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Medical geology: new relevance in the earth sciences

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The interdisciplinary field of "Medical Geology" responds to the need to better understand the relationships between human health and our surrounding environment. The influence of earth resources, natural environmental factors and land-use on human health has long been recognized, dating back to ancient Rome and Peru's Inca civilization. Today links between the natural environment and health can be found throughout the world. This review introduces the historical context of this particular type of research, contrasts the direct geological and indirect natural hazard influences on health as a framework of study, elaborates on pathways of elemental accumulation in the body and provides examples of specific geochemical behaviours and diseases that are often associated with either too much or not enough of certain elements which comprise the Earth.

Introduction

Recently the relation between adverse health effects and heavy metals in our environment has gained considerable attention in various professional journals as well as in the broader public media. Heavy metals or potential pollutants have been termed 'geogenic contaminants' and include such elements as As, Pb, Cd and Hg. Elevated levels of these and other potential pollutants have been recorded in many areas of the world including Canada, USA, India, China and Bangladesh to name a few examples (Figure 1). The recognition that an intimate relationship exists between geology, as measured by geochemistry, and human/animal health, has led to the development of a new field of science called Medical Geology.

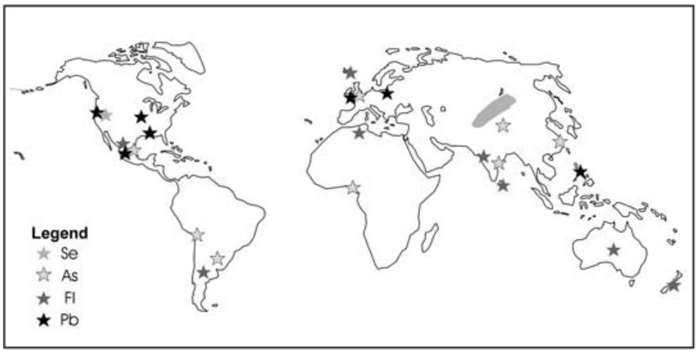


Figure 1 A map of the world indicating some areas that have experienced adverse health effects due to heavy metals.

For the purpose of this review **Medical Geology** is defined as *the science dealing with the relationship between geological factors and health problems in humans, animals and plants* (*cf.* Selinus 2002; Finkelman *et al*. 2001). Medical geology is also known as geomedicine, but medical geography on the other hand has had a slightly different meaning that is related to the broader field of medical geology. Medical geography looks at the geographical distribution of disease while not focusing on the underlying geology; it examines the causal associations between specific diseases and the physical and social environments (Foster, 2002). The field of study is complex and requires a multidisciplinary approach using a wide variety of specialists from geologists, geochemists and medical doctors to veterinarians and biologists.

Formal recognition of the sub-discipline appears to reside with Ziess who first introduced the term 'geomedicine' in 1931, and at the time considered it synonymous with 'geographic medicine' which was defined "a branch of medicine where geographical and cartographical methods are used to present medical research results" (Lag 1990, p. 5). Little changed until the 1970's when Lag (1990, p.6) redefined the term geomedicine as "the science dealing with the influence of ordinary environmental factors on the geographic distribution of health problems in man and animals".

This paper provides a general overview of the field of Medical Geology. The purpose of this review serves to introduce the reader to the historical context of this particular type of research, contrast the direct geological and indirect natural hazard influences on health as a framework of study, elaborate on pathways of elemental accumulation in the body and provide examples of specific element behaviours and diseases that are often associated with either too much or not enough of some elements which comprise the Earth. For a detailed treatment of medical geology the reader is encouraged to examine the treatise entitled Medical Geology: *Earth Science in Support of Public Health Protection* (Selinus, 2004).

Background

Ensuring human, animal and plant health requires accessibility to both essential (e.g. Cr, Cu, Fe, Ca, Se) and non-essential (e.g. toxic Pb, As, Hg) elements. Such elements occur in varying concentrations and forms throughout the atmosphere, lithosphere and hydrosphere. As a result, plants, animals and humans are regularly exposed to these and other elements. With respect to each essential element, all organisms depend on a specific range of tolerance or adequate range of exposure that is safe. Deficient or excess levels of concentration for the essential elements can lead to adverse health effects, and in certain cases, death. The concentration values of the elements are represented in a 'dose response curve', which is a graphical representation indicating the ideal amount of an element needed for maintaining good health, as well as amounts contributing to deficiency or toxicity levels (Figure 2). As expected the dose response curve for any given element may differ from organism to organism, but the underlying principle of deficiency, ideal concentration and toxicity remains constant. For example, V is essential for photosynthesis by blue green algae, and yet this element is highly toxic to humans. Similarly, Co is required for fixing N2 in blue-green algae and other microorganisms, however, it is unknown if it is needed in higher plants (Kabata-Pendias, 2001).

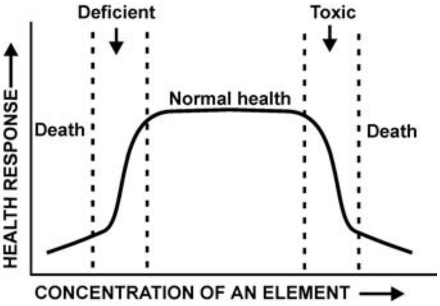


Figure 2 A generalized dose response curve.

History

The intimate relationship between geology and health has long been known. Ancient philosophers and physicians in countries such as Greece and China long-ago realized the importance of how geology influences health; although, it was not until the advent of modern medicine in the 19th century that actual elements essential to health were finally recognized.

The Greek philosopher Hippocrates (400 B.C.) is considered by most scientists to be the founder of medical geology. He recognized that environmental factors affected the distribution of disease (Lag, 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". Another example is that of Vitruvius, a Roman architect in the last century B.C., who recognized potential health dangers related to mining, noting that the water and pollution near mines posed negative 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 noted acid mists are often associated with the extraction of Cu from the ground (cited in Lindberg, 1992).

Chinese medical texts dating back to the 3rd century B.C. contain several relationships between geology and health. During both the Song Dynasty (1000 B.C.) and the Ming Dynasty (14–17th Century) lung problems related to rock crushing and symptoms of occupational Pb poisoning were recognized. Similarly, the Thang Dynasty alchemist Chen Shao-Wei stated that Pb, Ag, Cu, Sb, Au and Fe were poisonous (cited in Liang *et al*., 1998).

Contemporary archaeologists, osteologists and historians provide us with evidence that poor health reflected in the tissues of prehistoric cadavers and mummies can be often be linked to past detrimental environmental conditions. Goitre for instance, the result of severe I deficiency was widely prevalent in ancient China, Greece, Egypt as well as in the Inca state of Peru. This condition was often treated with seaweed, a high source of I, and indicates some degree of knowledge that these ancient civilizations had relating the treatment of dietary deficiencies through the use of natural supplements (Selinus, 2002).

Besides element deficiencies the use of heavy metals in everyday ancient society introduced the negative affects of toxicity related problems. Although the relationship between Pb and a variety of health risks are now well documented in modern society, the relationship has been less well known in the past. Lead has been exploited for over six millennia, with significant production beginning about 5000 years ago and increasing proportionately through the Copper, Bronze and Iron Ages, finally peaking about 2000 years ago (Hong *et a*l., 1994 and Nriagu, 1998). Several descriptions of Pb poisoning found in text from past civilizations further corroborate the heavy uses of Pb. Clay tablets from the Middle and Late Assyrian periods (1550 to 600 B.C.) provide accounts of Pb poisoning symptoms, as do ancient Egyptian medical papyri and Sanskrit texts dating to over 3000 years ago (Nriagu, 1983). During the Roman Empire it has been estimated that the annual production of Pb approached 80,000 tonnes (Hong *et al*., 1994 and Nriagu, 1996). Total production of Pb from 2000 years ago to about 1000 years ago is estimated at 29 million tonnes, indicating that about 24% of discovered Pb reserves were mined in ancient times (Nriagu, 1998). Copper, Zn and Hg were also mined extensively during the Roman Empire with an estimated annual production of about 14,000 tonnes, 9,000 tonnes and >2 tonnes, respectively (Nriagu, 1996). During the Roman Empire Pb usage exceeded 550 grams per person per year. The main sources being plumbing, architecture and shipbuilding. Lead salts were used to preserve fruits and vegetables and Pb was also added to wine to stop further fermentation and to add colour or bouquet (Nriagu, 1983). Large amounts of Pb usage in the daily life of Roman aristocracy had a number of negative health implications, including: epidemics of plumbism and saturnine gout, high incidence of sterility and stillbirths as well as mental incompetence. Physiological profiles of Roman Emperors dating between 50 B.C. and 250 B.C. suggest that the majority of individuals suffered from Pb poisoning (Nriagu, 1983). In turn, it is generally believed that a contributing factor to the fall of the Roman Empire, in 476 A.D., may have been the result of the excessive use of Pb (Hong *et al*., 1994). Following the Fall of the Roman Empire there was a dramatic decrease in Pb production due to the lack of deposits, such that during Medieval times production was as low as a few thousand tons per year before it again rose with the discovery of Pb and Ag deposits in Central Europe in about 1000 A.D. (Hong *et al*., 1994) (Figure 3).

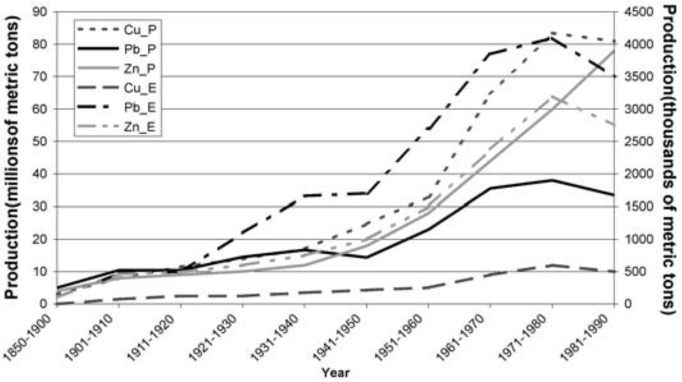


Figure 3 A graph indicating the production and emission of Pb, Cu and Zn through time (modified after Nriagu, 1996).

Besides Pb, other elements including Hg, Cu and As were also widely used in Roman and pre-Roman times (Fergusson, 1990). For instance, Hg was used during the Roman Empire to ease the pain of teething infants as well as in the recovery of Au and Ag, a method also widely used in Egypt in the 12th century and in Central and South America in the 16th century (Eaton and Robertson, 1994; Silver and Rothman, 1995). Mercury was also used to treat syphilis during the 16th century and in the felting process in the 1800's (Figure 4) (Fergusson, 1990).

Figure 4 During the 1800's mercury nitrate was used in the felting process, long term exposure led to Hg poisoning, thus the expression "Mad as a Hatter".

Copper, on the other hand, was first used in its native form approximately 7000 years ago, with significant production starting some 2000 years later, and eventually peaking at a production rate of about 15000 tonnes annually during the Roman Empire where it was used for both military and civilian purposes, especially coinage. As with Pb, there was a significant drop in the production of Cu following the fall of the Roman Empire remaining low until about 900 years ago when there was a dramatic increase in production in China reaching a maximum of 13000 tonnes annually (Hong *et al*., 1996).

Greeks, Romans, Arabs and Peruvians used As for therapeutic purposes, since small doses were thought to improve the complexion; however, it has also long been used as a poison (Fergusson, 1990). Selenium is another element with a number of associated health issues, especially recognized in China where there are both toxic and deficient regions of the element. Marco Polo during his travels in 1275 to China noted that some horses of certain regions suffered from an inexplicable and debilitating disease; this disease pattern is now linked to those regions that are high in Se (Selinus, 2002).

Along with the written records of "medical geology", archaeologists have also noted links between health and environmental factors. Analysis of elements in bone material has provided an excellent tool to study the diet and nutritional status of the past humans and animals (Krzysztof and Glab, 2001). For instance, the transition from a hunter gather society to an agriculturally based economy resulted in a major dietary change and an accompanying Fe deficiency in some populations. 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 Fe deficiency and anaemia amongst the general populace (Roberts and Manchester, 1995).

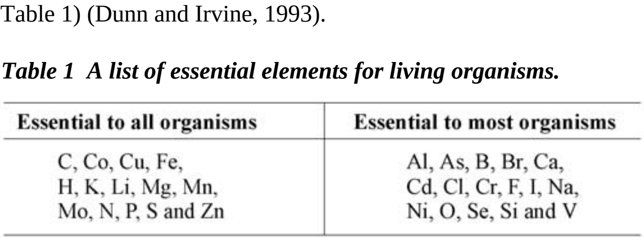
Skeletal remains found in the Kentucky Blue Grass area in the southeastern United States provide a prime example of the relationship between geology and human health. The area is blanketed by mineral deficient soils and animals present in the region avoid feeding there given the lack of available nutrients. Native Americans however, established permanent settlements in the area and began normal crop cultivation practices. As a result of the soil mineral deficiency, the maize produced was extremely low in Zn and Mn. The deficiencies led to a range of diet-related health effects that have been clearly documented through the study of dental and skeletal pathology in the human remains (Moynahan, 1979).

After first being observed in China in the 1930's, Keshan disease (a potentially fatal form of cardiomyopathy due to Se deficiency) was eventually linked in the 1970's to low concentrations of Se in the environment (Selinus, 2002).

By the 20th Century, links of environmental factors to various diseases and disorders led to the recognition that trace elements are essential to human, animal and plant health. In the early 1900's the link between drinking water containing a high F content and the disease called 'fluorosis' (the mottling of teeth and in extreme cases skeletal changes characterized by osteosclerosis and ligamental calcification) was determined. Leaching of rocks, dissolution of fluorides from volcanic gases, fresh and mineral springs and marine aerosols are all possible sources for F in surface and ground waters. The normal level of F is generally regarded as lying between 0.1 and 1 ppm, but in some areas of the world (e.g. parts of India, China and Africa) levels as high as 40 ppm have been recorded and shown to be responsible for serious dental and skeletal fluorosis (Selinus, 2002).

By the late 1950's, nine trace elements were recognised as essential to higher life. The number of essential elements grew to 14 in the 1970's and to 20 by the 1980's. Today there are 30 elements considered essential for the health and survival of living organisms (Table 1) (Dunn and Irvine, 1993).

Table 1 A list of essential elements for living organisms.



Essential to all organisms	Essential to most organisms
C, Co, Cu, Fe, H, K, Li, Mg, Mn, Mo, N, P, S and Zn	Al, As, B, Br, Ca, Cd, Cl, Cr, F, I, Na, Ni, O, Se, Si and V

Medical geology branches

Medical geology can be split into two primary branches based on the number and variability of element sources within the environment. The first branch is strictly related to the natural occurrence of elements in the geologic environment (e.g., ingestion of food grown in soils with either element deficiencies or toxicities), whereas the second branch relates to elemental occurrence relative to natural hazards (e.g., earthquakes, volcanic eruptions, flooding and landslides).

Geology

The geology of an area has a direct impact on the regional input of elements into the soil, air and water. In turn, these inputs, depending on composition, may result in adverse health effects in humans, animals and/or plants. Health issues related to a region's geology are visible in both humans and animals on almost every continent, and can range from As contaminated groundwater in Bangladesh to molybdenosis in Canadian cattle (Hastings *et al*., 1999). Today, the diverse geographical and geochemical source of human foods in developed nations creates a "homogenized diet" reflecting materials grown on a range of soil types, each with different chemical characteristics and potentially imported from a number of countries. As a result of this complex sourcing mechanism, element deficiencies or toxicities are generally rare in regards to dietary intake. Additionally, element imbalances in the soil are often amended before the growth of crops, thus eliminating any subsequent problems (Underwood, 1979; Plant *et al*., 1998). Thus, trace element deficiencies and/or toxicities that are a result of geological conditions are much easier to identify in animals and people in developing countries since much of the food and water ingested is obtained directly from the surrounding environment. A few examples will illustrate the effects of geology on the geochemical environment.

Arsenic

Areas which contain high levels of As in the groundwater are found all over the world, however, the Bengal Basin in India represents one of the largest problems, with an estimated 40 million individuals drinking water with elevated and potentially dangerous levels of As. The affected aquifers are situated in highly reducing environments which favour the mobilization of As. In general, the aquifers are shallow and consist of micaceous sand, silt and clay of Holocene age, capped by a layer of clay or silt and recent solid organic matter. Health problems were first identified in the 1980's, however, the first official diagnosis was not made until 1993. The dominant resulting health problems in the region are skin disorders (e.g., changes in skin pigmentation and keratosis) (Smedly and Kinniburgh, 2002).

Molybdenum

Elevated natural levels of molybdenum in the soil pose a serious health concern for grazing livestock in several areas around the world if it leads to Molybdenosis. Livestock that ingest elevated levels of Mo are unable to absorb Cu; and the resulting Cu deficiency may lead to growth or reproductive problems. Molybdenosis has been documented in impala of Lake Nakura National Park, Kenya and in cattle of Fort Fraser, British Columbia, Canada.

In the case of Lake Nakura National Park, the park is situated in a rift valley consisting of a Tertiary-Quaternary volcanic suite and associated alkaline sediments. Sodication is the predominant pedogenic process; the resulting alkaline solonetz soil thus has a low concentration of several essential trace elements. This low trace element status in combination with high pH has resulted in elevated levels of Mo in the surface vegetation, which in turn, helps explain the Cu deficiency found in the park impala population (Maskall and Thornton, 1996) (Figure 5).

Similar problems are evident for cattle near Fort Fraser, British Columbia, however the geologic process resulting in elevated values

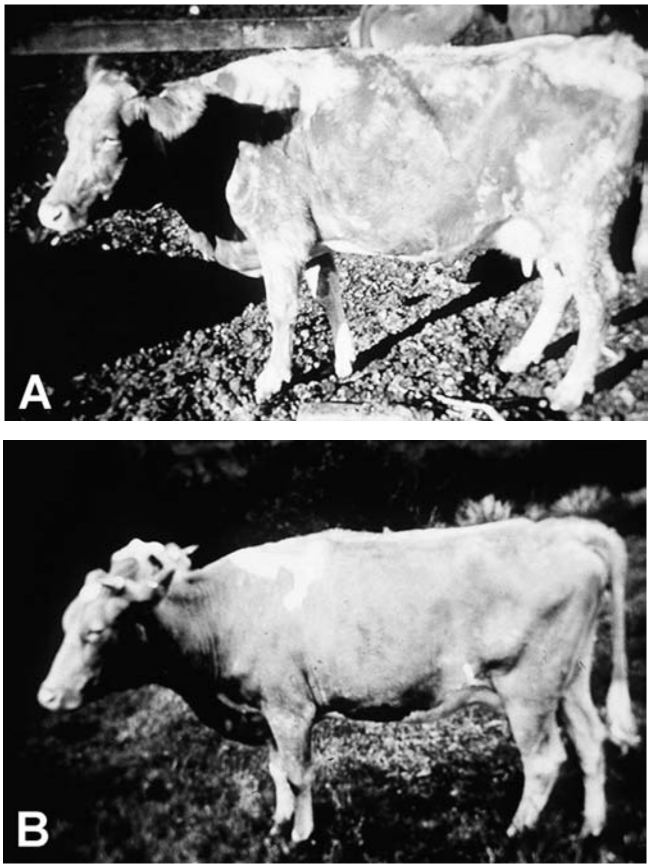


Figure 5 The effect of Cu deficiency: (A) A Cu deficient cow, note the rough hair and patches of lost hair; (B) the same cow after Cu therapy.

of Mo is different. This region of Canada contains a number of isolated molybdenum rich deposits, but a history of extensive glaciations and recent mining activity has resulted in expansive areas of soils containing widely distributed elevated levels of Mo. The enriched soils are extensively used for ranching and farming, thus exposing cattle to plants enriched in Mo, resulting in extensive molybdenosis in the cattle (Hastings *et al*., 1999).

Radon

Radon exposure provides an example of the relationship between geology and negative human health implications. Radon gas, a decay product of uranium, easily migrates through soil and in turn may leak into houses through cracks and drains making it a significant potential health threat of natural radiation (Philp, 1995). Although radon concentrations in the air tend to be very low due to a quick dilution, concentrations can become dangerously high in poorly ventilated buildings. The most common risk associated with radon exposure is lung cancer (Appleton and Ball, 2002).

Natural Hazards

The threat to health commonly associated with a natural disaster is some form of bodily harm or even death. And the type of natural hazard influences the extent of the impact on health. For example, volcanoes and earthquakes can directly, through the ejection of ash and magma, and indirectly, through the triggering of landslides, input and mobilize elements into the environment that may have immediate health implications or lead to long term or delayed health problems, usually depending on the amount and concentration of the particular elements. A direct risk can also transform into an indirect risk, for instance volcanic ash fall directly affects an organism's lungs but in settling, it introduces new elements into the surrounding environment, possibly contributing hazardous elements into the food chain.

Volcanism and related hydrothermal activity are the principle processes that bring metals and other potentially dangerous pollutants to the surface from deep within the earth. Trace elements such as Se, Pb, Cd, Cu, Zn and As are so abundant in plumes of quiescent or passive volcanoes, that they commonly become minor or major elements. The annual global release of such elements is estimated at 9000 tonnes (Hinkley *et al*., 1999). However, one explosive eruption can introduce a large incredible volume of elements into the surface environment. For example, during the eruption of Mt. Pinatubo in June of 1991 an estimated 10 billion tonnes of magma was released to the surface and about 20 million tonnes of SO_2 was released into the atmosphere. Ash ejected from this eruption contained every element in the periodic table including 2 million tonnes of Zn, 1 million tonnes of Cu and 5500 tonnes of Cd (Selinus, 2002). Once deposited the elements may lead to future health problems as different processes and activities, such as acid rain and agricultural behaviours, contribute to the remobilization of the elements. The 1783 Lakagigar eruption in Iceland introduced fluoride into the terrestrial environment that is believed to account for the higher proportion of livestock death that occurred in the area shortly thereafter (Gregory, 1996). This also caused a sharp decrease in the economy of Iceland as well as causing famine. Similarily, after the 1970 Hekla eruption, the incidence of fluorosis in the human population of Iceland displayed a measurable increase (Lag, 1990).

The threat to animal and human health as a result of such eruptions provides a good example of both the direct and indirect impact significance of volcanism. The direct impact includes everything from respiratory problems to death as a result of ash fall and lava flows to gas clouds; whereas, indirect impact varies widely from monsoon induced landslides to soil contamination. Ash poses one of the largest health risks in a volcanic eruption, causing both short and long term health problems such as minor lung irritation to silicosis. Volcanoes can eject large volumes of ash containing high percentages of crystalline silica known as cristobalite (Figure 6). The amount of crystalline silica contained in the ash varies between volcanoes depending on the composition and the type of eruption. Long-lived andesite dome eruptions often generate a large amount of fine and crystalline silicate (>3 micrometers in diameters), a result of vapour phase crystallization within pyroclastic flows. This was the case for the Soufrière Hills volcano, Montserrat, British West Indies eruption, spanning the summer of 1995 to the spring of 1998 whose ash contained 10–24% by weight crystalline silica. Long-term exposure to crystalline silicate can result in silicosis, a fatal lung disease. Areas that were the most susceptible to ash hazard had to be evacuated to prevent the risk of silicosis (Baxter *et al*., 1999). In contrast, the 1980 Mount St. Helens, Washington State, eruption was short lived and the ash only contained 4% by weight cristobalite, hence greatly reducing the risk of long-term health problems (Wakefield, 2000).

Figure 6 A 10km high ash-cloud from the Soufrière Hills volcano (photo courtesy of Paul Cole).

Silicosis is a common occupational lung disease in the mining and aggregate industry, but it also occurs in non-industrial settings due to its abundance in the soil (Figure 7). Silica can become airborne under arid windy conditions or during agriculture, urban or construction activities as well as during volcanic eruptions. Once in the lungs the small crystalline silica particles are taken up by microphages that die and accumulate near blood vessels; the connective tissue, collagen, forms around these masses producing fibrous nodules in the lungs, resulting in major respiratory problems and, in extreme cases, death (Castranova and Vallyathan, 2000).

Like volcanoes, earthquakes pose both direct and indirect threats to human and animal health. Direct effects include the destruction of property, injury and death; however, the indirect effects are the focus of medical geology. The majority of these indirect health problems result from earthquake-induced landslides that remobilize elements and other potential risk agents such as fungus. In 1994, a 6.7M earthquake near Los Angeles triggered approximately 11,000 landslides that disturbed soil containing a dimorphic fungus, known to cause coccidioidomycosis or valley fever. This lung infection results from the inhalation of airborne arthospores that have been dislodged from the topsoil of semi-arid regions often in the western hemisphere. In the eight weeks following the earthquake, an outbreak of coccidioidomycosis occurred consisting of 203 reported cases, 3 of which were fatal; statistics an order of magnitude higher than normal (Schneider et al., 1997) (Figure 8).

Figure 7 An x-ray of lungs with silicosis (photo courtesy of K.C. Wan).

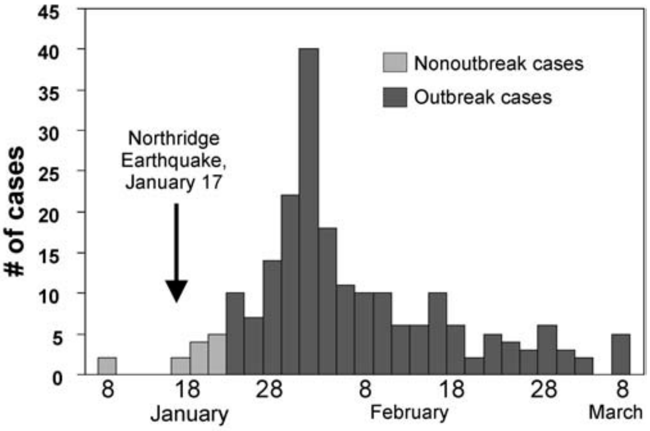


Figure 8 Coccidiodomycosis cases before and after the 1994 Northridge earthquake (after Schneider et al., 1997).

Pathways, intake, uptake, and excretion

The transfer of heavy metals through living tissue can be addressed as follows: (1) pathways; (2) intake; (3) uptake; and (4) excretion (Fergusson, 1990) (Figure 9). There are a number of pathways through which heavy metal exposure may occur ranging from soil and dust to water to diet. Depending on the pathway, intake is either through ingestion, inhalation or dermal absorption. Ingestion is the most common route of exposure for the general populace, whereas inhalation and dermal absorption are significant in certain occupational settings (Adriano, 2001). Once in the body, uptake of an element depends on a variety of factors including nutritional status of the individual and size of the particle. The majority of elements are excreted by a number of different mechanisms such as sneezing or vomiting.

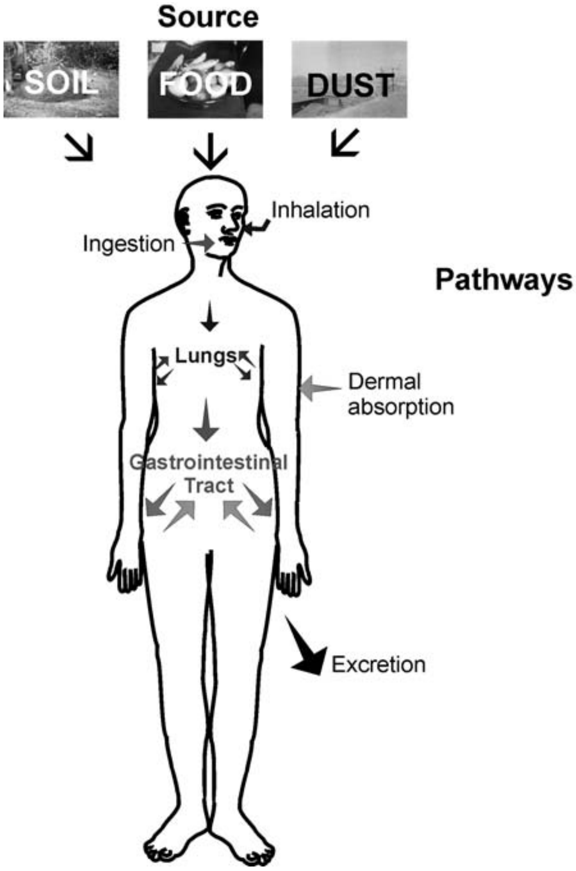


Figure 9 Pathways, intake, uptake and excretion of heavy metals in the human body.

Elements may be present at toxic or deficient levels within the environment, but may not necessarily pose a direct risk to health. Exposure, and more importantly bioavailability, depends on a number of factors including concentration in the source, soil type, particle size as well as the specific physical and chemical properties of the contaminant itself. In other words, the concentration of an element in the soil or other medium is not sufficient to provide biological availability to the individual organism.

Bioavailability is the fraction or amount of element, which is actually available for uptake by living matter (Plant *et al*., 1998). The fate of elements within soil are governed by the chemical system of the soil and are characterized by: a) the heterogeneous distribution of compounds, b) seasonal and spatial alterations in physical and chemical properties (e.g., pH), c) the transformation of chemical species (e.g., electron transfer reactions, diffusion-adsorption into solids), and d) bio-uptake and bio-accumulation. Time, vegetation, microbial activity, water content, geology and heterogeneity of the solid state phase all influence the concentration of trace elements in soils. Rainfall, evaporation and plant transpiration can change the concentration of trace elements more than tenfold (Kabata-Pendias and Pendias, 1992); however, the observed variation of major ions is much less. Reactions involving trace elements vary depending on the weathering environment, the mobility during the weathering process as determined by the stability of the host minerals, and the electrochemical properties of the element (Table 2). Rates of trace element migration in soils are affected by chemical, physical, and biological soil properties including: Eh-pH system, ionic strength, cation exchange capacity and salt content, amount and quality of organic matter, water and temperature, suspended colloidal material, plant

Table 2. Behaviour of certain trace elelments in various weathering environments (based on Kabata-Pendias and Pendias 1992).

Degree of mobility	Environmental conditions	Trace elements
High	Neutral or alkaline	V, Zn
Medium	Oxidizing and acid	Se, Cd, Hg, Cu, Ag, Zn
	Mainly acid	Ag, Se, Cd, Co, Cu, Ni, Hg
	Reducing with variable potential	As, Cd, Co, Cr, Mn, V
Low	Neutral or alkaline	Co, Cu, Mn, Ni
Very Low	Oxidizing and acid	Cr, Se
	Neutral or alkaline	Ag, Cu, Co, Ni
	Reducing	Ag, As, Cd, Co, Cu, Hg, Mo, Ni, Pb, V, Zn

species, as well as micro and mesobiota activities (Kabata-Pendias and Pendias, 1992 and Wolt, 1994).

pH is an important property concerning metal behaviour in soil systems and probably the most important factor affecting metal speciation in soils. Under natural soil conditions the pH ranges between 5 and 7 (Kabata-Pendias and Pendias, 1992). However, soils that are waterlogged repeatedly change the redox potential thus affecting soil pH. Reducing conditions result in a pH increase, whereas oxidation results in a pH decrease. Acidity is associated with leached soils, whereas, alkalinity is associated with drier environments. The acidity of the soil is dictated by inputs of acidity from vegetation, microbial mass, the atmosphere and the ability of primary minerals to resist the acidifying affects of leaching. Alkalinity is determined by parent material, vegetation and hydrology. In general, desorption of metals increases with increasing pH; thus, metals are more soluble in an acidic environment. In such environments, Zn, Mn, Cu, Fe, Co and B are easily leached, and if the pH rises above 7, they are likely to form stable compounds, however, the reverse is true for Mo and Se (Kabata-Pendias and Pendias, 1992).

Organic matter influences the physical, chemical, and biological properties of soil including its structure, macro and micro nutrient supply, cation exchange capacity, and pH buffering capabilities (Pierzynski *et al*., 1994). Thus, the organic matter content of soil influences the bioavailability of certain elements. Organic matter is essential to biochemical weathering and the geochemical cycling of trace elements (Kabata-Pendias and Pendias, 1992). All reactions between organic matter and individual cations result in water-soluble and/or water-insoluble substances. Organic matter can absorb trace elements and organic pollutants as well as inorganic and organic gases, therefore reducing the risk of contamination of surface and groundwater.

Intake

Ingestion

Ingestion is the primary source of element exposure and is expressed through diet, food and beverage, and soil and dust. Even though the main intake of heavy metals through ingestion occurs via diet, geophagia also contributes towards accumulation. Geophagia, also known as pica, is the intentional or unintentional eating of soil or clay and is a common practice in some cultures and countries, especially within Africa (Abrahams, 1997). Geophagia is often an attempt to offset mineral imbalances or deficiencies, however it may also impair the intestinal uptake of trace elements such as Fe and Zn (Mills, 1996; Smith et al., 2000). Studies of Turkish women who use geophagia to supplement their diet with Fe suggest that the practice may in fact be causing the Fe deficiency (Moynahan, 1979). Geophagia was a common practice in certain ancient cultures; for example, the consumption of edible clays was so common in prehistoric South America that an extensive network was established (Browman, 1981).(Figure 10).

Figure 10 Photograph of geophagical materials that are available for purchase in Kampala, the capital of Uganda (Photo courtesy of P. Abrahams).

As noted earlier, in developed countries where food comes from a variety of sources, element deficiency or toxicity is not typically a problem. Nonetheless, the ingestion of soil and dust is a major source of element exposure in young children and may therefore be a concern (Fergusson, 1990). Ingestion is the most important route of exposure to contaminants in soil or dust, with children between the ages of 4 months and 4 years being the most susceptible group. Between the ages of 0 and 2 children typically ingest small amounts of dust and soil through normal mouthing behaviour, whereas between the ages of 2 and 7 the largest quantities are often ingested, and after the age of 7, ingestion is considered insignificant. It is estimated that the average child ingests about 80 milligrams of soil and dust each day. Up to 80% of an entire lifetime dose of some persistent heavy metals may occur in the first 5 years of life (Ontario Ministry of Health, 1997).

Inhalation

Inhalation is the primary pathway for airborne particles such as dust. Due to the minimal amount of soil or dust normally inhaled, this route of exposure is not considered a significant risk to human health. Still, under certain conditions such as volcanic eruptions, in highly arid or desert regions or in areas with high concentrations of certain elements, lung disease may result from this exposure pathway in the general population (Ruttenber and Kimbrough, 1995). The amount of material inhaled and the amount of aerosols deposited internally in the lungs is often controlled by an individual's breathing cycle (breaths per minute) and ventilation rate (volume breathed per day) (Fergusson, 1990) (Figure 11).

Dermal Absorption

The skin of humans can act as a barrier to water, particles, ionic inorganic species and materials of a high molecular weight, but it is vulnerable to lipid soluble non-polar substances (e.g., organometallic compounds and compounds soluble in some organic solvents). The only way for an exogenous compound to penetrate the skin is to diffuse directly through the cells or between the cells. The space between the cells contains fat that can be dissolved by organic solvents increasing the skins permeability to certain chemicals (Sterner, 1999). Control on chemical absorption include: area of contact, duration of contact, chemical and physical attraction between the contaminant and the skin, and the ability of the contaminant to penetrate the skin (Fergusson, 1990; Ruttenber and Kimbrough, 1995) and water content of the skin where there is a dramatic increase in the diffusion rate with increased moisture content (Sterner, 1999). For

Figure 11 Dust storms and other similar events may result in the inhalation of heavy metals.

example, the skin of the legs and arms is roughly ten times thinner than that of the palm, making chemical absorption much faster in the former areas of the body.

Uptake

Depending on the mechanism of intake, ingestion, inhalation or dermal absorption, elements must pass through a series of organs before entering the blood stream. Ingested particles pass through the gastrointestinal tract, inhaled particles pass through the respiratory tract, and dermally absorbed elements enter directly into the blood stream. The intake of an element also dictates how much the body will absorb, for example only 6% of ingested Cd is absorbed in contrast to 50% of inhaled Cd (Philp, 1995).

Once an element is ingested there are a number of factors that influence the absorption process. These include the chemistry of the metal, especially solubility, the amount of food eaten as well as the type of diet. For example, with a full stomach one is likely to absorb much less Pb as compared to an empty stomach. In general, metals with low solubility in water are less readily absorbed than soluble compounds (e.g. Cd, Hg, Tl). After the material has been ingested it moves through the oesophagus into the stomach. The stomach has a normal pH between 1 and 3 and under these highly acidic conditions heavy metals will turn into their chemical form and become cationic or anionic. From the stomach, the digested material then moves to the duodenum and small intestines where the pH is between 6-7. Most of the absorption of elements occurs in the duodenum, jejunum and ileum. In the small intestine metals are absorbed through diffusion as well as fitting into specific membrane transport systems (Sterner, 1999). An example of this is the association between Ca and Pb. Because Ca and Pb are roughly the same size, the body cannot readily distinguish between the two elements, thus the incorporation of Pb into bone matrix can occur at the expense of Ca. Lead does not pose a direct risk in this form but it can exchange freely with Ca in blood and may result in easily broken bones with age. Dietary deficiencies of Ca, Cu, Fe, Zn, protein and Vitamin D have been shown to promote gastrointestinal tract absorption of Pb and Cd, whereas Ca deficiency results in greater Pb retention in the bones (Smith, 1992). The absorption factor varies greatly from element to element, and can be as high as 100% for As and as low as <5% for Bi and Tl. The absorption factor of Pb in adults is approximately 7%, but in infants absorption ranges from about 25 to 53% (Fergusson, 1990).

Mucosa of the gastrointestinal tract protects against many chemical and biological agents, preferentially allowing lipid-soluble compounds to pass into the bloodstream. Chemicals not absorbed by the upper gastrointestinal tract can damage the lining of the large intestine. Materials on the surface of the gastrointestinal tract can be absorbed through the walls and move directly into the blood stream. Vomiting and diarrhoea are highly effective ways to remove toxins from the gastrointestinal tract (Rottener and Kimbrough, 1995).

Once inhaled, particle size, shape and charge all play a key role in the fate of the elements within the body. Material deposited in the upper airways of the respiratory system is absorbed through the epithelium or cleared by a variety of processes at three levels within the respiratory tract: (1) nasopharynx, (2) tracheobronchial tree, and (3) lower alveolar zone. Particles between 5 and 20 micrometers are deposited in the nose and the pharynx, particles between 1 and 5 micrometers reach the bronchioles and alveoli, and particles less than 0.5 micrometers are usually exhaled. In the nasopharynx, the inhaled particles are deposited on fine hairs and the epithelium in the passages of the nose. Expulsion is achieved through nose blowing, sneezing, coughing, mucociliary action and swallowing. Relatively insoluble particles that are present on the ciliated regions of the nasopharynx are deposited on a mucous blanket. This mucous blanket is essential to clearance of particles in this region of the respiratory tract, for it moves the particles to the pharynx where they are mixed with saliva and swallowed (Ruttenber and Kimbrough, 1995). However, the intestine may absorb any particle size that travels down with the mucous to the stomach. In other words, the mucous blanket does not excrete particles from the body but does protect the lungs (Sterner, 1999). In the tracheobronchial tree, inhaled particles are removed from the air stream through sedimentation and diffusion. Once a particle is deposited it is either removed by coughing and/or mucociliary action or it is absorbed in the blood. The lower alveolar zone is not ciliated and the inhaled particles that are deposited here may be phagocytized and moved towards the ciliated epithelium by alveolar macrophages. The cells help in preventing particles from penetrating the alveolar wall. Macrophages, however, tend to concentrate irritants and toxins, magnifying their pathogenic effects. Particles that are not cleared may be transported across the respiratory epithelium to the lymphatic and circulatory systems, whereas particles that remain trapped in the lungs may result in lung disease (Ruttenber and Kimbrough, 1995).

Lung diseases, such as asbestosis and beryliosis among others, are the biggest health risk related to the inhalation of particles. Pneumoconiosis is a general term for lung diseases caused by inhaled particles that accumulate in bronchioles and alveoli where they cannot be expelled. The accumulation of significant quantities of asbestos fibres in the lungs leads to local tissue reaction, which consists mainly of a diffuse fibrous and thickening of the walls of the alveoli; otherwise know as asbestosis. Beryliosis is a rare form of pneumoconiosis attributed to beryllium exposure (Rowland and Cooper, 1983).

Regardless of the intake, ingestion, inhalation or dermal absorption, eventually a fraction of the initial element enters the blood stream. Once an element enters into the blood, it is circulated throughout the blood stream and reabsorbed by various organs. Depending on the element, toxic agents can damage developing and mature blood cells and induce illness by activating the immune system. For instance, in mature red blood cells, Pb inhibits enzymes and alters cell metabolism, impairing heme synthesis and shortening the lifespan of red blood cells, generating the condition known as anaemia (Ontario Ministry of Health, 1997).

The body eliminates toxic elements in a variety of ways. At the cellular level, elimination occurs through active transport, filtration and diffusion, whereas particles are either exhaled through the lungs, excreted in urine by the kidneys, faeces, secreted in sweat, saliva or sputum or are further metabolized in the digestive system and then eliminated through feces (Sterner, 1999; Ruttenber and Kimbrough, 1995).

Conclusion

The interdisciplinary field of “Medical Geology” has arisen from the need to understand the relationships between human health and our surrounding environment, both natural and anthropogenic. It deals with the links between geology and associated health problems in humans, animals and plants and is recognised by numerous leading scientific organisations including the Geological Society of America, the International Society of Trace Element Biochemistry, the International Academy of Pathology, United States Geological Survey and the Society for Environmental Geochemistry and Health.

The influences of earth resources, natural environmental factors and land-use on human health have been recognized for thousands of years. The Romans noted links between mining and negative health effects, while ancient Chinese texts describe the relationship between rock crushing and lung disease. Element deficiencies were also addressed in the ancient world with many civilizations treating goitre using seaweed. Since the industrial revolution, but especially over the past few decades, there has been a growing concern on the impact of agriculture, resource exploitation and urbanization on human health. For example, in China there is both high and low Se areas each with their own set of health problems (e.g., Keshan disease and Kaschin-Beck disease).

Most research focuses on agricultural and industrial landscapes in developing countries where a direct relationship between the geology and element intake is observed (e.g. As rich coal in China, endemic fluorosis in regions of India). Numerous of studies have also examined health issues in the urban-industrial environment. For instance, in the United States, Mielke (1993), Mielke et al. (1983) and Mielke et al. (1997) have linked inner-city Pb levels with elevated blood Pb levels in children. Similar results have also been reported in Europe (Kelly et al., 1996; Osman et al., 1998; Patterson et al., 1996). These studies are not directly related to the geology of a region, rather the contamination due to industrialization and automobile use.

All of the above studies show that knowledge of geology and geomorphology is essential to understanding, and thus eradicating, or preventing, a range of environmental health problems. IGCP project 454 has made great progress in advancing the field of Medical Geology through numerous short courses on Metals, Health and the Environment held worldwide, including Zambia (2001), Chile and Russia (2002) and Lithuania (2003).

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References

Abrahams, P.W. 1997. Geophagy (soil consumption) and iron supplementation in Uganda. Tropical Medicine and International Health, 2: 617-623.

Adriano, D.C. 2001. Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability and Risk of Metals. Springe Verlag, p. 867.

Appleton, J.D. and Ball, T.K., 2002, Geological radon potential mapping, in P.T. Bobrowsky, ed, Geoenvironmental Mapping: Methods, theory and practice: A.A. Balkema, pp. 577-614.

Baxter, P.J., Bonadonna, C., Dupree, R., Hards, V.L., Kohn, S.C., Murphy, M.D., Nichols, A., Nicholson, R.A., Norton, G., Searl, A., Sparks, R.S., and Vickers, B.P., 1999, Cristobalite in Volcanic Ash of the Soufriere Hills Volcano, Montserrat, British West Indies: Science, 283, pp. 1142-1145.

Bowman, C.A. and Bobrowsky, P.T., 2002, Urban geochemistry and associated health hazards in the sediments of Victoria, British Columbia (abs): Geological Society of America Program with Abstracts, vol. 34, no. 6, pp. 419.

Browman, D.L., 1981, Prehistoric Nutrition and Medicine in Lake Titicaca Basin, in J.W. Bastien and J.M. Donahue, eds, Health in the Andes: Special Publication of Amerian Anthropological Association no.12, pp. 103-118.

Castranova, V. and Vallyathan, V., 2000, Silicosis and Coal Workers' Pneumoconiosis: Environmental Health Perspectives, 108, pp. 675-684.

Dunn, C.E. and Irvine, D.G., 1993, Relevance of a lithogeochemical database to epidemiological studies in central Saskatchewan, Canada: Applied Geochemistry, 2, pp. 215-222.

Eaton, D.L. and Robertson, W.O., 1994, Toxicology, in L. Rosenstick and M.R. Cullen, eds, Textbook of Clinical Occupational and Environmental Medicine: W.B. Saunders Company, pp.116-117.

Fergusson, J.E., 1990, The Heavy Elements: Chemistry, Environmental Impact and Health Effects: Permagon Press, 614 p.

Foster, H.D., 2002, The geography of disease family trees: The case of selenium, in P.T. Bobrowsky, ed, Geoenvironmental Mapping: Methods, theory and practice: A.A. Balkema, pp. 497-529.

Finkelman, R.B., Skinner, H.C.W., Plumlee, G.S., and Bunnell, J.E., 2001, Medical Geology: Geotimes, November, pp. 20-23.

Gregory, N., 1996, Toxicity hazards rising from volcanic activity: Surveillance 23, pp.14-15.

Hastings, N., Plouffe, A., Struik, L.C., Turner, R.J.W., Anderson, R.G., Clague, J.J., Williams, S.P., Kung, R. and Taccogna, G., 1999, Geoscape Fort Fraser, British Columbia, Miscellaneous Report, 66: Geological Society of Canada, pp. 1.

Hinkley, T.K., Lamothe, P.J., Wilson, S.A., Finnegan, D.L., and Gerlach, T.M., 1999, Metal emissions from Kiauea, and suggested revision of the estimated worldwide metal output by quiescent degassing of volcanoes: Earth and Planetary Letters, 170, pp. 315-325.

Hong, S., Candelone, J.P., Patterson, C.C., and Boutron, C.F., 1994, Greenland ice evidence of hemisphere lead pollution two millennia ago by Greek and Roman civilizations: Science, 265, pp. 1841-1843.

Hong, S., Candelone, J.P., Patterson, C.C., and Boutron, C.F., 1996, History of ancient copper smelting pollution during Roman and Medieval times recorded in Greenland ice: Science, 272, pp. 246-248.

Kabata-Pendias, A. and Pendias, H., 1992, Trace elements in soils and plants, second edition: CRC Press, 365 p.

Kabata-Pendias, A., 2001, Trace elements in soils and plants, third edition: CRC Press, 413 p.

Kelly, J., Thornton, I., and Simpson, P.R., 1996, Urban Geochemistry: A study of the influence of anthropogenic activity on the heavy metal content of soils in traditionally industrial and non-industrial areas of Britain: Applied Geochemistry, 11, pp. 363-370.

Krzysztof, K. and Glab, H., 2001, Trace element concentrations in human teeth from Neolithic common grave at Nakonowo (Central Poland): Variability and Evolution, 9, pp. 51-59.

Lag, J., 1990, General Survey of Geomedicine, in J. Lag, ed, Geomedicine: CRC Press.1-24 p.

Liang, Y.X., Fu, H. and Gu, X.Q., 1998, Asian-Pacific Newsletter, 2. www.occuphealth.fi/e/info/asian/ap298/Liang&Gu.htm,

Lindberg, D.C., 1992, The Beginnings of Western Science: University of Chicago Press, 455 p.

Maskall, J. and Thornton, I., 1996, The distribution of trace and major elements in Kenyan soil profiles and implications for wildlife nutrition, in J.D. Appleton, R. Fuge and G.J.H. McCall, eds, Environmental Geochemistry and Health: Geological Society Special Publication no.113, pp. 47-62.

Mills, C.F., 1996, Geochemical aspects of aetiology of trace elements and related diseases. in J.D. Appleton, R. Fuge and G.J.H. McCall, eds, Environmental Geochemistry and Health: Geological Society Special Publication no.113, pp. 1-6.

Mielke, H.W., 1993, Lead dust contaminated U.S.A. communities: comparison of Louisiana and Minnesota: Applied Geochemistry, Supplement 2, pp. 257-261.

Mielke, H.W., Anderson, J.C., Berry, K.J., Mielke, P.W., Chaney, R.L., and Leech, M., 1983, Lead Concentrations in Inner-City Soils As a Factor in the Child Lead Problem: American Journal of Public Health 7, pp. 1366-1369.

Mielke, H.W., Dugas, D., Mielke, P.W., Smith, K.S., Smith, S.L., and Gonzales, C.R., 1997, Associations between Soil Lead and Childhood Blood Lead in Urban New Orleans and Rural Lafourche Parish of Louisiana: Environmental Health Perspectives, 105, pp. 950-954.

Moynahan, E.J., 1979, Trace elements in man. Phil. Trans. R. Society London, 288, pp. 65-79.

Nriagu, J.O., 1983, Lead Exposure and Lead Poisoning, in Lead and Lead Poisoning in Antiquity: John Wiley & Sons, pp. 309-424.

Nriagu, J.O., 1996, A History of Global Metal Pollution: Science, 272, pp. 223-224.

Nriagu, J.O., 1998, Tales told in lead: Science, 281, pp.1622-1623.

Ontario Ministry of Health, 1997, The Great Lakes Health Effects Program, Health Canada, and Public Health Branch, The Health and Environment Handbook for Health Professionals: Ministry of Health, 191 p.

Osman, K., Zejda, J.E., Schutz, A., Mielzynska, D., Elinder, C.G., and Vahter, M., 1998, Exposure to lead and other metals in children from Katowice district, Poland: International Archives of Occupupational and Environmental Health, 71, pp. 180-186.

Patterson, E., Sanka, M. and Clark,L., 1996, Urban soils as pollutant sinks - a case study from Aberdeen, Scotland: Applied Geochemistry 11, pp. 129-131.

Pierzynski, G.M., Sims, J.T., and Vance, G.F., 1994, Soils and Environmental Quality: CRC Press, 313 p.

Philp, R.B., 1995, Environmental Hazards and Human Health: CRC Press, 306 p.

Plant, J., Baldock, J., Haslam, H., and Smith, B., 1998, The role of geochemistry in environmental and epidemiological studies in developing countries: Episodes, 21, pp. 19-27.

Roberts, C. and Manchester, K., 1995, Metabolic and Endocrine Disease, in The Archaeology of Disease: Alan Sutton Publishing Ltd., pp. 163-185.

Rowland, A.J. and Cooper, P., 1983, Environment and Health: Castlefield Press, 205 p.

Ruttenber, A.J. and Kimbrough, R.D. (Eds), 1995, Introduction to Environmental Health, second edition: Springer, 372 p.

Selinus, O., 2002. Medical Geology: Method, theory and practice, in P.T. Bobrowsky, eds, Geoenvironmental Mapping: Methods, theory and practice: A.A. Balkema, pp. 473-496.

Selinus, O., 2004, Medical Geology: Earth Science in Support of Public Health Protection: Academic Press, in press.

Schneider, E., Hajjeh, A., Spiegel, R.A., Jibson, R.W., Harp, E.L., Marshall, G.A., Gunn, R.A., McNeil, M.M., Pinner, R.W., Baron, R.C., Burger, R.C., Hutwagner, L.C., Crump, C., Kaufman, L., Reef, S.E., Feldman, G.M., Pappagianis, D., and Werner, S.B., 1997, A Coccidioidmycosis Outbreak Following the Northridge, Calf, Earthquake: JAMA, 277, pp. 904-908.

Silver, C.S. and Rothman, D.S., 1995, Toxics and Health: The Potential Long-Term Effects of Industrial Activity: World Resources, Institute, 7 p.

Smedley, P.L. and Kinniburgh, D.G. 2002. A review of the source, behaviour and distribution of arsenic in natural waters. Applied Geochemistry, 17: 517-568.

Smith, R.P., 1992, A Primer of Environmental Toxicology: Lea and Febiger, 300 p.

Smith, B., Rawlins, B.G., Cordeiro, M.J.A.R., Hutchins, M.G., Tiberindwa, J.V., Serunjogi, L. and Tomkins, A.M., 2000, The bioaccessibility of essential and potentially toxic trace elements in tropical soils from Mukono District, Uganda: Journal of the Geological Society, London: 157, pp. 885-891.

Sterner, O., 1999, Chemistry, Health and Environment: Wiley-VCH, 345 p.

Underwood, E.J., 1979, Trace elements and health: an overview. Phil. Trans. Royal Society of London, 288, pp. 5-14.

Wakefield, J., 2000, An Eruption of Silicosis: Environmental Health Perspectives, 108, pp. A 300.

Wolt, J., 1994, Soil Solution Chemistry: Applications to Environmental Science and Agriculture: John Wiley & Sons, kInc., 345 p.

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