (FeS_2) and the ores of lead (galena, PbS) or zinc (sphalerite, ZnS). This same thiophilic tendency underlies the toxicity of lead, mercury, and cadmium because they readily link to the —SH groups of enzymes and thereby deactivate them. Goldschmidt's empirical classification of chalcophilic elements is now reinterpreted in terms of hard and soft acids and bases; soft bases (e.g., R—SH or R—S^-) preferentially bind to soft acids (e.g., Cd^{2+} or Hg^{2+}).

Goldschmidt's (and Pauling's) second important concept was the importance of ionic size in explaining both the three-dimensional structures of silicate crystals and how other elements can become incorporated in them. The rules are now generally known as *Goldschmidt's rules of substitution*:

1. The ions of one element can replace another in ionic crystals if their radii differ by less than about 15%.
2. Ions whose charges differ by one unit can substitute provided electrical neutrality of the crystal is maintained.
3. For two competing ions in substitution, the one with the higher ionic potential (charge/radius ratio) is preferred.
4. Substitution is limited when competing ions differ in electronegativity and form bonds of different ionic character.

These rules of substitution and the geochemical classification of elements are fundamental to our growing understanding of medical geology, for they explain many environmental occurrences of toxic elements and allow scientists to predict where such occurrences might be found.

1.3 Contributions to Medical Geology from Public Health and Environmental Medicine

Although most public health problems involve diseases caused by pathogens, inorganic elements and their compounds can also affect public health; among these elements are arsenic, cadmium, and mercury. The effects of mercury on human health can be traced back several centuries. For example, in the sixteenth century and later, mercury and its compounds were widely used to treat syphilis despite its known toxicity (D'itri and D'itri 1977), and mercuric nitrate solution was used to soften fur for hat making. Long-term exposure caused neurological damage in workers handling mercury and gave rise to expressions such as "mad as a hatter" or the "Danbury shakes." In Birmingham, England, buttons were gilded by exposing them to a gold–mercury (Au–Hg) amalgam followed by vaporization of the mercury. By 1891, many tons of mercury had been dissipated around Birmingham, to the great detriment of that city's inhabitants, many of whom suffered from "Gilder's palsy". Neurological damage due to exposure to inorganic mercury compounds was well understood by the end of the nineteenth century. In recent decades there has been concern about environmental levels of mercury in Amazonia, where the amalgamation of gold by mercury in small-scale mining operations has caused widespread mercury pollution

Modern concerns are focussed on methyl mercury, a lipid-soluble organic compound that concentrates up the food chain. Recognition of such a problem resulted from the outbreak of methylmercury poisoning in 1956 in Minamata city in Japan, thus the name used today—Minamata disease (Harada 1995). Subsequently, methylmercury poisoning has been observed in, for example, Niigata (Japan), Sweden, Iraq, and the United States. In the USA mercury emissions from coal burning have led to restrictions on lake and river fishing (EPA 2011).

Concern about environmental cadmium can be traced back to the outbreak of itai itai disease in Japan earlier in the twentieth century (Chaney et al. 1998). The disease resulted in severe bone malformations in elderly women, and a zinc mine in the upper reaches of the Jintsu river was found to be the source of the cadmium that caused the disease. Later, cadmium was found to be linked to kidney damage, and the element was found to build up in soil following the application of some sewage sludges. Many countries now control the land application of sludge and have set limits in terms of permissible cadmium additions (Friberg et al. 1974).

The coloured compounds of arsenic were used as pigments as early as the Bronze Age, and knowledge of its toxicity is just as old. Of concern today are the skin lesions and cancers observed among the millions of people drinking arsenic-rich well water, especially in West Bengal and Bangladesh. As with mercury, links between arsenic and certain cancers were identified early on. Fowler's solution, which contained potassium arsenite, was widely prescribed as a tonic. Patients who believed that if a little of something (a few drops) would do them good then a lot of it must do them a lot of good and tended to overdose on the solution. By the late eighteenth century, it was recognized that injudicious use of Fowler's solution led first to peripheral neuritis, which was followed by skin lesions and cancer (see also Chaps. 12 and 25, this volume).

Coal is a sedimentary rock formed by the diagenesis of buried peats, which, in turn, form from organic debris under wet, reducing conditions. This process favors the precipitation of the sulfides of chalcophilic metals (especially pyrite, FeS_2). Pyrite can contain significant concentrations of arsenic as well as mercury, thallium, selenium, nickel, lead, and cobalt. Incineration of coal releases mercury to the atmosphere; sulfur gases, which cause acid precipitation, and arsenic compounds may also be released or remain in the ash.

In the autumn of 1900, an epidemic of arsenic poisoning occurred among beer drinkers in Manchester, Salford, and Liverpool in England. The poisoning was first traced to the use of sulfuric acid to make the glucose required for the brewing process; apparently, the breweries had unknowingly switched from de-arsenicated acid (sulfuric acid is a valuable by-product of smelting industries, including those dealing with arsenic ores). Additionally, however, malted barley was dried over coal fires, which contributed to the problem. Even moderate beer drinkers suffered from peripheral neuritis and shingles (herpes zoster), which can be induced by arsenic exposure. Arsenic poisoning has recently emerged again in China, where severe arsenic poisoning has been reported in recent years as a result of consumption of vegetables dried over coal fires (Finkelman et al. 1999).

1.4 Development of Medical Geology

1.4.1 The Knowledge Gained from Single-Element Studies

Over the course of the twentieth century, geoscientists and epidemiologists gained a greater understanding of the many ways in which the environment of Earth can affect the health of its inhabitants. Incidents of metal poisoning and the identification of specific relationships between dietary constituents and health became representative examples of more general human reactions to exposures to the geochemical environment. The clearest example of the relationship between geology and health is when the presence of too much or too little of a single element in the environment is found to cause or influence disease as a result of being transferred into the body through dust in the soil or air or via water or food.

Iodine remains the classic success story in medical geology as far as human health is concerned. The most common health effect associated with an iodine deficiency is goiter, a swelling of the thyroid gland. Late in the nineteenth century, it was determined that iodine concentrates in the thyroid gland, but the iodine concentrations were reduced in the thyroids of patients from endemic goitrous areas. Iodine deficiency disorders (IDDs) remain a major threat to the health and development of populations the world over. Clinical treatment of IDDs is, of course, the prerogative of medical doctors; nonetheless, a greater understanding of the conditions leading to IDDs has resulted from the work of geoscientists. (Iodine is described in detail in Chap. 17.)

The study of arsenic remained the province of toxicology and forensic medicine until the middle twentieth century. A paper on arsenic in well water in the Canadian Province of Ontario stated: "The occurrence of arsenic in well water is sufficiently rare to merit description" (Wyllie 1937). Pictures accompanying the text illustrate keratosis on the feet and the palm of a hand. It was concluded in the article that the occurrence of arsenic poisoning from well water was infrequent. Less than 40 years later, however, the scientific world learned of "blackfoot disease" in the Republic of China (Taiwan), and skin disorders and cancer due to arsenic-polluted well water have been described in Chile, Mexico, and Argentina. Serious problems are currently being reported in West Bengal and Bangladesh. In all cases, the geological link is clear (described in detail in Chaps. 12 and 25).

Cobalt deficiency provides a good example of the relationship between animal health and the geological environment. In New Zealand, cobalt deficiency was known as "bush sickness" or Morton Mains disease; in Kenya, as *nakuruitis*; in England, as pining; in Denmark, as *vosk* or *voskhed*; and in Germany, as *hinsch*. The underlying cause was discovered by Dr. Eric Underwood, an early expert in the medical geology field (Underwood and Filmer 1935). His discovery in 1935 of the essentiality of cobalt is an example of triumph over analytical difficulty. Underwood and Filmer showed that "enzootic marasmus" could be cured by treatment with an acid extract of the iron oxide limonite, from which all but negligible quantities of iron had been removed using the laborious methods of classical qualitative analysis. In all cases, the problem can be traced back to a low cobalt content of the soil parent material. Inadequate cobalt is passed up the food chain for microflora in the gut of herbivores to use in the synthesis of the essential cobalt-containing cobalamin or vitamin B_{12}. Only one case of human cobalt deficiency appears to have been published (Shuttleworth et al. 1961). A 16 month-old girl on an isolated Welsh hill farm was a persistent dirt eater and suffered from anemia and behavioral problems. The cattle on the farm were being treated for cobalt deficiency, and the child recovered her health after oral administration of cobaltous chloride.

Lead poisoning has dominated the environmental agenda for several decades. It is interesting to note that geologists were aware of the potential health problems associated with lead when medical opinion on the subject was still mixed. In mid-nineteenth century Britain, residents expressed growing concern about the unregulated disposal of mine and industrial wastes in rivers. In west Wales, farmers complained that lead mining was ruining their fields as a result of the deposition of polluted sediment when rivers flooded. A Royal Commission in 1874 evaluated their complaints, and legislation soon followed (River Pollution Prevention Act, 1878); however, it was too late. Well into the twentieth century, cattle poisoning in the Ystwyth valley of west Wales continued to occur due to the earlier contamination by mines in the previous century. As late as 1938, the recovery of these rivers was monitored, and even in the 1970s evidence of past pollution was still evident (Davies and Lewin 1974). It was the late Professor Harry Warren in Vancouver, Canada, who first recognized the important implications of high levels of environmental lead. He devoted the last 30 years of his professional life to arguing for the significance of lead uptake by garden vegetables and its possible role in the etiology of multiple sclerosis. Warren had pioneered the use of tree twigs in prospecting for mineral ores in British Columbia, Canada, and he was surprised to observe that lead contents were often higher in forests bordering roads and concluded that "industrial salting" was a widespread and serious problem. Nonetheless, until the 1960s, environmental lead remained a mere curiosity. Health problems were thought to occur only from industrial exposure or due to domestic poisoning from lead dissolved by soft water from lead pipes.

Over the past 20 years, the removal of lead from gasoline, food cans, and paint has reduced US population blood lead levels by over 80%. Milestones along the way included evidence that dust on hands and direct soil consumption (pica) by children represented a major pathway of lead exposure (Gallacher et al. 1984). The phasing out of lead in gasoline in the United States was accompanied by a general reduction in blood lead levels (Mahaffey et al. 1982). Adding to the debate was the contention that even relatively low levels of lead exposure could harm the development of a child's brain (Davies and Thornton 1989; Nriagu 1983; Ratcliffe 1981; Warren and Delavault 1971).

The medical geology of selenium provides a good example of the interaction between geology and medicine. In the late 1960s, selenium was shown to be essential for animals and to be an integral part of glutathione oxidase, an enzyme that catalyzes the breakdown of hydrogen peroxide in cells (Prasad 1978). In sheep and cattle, a deficiency in selenium accounted for "white muscle disease" (especially degeneration of the heart muscle), and glutathione peroxidase activity was found to be a good measure of selenium status. The problem was particularly widespread among farm animals in Great Britain (Anderson et al. 1979). Humans have also been shown to suffer from selenium deficiency, and in China this condition is referred to as Keshan disease (Rosenfeld and Beath 1964; Frankenberger and Benson 1994; Frankenberger and Engberg 1998). The disease has occurred in those areas of China where dietary intakes of selenium are less than 0.03 mg/day because the selenium content of the soils is low. The condition is characterized by heart enlargement and congestive heart failure. The disease has been primarily seen in rural areas and predominantly among peasants and their families. Those most susceptible have been children from 2 to 15 years of age and women of child-bearing age (Chen et al. 1980; Jianan 1985). Also, it has been suggested that adequate selenium intake may be protective for cancers (Diplock 1984), and self-medication with selenium supplements has become widespread with the belief that a lack of selenium is a risk factor in heart diseases. (Selenium is described in greater detail in Chap. 16.)

1.4.2 The Importance of Element Interactions is Recognized

The number of productive single-element studies has obscured two fundamental geochemical principles: First, from a geochemistry perspective, elements tend to group together, and, second, the study of physiology recognizes that elements can be synergistic or antagonistic. Cadmium is a good example of both principles. In some environments, soil cadmium levels are high because of rock type (such as black shales) or from mining contamination. A highly publicized polluted environment is that of the village of Shipham, which in the eighteenth century was a thriving zinc mining village in the west of England.

A study in 1979 suggested that 22 out of 31 residents showed signs of ill health that could be traced to cadmium (Carruthers and Smith 1979). As a result, the health of over 500 residents was subsequently assessed and compared with that of a matching control population from a nearby non-mining village, but "there was no evidence of adverse health effects in the members of the population studied in Shipham" (Morgan and Simms 1988, Thornton et al. 1980). Chaney et al. (1998) have commented on the disparity between the reports of ill health in Japan and no-effect observations from other parts of the world: "research has shown that Cd transfer in the subsistence-rice food-chain is unique, and that other food-chains do not comprise such high risk per unit soil Cd" and "Evidence indicates that combined Fe and Zn deficiencies can increase Cd retention by 15-fold compared to Fe and Zn adequate diets…it is now understood that rice grain is seriously deficient in Fe, Zn, and Ca for human needs".

Copper and molybdenum taken individually and together demonstrate the importance of not relying upon simple single-cause relationships. In Somerset (England) there is an area in which pasture causes scouring in cattle. The land is known locally as "teart" and was first reported in the scientific literature in 1862 (Gimingham 1914), but the cause of the disorder (molybdenum) was not ascertained until 1943 (Ferguson et al. 1943), when it was shown that the grass contained 20–200 mg molybdenum per kg (d.m.) and that the disorder could be cured by adding cupric sulfate to the feed. The origin of the excess molybdenum was the local black shales (Lower Lias) (Lewis 1943). Over 20 years later, geochemical reconnaissance of the Lower Lias throughout the British Isles showed that elevated molybdenum contents in soils and herbage were a widespread problem over black shale, regardless of geological age, and that this excess molybdenum was the cause of bovine hypocuprosis (Thornton et al. 1966, 1969; Thomson et al. 1972). A moose disease in Sweden provides another example of the effects of molybdenum, in this case resulting from the interaction of molybdenum with copper.

This disease is covered in detail in Chap. 21 (see also Kabata-Pendias and Pendias 1992; Kabata-Pendias 2001; Adriano 2001).

1.4.3 Mapping Diseases as a Tool in Medical Geology

Medical geology benefits from the work of medical geographers who have mapped diseases in different countries. For some important groups of diseases (e.g., cancers, diseases of the central nervous system, and cardiovascular disease), the causes are by and large uncertain. When the incidence or prevalence of these diseases has been mapped, especially in countries of western Europe, significant differences from place to place have been reported that are not easily explained by genetic traits or social or dietary differences. Howe (1963) pioneered the use of standardized epidemiological data in his 'National Atlas of Disease Mortality in the United Kingdom'. His stomach cancer maps clearly identified very high rates in Wales. Environmental influences appear to be involved in the etiologies, and a role for geology has been suggested by many authors (see, for example, Chap. 14). An early study of gastrointestinal cancer in north Montgomeryshire, Wales (Millar 1961) seemed to show an association with environmental radioactivity because local black shales were rich in uranium. There was no direct evidence to support the hypothesis, and the study was marked by a problem of earlier work—namely, an indiscriminate use of statistics. Work in 1960 in the Tamar valley of the west of England appeared to show that mortality from cancer was unusually low in certain villages and unusually high in others (Davies 1971). Within the village of Horrabridge, mortality was linked to the origin of different water supplies: The lowest mortality was associated with reservoir water from Dartmoor, whereas the highest mortality was associated with well or spring water derived from mineralized rock strata. Although this study was again statistically suspect, it stimulated a resurgence of interest in the link between cancer and the environment.

Stocks and Davies (1964) sought direct associations between garden soil composition and the frequency of stomach cancer in north Wales, Cheshire, and two localities in Devon. Soil organic matter, zinc, and cobalt were related positively with stomach cancer incidence but not with other intestinal cancer. Chromium was connected with the incidence of both. The average logarithm of the ratio of zinc/copper in garden soils was always higher where a person had just died of stomach cancer after 10 or more years of residence than it was at houses where a person had died similarly of a nonmalignant cause. The effect was more pronounced and consistent in soils taken from vegetable gardens, and it was not found where the duration of residence was less than 10 years.

Association is not necessarily evidence for cause and effect. For mapping approaches to be reliable, two conditions must be satisfied. First, it is essential to be able to show a clear pathway from source (e.g., soil) to exposure (e.g., dirt on hands) to assimilation (e.g., gastric absorption) to a target organ or physiological mechanism (e.g., enzyme system). The second condition, rarely satisfied, is that the hypothetical association must be predictive: If the association is positive in one area, then it should also be positive in a geologically similar area; if not, why not? This condition is well illustrated by fluoride and dental caries—environments where fluoride is naturally higher in drinking water have consistently proved to have lower caries rates.

A possible link between the quality of water supply, especially its hardness, was the focus of much research in the 1970s and 1980s. This was noticed, for example, in Japan in 1957. A statistical relationship was found between deaths from cerebral hemorrhage and the sulfate/carbonate ratio in river water which, in turn, reflected the geochemical nature of the catchment area. In Britain, calcium in water was found to correlate inversely with cardiovascular disease, but the presence of magnesium did not; thus, hard water may exercise some protective effect. Attention has also been paid to a possible role for magnesium, because diseased heart muscle tissue is seen to contain less magnesium than healthy tissue. Still, it has to be pointed out that hard waters do not necessarily contain raised concentrations of magnesium; this occurs only when the limestones through which aquifer water passes are dolomitized, and most English limestones are not. More details can be found in Chap. 14.

Mapping diseases has also been a valuable tool for a long time in China, where pioneering work has been done by Tan Jianan (1989). Modern mapping techniques are now widely used in medical geology; mapping and analytical approaches to epidemiological data are covered in Cliff and Haggett (1988), while discussions on using GIS and remote sensing, as well as several examples, are offered in Chaps. 28 and 29.

1.4.4 Dental Health Provides an Example of the Significance of Element Substitutions in Crystals

Dental epidemiology has provided some of the most convincing evidence that trace elements can affect the health of communities (Davies and Anderson 1987). Dental caries is endemic and epidemic in many countries, so a large population is always available for study. Because diagnosis relies upon a noninvasive visual inspection that minimizes ethical restrictions, a high proportion of a target population can be surveyed. Where the survey population is comprised of children (typically 12 year olds), the time interval between supposed cause and effect is short, and it is possible to make direct associations between environmental quality and disease prevalence. In the case of fluoride, a direct link was established over 50 years ago that led to the successful fluoridation of public water supplies. This is an example of medical geology influencing public health policy. The relationship between dental caries and environmental fluoride, especially in drinking water, is probably one of the best known examples of medical geology. So strong is the relationship that the addition of 1 mg of fluoride per liter to public water supplies has been undertaken regularly by many water utilities as a public health measure.

The history of the fluoride connection is worth recounting. In 1901, Dr. Frederick McKay opened a dental practice in Colorado Springs, Colorado, and encountered a mottling and staining of teeth that was known locally as "Colorado stain." The condition was so prevalent that it was regarded as commonplace but no reference to it could be found in the available literature. A survey of schoolchildren in 1909 revealed that 87.5% of those born and reared locally had mottled teeth. Inquiries established that an identical pattern of mottling in teeth had been observed in some other American areas and among immigrants coming from the volcanic areas of Naples, Italy. Field work in South Dakota and reports from Italy and the Bahamas convinced McKay that the quality of the water supply was somehow involved in the etiology of the condition. He found direct evidence for this in Oakley, Idaho, where, in 1908, a new piped water supply was installed from a nearby thermal spring and, within a few years, it was noticed that the teeth of local children were becoming mottled. In 1925, McKay persuaded his local community to change their water supply to a different spring, after which stained teeth became rare.

A second similar case was identified in Bauxite, Arkansas, where the water supply was analyzed for trace constituents, as were samples from other areas. The results revealed that all the waters associated with mottled teeth had in common a high fluoride content 2–13 mg of fluoride per liter. In the 1930s, it was suggested that the possibility of controlling dental caries through the domestic water supply warranted thorough epidemiological-chemical investigation. The U.S. Public Health Service concluded that a concentration of 1 mg fluoride per liter drinking water would be beneficial for dental health but would not be in any way injurious to general health. Fluoride was first added to public water supplies in 1945 in Grand Rapids, Michigan. Fluoridation schemes were subsequently introduced in Brantford, Ontario (1945); Tiel, The Netherlands (1953); Hastings, New Zealand (1954); and Watford, Anglesey, and Kilmarnock in Great Britain (1955). There is no doubt that whenever fluorides have been used a reduction in the prevalence of dental caries follows (Davies and Anderson 1987; Leverett 1982) (see also Chap. 13, this volume).

1.5 An Emerging Profession

The field of medical geology (or geomedicine) has developed around the world over the last few decades. The development of activities and the organizational structure of medical geology in a number of regions will be discussed in this section, including the United States, Great Britain, Scandinavia, some African countries, and China.

As research interest in medical geology grew during the 1960s, the desire emerged for conference sessions or even entire conferences dedicated to the subject. The late Dr. Delbert D. Hemphill of the University of Missouri organized the first Annual Conference on Trace Substances in Environmental Health in 1967, and these meetings continued for a quarter of a century. Early in the 1970s, several countries took the initiative to organize activities within the field of medical geology, and a symposium was held in Heidelberg, West Germany, in October 1972. In the United States, Canada, and Great Britain, research on relationships between geochemistry and health were carried out, and the Society for Environmental Geochemistry and Health (SEGH) was established. Geochemistry has for a long time maintained a strong position in the former Soviet Union, and basic knowledge of this science is routinely applied to medical investigations. Medical geology has a long tradition in northern Europe, and the development of this emerging discipline in Scandinavia has been strong. In Norway, too, geochemical research has been regarded as important for quite some time.

In North America in the 1960s and 1970s, a number of researchers made important contributions to our understanding of the role of trace elements in the environment and their health effects; among these are Helen Cannon and Howard Hopps (1972), H. T. Shacklette et al. (1972), and Harry V. Warren (1964). A meeting on environmental geochemistry and health was held and sponsored by the British Royal Society in 1978 (Bowie and Webb 1980). Another landmark date was 1979, when the Council of the Royal Society (London) appointed a working party to investigate the role in national policy for studies linking environmental geochemistry to health. This was chaired by Professor S. H. U. Bowie of the British Geological Survey (Bowie and Thornton 1985). In 1985, the International Association of Geochemistry and Cosmochemistry (IAGC) co-sponsored with the Society for Environmental Geochemistry and Health (SEGH) and Imperial College, London, the first International Symposium on Geochemistry and Health (Thornton 1985). In 1985 Professor B E Davies became editor of a journal then titled 'Minerals and the Environment', rebranded it as 'Environmental Geochemistry and Health' (Davies 1985) and formally linked it with SEGH. The journal is now published by Springer under the editorship of Professor Wong Ming Hung and is in its 34th volume.

In 1987, a meeting on geochemistry and health was held at the Royal Society in London, and in 1993 a meeting on environmental geochemistry and health in developing countries was conducted at the Geological Society in London (Appleton et al. 1996).

Traditionally, the terms *geomedicine* and *environmental geochemistry and health* have been used. Formal recognition of the field of geomedicine is attributed to Ziess, who first introduced the term in 1931 and at the time considered it synonymous with *geographic medicine*, which was defined as "a branch of medicine where geographical and cartographical methods are used to present medical research results." Little changed until the 1970s, when Dr. J. Låg, of Norway, redefined the term as the "science dealing with the influence of ordinary environmental factors on the geographic distribution of health problems in man and animals" (Låg 1990).

The Norwegian Academy of Science and Letters has been very active in the field of medical geology and has arranged many medical geology symposia, some of them in cooperation with other organizations. The proceedings of 13 of these symposia have been published. Since 1986, these symposia have been arranged in collaboration with the working group Soil Science and Geomedicine of the International Union of Soil Science. The initiator of this series of meetings was the late Dr. Låg, who was Professor of Soil Science at the Agricultural University of Norway from 1949 to 1985 and who was among the most prominent soil scientists of his generation, having made significant contributions to several scientific disciplines. During his later years, much of Dr. Låg's work was devoted to medical geology, which he promoted internationally through his book (Låg 1990).

The countries of Africa have also experienced growth in the field of medical geology. The relationships between the geological environment and regional and local variations in diseases such as IDDs, fluorosis, and various human cancers have been observed for many years in Africa. Such research grew rapidly from the late 1960s, at about the same time that the principles of geochemical exploration began to be incorporated in mineral exploration programs on the continent. In Africa, evidence suggesting associations between the geological environment and the occurrence of disease continues to accumulate (see, for example, Davies 2003, 2008; Davies and Mundalamo 2010), but in many cases the real significance of these findings remains to be fully appreciated. The reasons are threefold: (1) the paucity of reliable epidemiological data regarding incidence, prevalence, and trends in disease occurrence; (2) the lack of geochemists on teams investigating disease epidemiology and etiology; and (3) a shortage of analytical facilities for measuring the contents of nutritional and toxic elements at very low concentration levels in environmental samples (Davies 1996). Confronting these challenges, however, could prove to be exceedingly rewarding, for it is thought that the strongest potential significance of such correlations exists in Africa and other developing regions of the world. Unlike the developed world, where most people no longer eat food grown only in their own area, most of the people in Africa live close to the land and are exposed in their daily lives, through food and water intake, to whatever trace elements have become concentrated (or depleted) in crops from their farms (Appleton et al. 1996; Davies 2000).

The first real attempt to coordinate research aimed at clarifying these relationships took place in Nairobi in 1999, when the first East and Southern Africa Regional Workshop was convened, bringing together over 60 interdisciplinary scientists from the region (Davies and Schlüter 2002). One outcome of this workshop was the constitution of the East and Southern Africa Association of Medical Geology (ESAAMEG), establishing it as a chapter of the International Medical Geology Association (IMGA). The Geomed 2001 workshop held in Zambia testified to the burst of interest and research activities generated by that first workshop (Ceruti et al. 2001). As a result of this increasing awareness of medical geology problems around the continent, membership and activities of the ESAAMEG have continued to grow. This is a welcome sign on both sides of what has hitherto been an unbridged chasm between geology and health in Africa.

China has a long history of medical geology. Chinese medical texts dating back to the third century BC contain several references to relationships between geology and health. During both the Song Dynasty (1000 BC) and the Ming Dynasty (fourteenth to seventeenth century), lung ailments related to rock crushing and symptoms of occupational lead poisoning were recognized. Similarly, as noted earlier, the Tang Dynasty alchemist Chen Shao-Wei stated that lead, silver, copper, antimony, gold, and iron were poisonous.

In the twentieth century, much research has been carried out in China (for example, on the selenium-responsive Keshan and Kashin Beck diseases) that has resulted in clarification of the causes of a number of diseases, including endemic goiter and endemic fluorosis. One of the centers for this research has been the Department of Chemical Geography at the Chinese Academy of Sciences. At this institute, several publications have been produced, such as *The Atlas of Endemic Diseases and Their Environments in the People's Republic of China* (Jianan 1985). Also the Institute of Geochemistry in Guiyang in Southern China is known for its studies in the field that is now referred to as medical geology.

International Medical Geology Association, IMGA, (Fig. 1.1) (www.medicalgeology.com) in its present form was founded in January 2006, but began as an idea 10 years before in 1996 when a working group on Medical Geology

Fig. 1.1 International Medical Geology Association, IMGA

was established by International Union of Geological Sciences (Skinner and Berger 2003). Its primary aim was to increase awareness among scientists, medical specialists and the general public on the importance of geological factors for health and wellbeing. It was recognised that the limited extent of cooperation and communication among these groups restricted the ability of scientists and public health workers to solve a range of complex environmental health problems. The term "Medical Geology" was adopted in 1997.

A first short course on Medical Geology was carried out in Lusaka, Zambia and at the University of Zambia. It was decided that the short course would be brought to developing countries which faced critical Medical Geology problems. This proposal was supported by the International Commission on Scientific Unions (ICSU) and later on UNESCO in support of short courses in Medical Geology to be held in 2002–2003. Since 2001 short courses in medical geology have been held in more than 50 countries.

A first Hemispheric Conference on Medical Geology was organized in Puerto Rico in 2005. The International Medical Geology Association, IMGA, was established 2006. This year also a special symposium on Medical Geology was held at the Royal Academy of Sciences in Stockholm. The 2nd Hemispheric Conference on Medical Geology was held in Atibaya, Brazil in 2007. United Nations announced in 2008 Medical Geology as one of the themes of the International Year of Planet Earth. IMGA also had several sessions and a short course at the 33 International Geological Conference in Oslo with 7,000 participants. In 2009 IMGA was involved in 'Mapping GeoUnions to the ICSU Framework for Sustainable Health and Wellbeing' as full members. The 3rd Hemispheric Conference on Medical Geology was held in Montevideo, Uruguay and in 2011 the 4th International conference in medical geology was organised in Italy with more than 400 participants.

The development of medical geology has been tremendous and education has started at several universities and medical geology is on the agenda all over the world with many active local chapters spread in all continents (Selinus et al. 2010).

1.6 Prospects

As we progress into the early years of the twenty-first century, it can be safely claimed that medical geology has emerged as a serious professional discipline. If respect for medical geology as a discipline is to continue to grow, then future studies must go well beyond simplistic comparisons of geochemical and epidemiological data. Dietary or other pathways must be traced and quantified and causative roles must be identified with regard to target organs or body processes. Moreover, studies must become predictive. Occasionally, simple direct links between geochemistry and health may be identified, but even in these instances confounding factors may be present (for example, the possible role of humic acids in arsenic exposure or the established role of goitrogenic substance in goiter). Ordinarily, geochemistry will provide at best only a risk factor: Unusual exposures, trace element deficiencies, or elemental imbalances will contribute toward the disturbance of cellular processes or activation of genes that will result in clinical disease. The problem of geographical variability in disease incidence will remain.

Rapid growth in the field of medical geology is predicted, as it is a discipline that will continue to make valuable contributions to the study of epidemiology and public health, providing hyperbole is avoided and a dialogue is maintained among geochemists, epidemiologists, clinicians, and veterinarians.

The structure of all living organisms, including humans and animals, is based on major, minor, and trace elements—given by nature and supplied by geology. The occurrence of these gifts in nature, however, is distributed unevenly. The type and quantity of elements vary from location to location—sometimes too much, sometimes too little. It is our privilege and duty to study and gain knowledge about natural conditions (e.g., the bioavailability of elements essential to a healthy life), and the field of medical geology offers us the potential to reveal the secrets of nature.

See Also the Following Chapters. Chapter 10 (Volcanic Emissions and Health) • Chapter 12 (Arsenic in Groundwater and the Environment) • Chapter 13 (Fluoride in Natural Waters) • Chapter 14 (Water Hardness and Health Effects)

• Chapter 15 (Bioavailability of Elements in Soil) • Chapter 16 (Selenium Deficiency and Toxicity in the Environment) • Chapter 17 (Soils and Iodine Deficiency) • Chapter 21 (Animals and Medical Geology) • Chapter 25 (Environmental Pathology) • Chapter 28 (GIS in Human Health Studies) • Chapter 29 (Investigating Vector-Borne and Zoonotic Diseases with Remote Sensing and GIS).

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Geomedical aspects in present and future research (1980)
Geomedical research in relation to geochemical registrations (1984)
Geomedical consequences of chemical composition of freshwater (1987)
Commercial fertilizers and geomedical problems (1987)
Health problems in connection with radiation from radioactive matter in fertilizers, soils, and rocks (1988)
Excess and deficiency of trace elements in relation to human and animal health in Arctic and Subarctic regions (1990)
Human and animal health in relation to circulation processes of selenium and cadmium (1991)
Chemical climatology and geomedical problems (1992)
Geomedical problems related to aluminum, iron, and manganese (1994)
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