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Medical Geology: a globally emerging discipline

J.E. BUNNELL[1] R.B. FINKELMAN[1] J.A. CENTENO[2] and O. SELINUS[3]

[1] **US Geological Survey**
Reston, VA, USA. Bunnell E-mail: jbunnell@usgs.gov

[2] **US Armed Forces Institute of Pathology**
Washington, DC 20306-6000 USA

[3] **Geological Survey of Sweden**
Uppsala, Sweden

Corresponding author's address:
Joseph E. Bunnell, Ph.D., USGS/EERT 956 National Center, 12201 Sunrise Valley Drive,
Reston, Virginia 20192, USA

ABSTRACT

Medical Geology, the study of the impacts of geologic materials and processes on animal and human health, is a dynamic emerging discipline bringing together the geoscience, biomedical, and public health communities to solve a wide range of environmental health problems. Among the Medical Geology described in this review are examples of both deficiency and toxicity of trace element exposure. Goiter is a widespread and potentially serious health problem caused by deficiency of iodine. In many locations the deficiency is attributable to low concentrations of iodine in the bedrock. Similarly, deficiency of selenium in the soil has been cited as the principal cause of juvenile cardiomyopathy and muscular abnormalities. Overexposure to arsenic is one of the most widespread Medical Geology problems affecting more than one hundred million people in Bangladesh, India, China, Europe, Africa and North and South America. The arsenic exposure is primarily due to naturally high levels in groundwater but combustion of mineralized coal has also caused arsenic poisoning. Dental and skeletal fluorosis also impacts the health of millions of people around the world and, like arsenic, is due to naturally high concentrations in drinking water and, to a lesser extent, coal combustion. Other Medical Geology issues described include geophagia, the deliberate ingestion of soil, exposure to radon, and ingestion of high concentrations of organic compounds in drinking water. Geoscience and biomedical/public health researchers are teaming to help mitigate these health problems as well as various non-traditional issues for geoscientists such as vector-borne diseases.

KEYWORDS **Medical geology. Environmental health. Public health. Human health.**

INTRODUCTION

Emerging diseases present the medical and public health communities with many challenges. However, emerging disciplines may offer these communities new opportunities to address a wide range of health problems, including the emerging and re-emerging diseases. One such emerging discipline is Medical Geology, a rapidly growing discipline that has the potential to help medical communities to pursue a wide range of environmental health issues and improve public health. In this paper article we provide an overview of selected health problems addressed by practitioners of this emerging discipline.

Medical Geology is the science that deals with the impacts of geologic materials and processes on animal and human health. Consequently, Medical Geology required that geoscientists and biomedical/public health researchers collaborate on health problems caused or exacerbated by geologic materials such as trace elements, rocks, minerals, water, petroleum, and geologic processes such as volcanic eruptions, earthquakes and dust.

Medical geology is not strictly an emerging discipline but rather a re-emerging discipline. The relationship between geologic materials such as rocks and minerals and human health has been known for centuries. Ancient Chinese, Egyptian, Islamic, and Greek texts describe the many therapeutic applications of various rocks and minerals and many health problems that they may cause. More than 2,000 years ago Chinese texts describe 46 different minerals that were used for medicinal purposes. Arsenic minerals for example, orphiment (As_2S_2) and realgar (AsS), were extensively featured in the *materia medica* of ancient cultures. Health effects associated with the use of these minerals were described by Hippocrates (460-377 B.C.) as "…as corrosive, burning of the skin, with severe pain."

In the past, geoscientists and biomedical scientists have collaborated on a range of environmental health issues (Maskall and Thornton, 1996; Bencko and Vostal, 1999; Cronin and Sharp, 2002; Centeno et al., 2002a), but these studies were largely driven by the interests and enthusiasm of individual scientists. In contrast, Medical Geology is today receiving institutional support from many organizations all over the world.

Practitioners of Medical Geology have five principal goals:

1) To identify geochemical anomalies in soils, sediments, and water that may adversely impact human and animal health; 2) To identify the environmental causes of known health problems and, in collaboration with biomedical/public health researchers, seek solutions to prevent or minimize these problems; 3) To evaluate the beneficial health effects of geologic materials and process; 4) To reassure the public when there are unwarranted environmental health concerns associated with geologic materials or processes; and 5) To forge links between developed and developing countries to find solutions for environmental health problems.

Among the environmental health problems that geologists and the medical community need to collaborate on include: exposure to natural dust and to radioactivity; exposure to toxic levels of trace essential and non-essential elements such as arsenic and mercury; nutrient trace element deficiencies; naturally occurring toxic organic and inorganic compounds in drinking water; identification and affects of volcanic emissions, etc. Geoscientists have also developed an array of tools and databases that can be used by the environmental health community to study vector-borne diseases, to model the dispersion of pollutants in surface and ground water and in the air, and can be applied to occupational health problems resulting from exposure to minerals.

NATURALLY OCCURRING DUSTS

Exposure to mineral dust can cause a wide range of respiratory problems. The dust can be generated by mining rocks or coal, sandblasting, and smoke plumes from fires (both natural and man-made) or simply from the wind dispersing fine-grained minerals from the earth's surface.

Dust can also be stirred up by earthquakes such as happens in the arid regions of the southwestern U.S. and northern Mexico. This dust carries spores of a fungus (*Coccidioides immitis*) responsible for Valley Fever, a serious respiratory problem that can lead to fatigue, cough, fever, rash, and damage to internal organs and skin, bones, and joints. Dust exposure can even take on global dimensions. For example ash ejected from volcanic eruptions can travel many times around the world, and recent satellite images have shown wind-borne dust from the Sahara and Gobi deserts blown halfway around the world (Fig. 1). Of greatest concern for its affects on human health are the finer particles of respirable (inhalable) dusts. In this regard, considerable work is being conducted to identify dust particles derived from soils, sediment, and weathered rocks.

Asbestos is a diverse group of minerals with several common properties; separation into long thin fibers, heat resistance, and chemically inertness. In the 1980s the U.S. medical community recognized that exposure to respirable asbestos fibers can cause severe health problems including mesothelioma, lung cancer, and asbestosis. Hence, many commercial asbestos mines were closed and a concerted effort was made to remove asbestos from schools, work places, and public buildings.

Unfortunately, the problem did not end there. Recently, it was found that small amounts of asbestos associated with commercial deposits of vermiculite, a micaceous mineral used for insulation, packaging, kitty litter, and other applications, has caused significant health problems in the mining community of Libby, Montana, USA (Van Gosen et al., 2002). Lung abnormalities (such as pleural thickening or scarring) occurred in about 18 percent of the adults tested.

TRACE ELEMENT EXPOSURE: DEFICIENCY AND TOXICITY

Trace elements play an essential role in the normal metabolism and physiological functions of animals and humans. Some 22 such elements are known or thought to be "essential" for humans and other animals. "Macronutrients" are required in fairly large amounts (e.g., grams per kilogram of diet), whereas "micronutrients" are required in much smaller amounts (e.g., microgram-to-milligrams per kilogram of diet). Sixteen elements are established as being essential for good health. Calcium, phosphorus, magnesium, and fluoride for example, are required for structural functions in bone and membranes. Sodium, potassium, and chloride are required for the maintenance of water and electrolyte balance in cells. Zinc, copper, selenium, manganese, and molybdenum are essential constituents of enzymes or serve as carriers (iron) for ligands essential in metabolism. Chemical elements are also important in the functioning of the endocrine system. For instance, iodine is an essential component of the thyroid hormone thyroxine, and chromium is the central atom of the hormone-like glucose tolerance factor. Because these are all critical life functions, the tissue levels of many "nutritionally essential elements" tend to be regulated within certain ranges, and dependent on several physiological processes, especially homeostatic control of enteric absorption, tissue storage, and/or excretion. Changes in these physiological processes may exacerbate the effects of short-term dietary deficiencies or excess of trace elements.

Food is a major source of trace elements in humans and animals. However, other sources such as the deliberate eating of soil (geophagia) and water supplies may also contribute to dietary intake of trace elements. Diseases due to trace element deficiencies as well as excesses are known for iodine, copper, zinc, selenium, molybdenum, manganese, iron, calcium, arsenic, and cadmium (Lindh, 2005). Endemic diseases correlative with soil deficiencies in selenium and iodine have been described in at least two general cases, the juvenile cardiomyopathy "Keshan Disease" (Fordyce, 2005) and the iodine deficiency disorders including goiter and myxedematous cretinism (Nordberg and Cherian, 2005), respectively. In the following paragraphs, examples of adverse health affects due to trace element deficiencies and excesses are described. Chronic exposure to non-essential elements such as arsenic is also described.

Diseases Due to Trace Element Deficiencies

Iodine

The connection between geologic materials and trace element deficiency is well documented for iodine. Iodine Deficiency Disorders (IDD) include goiter (enlargement of the thyroid gland), cretinism (mental retardation with physical deformities), reduced IQ, miscarriages, and birth defects. In ancient China, Greece and Egypt as well as among the Incas, people affected by goiter, were given seaweed to provide the needed iodine (Fuge, 2005). Goi-

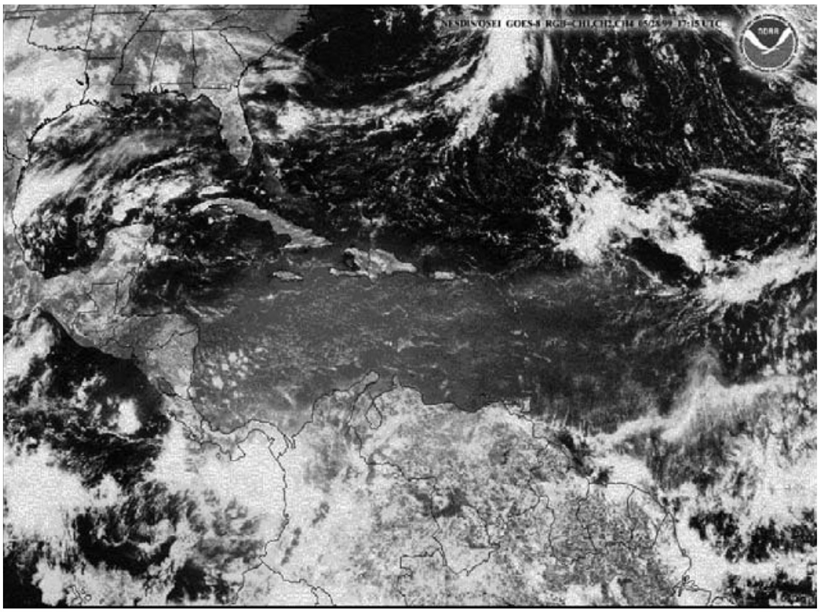


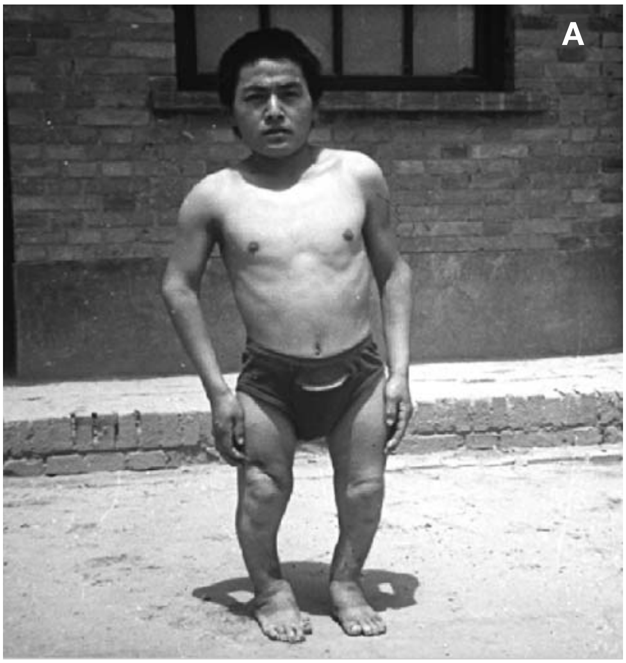
FIGURE 1 **This satellite image shows a dust cloud from North Africa moving across the Atlantic Ocean, over northern South America and then over the Caribbean and the southern U.S. These dust storms occur several times a year resulting in increased incidences of asthma and allergies in the Caribbean region. The dust is not exclusively fine-grained minerals. Researchers have found more than 140 different organisms hitchhiking from Africa to the Western Hemisphere.**

ter is still a serious disease in many parts of the world. China alone has 425 million people (40% of the world's population) at risk of IDD. In all, more than a billion people, mostly living in the developing countries, are at risk of IDD. In all the places where the risk of IDD is high, the content of iodine in drinking water is very low because of low concentrations of iodine in bedrock.

Selenium

Selenium is an essential trace element having antioxidant protective functions as well as redox and thyroid hormone regulation properties. However, selenium deficiency (due to soils low in selenium), has been shown to cause severe physiological impairment and organ damage such as a juvenile cardiomyopathy (Keshan disease) and muscular abnormalities in adults (Kashin-Beck disease; Fig. 2). In the 1960s scientists suspected that these diseases were of geological origin, and in the 1970s the probable solution was found. These diseases were always located in areas with low selenium soils (Fordyce, 2005). The use of dietary selenium in the prevention and treatment of these diseases has been a great success.

The occurrence of low selenium is thought to contribute to other illnesses including impaired reproduction, various cancers, infectious diseases, and, due to its antioxidant properties, rapid aging. Also, metabolic selenium combined with other trace elements appears to promote good health. For example, the ratio of selenium to arsenic in the body can modulate the toxic effects of either element alone (Selinus and Frank, 2000). The effects of Se intake on As methylation have only been recently studied in epidemiologic studies of As exposed individuals (Christian et al., 2006).



Toxicity of Essential and Non-essential Elements

Arsenic

Arsenic and arsenic compounds are human carcinogens (IARC, 1987). Exposure to arsenic may occur through several anthropogenic sources, including mining, pesticides, pharmaceuticals, glass and microelectronics, and most commonly, natural sources. Exposure to arsenic occurs via ingestion, inhalation, dermal contact and the parenteral route to some extent. Drinking water contaminated with arsenic is a major public health problem. Acute and chronic arsenic exposure via drinking water has been reported in many countries of the world, where a large proportion of the drinking water is contaminated with high concentrations of arsenic. General health effects associated with arsenic exposure include cardiovascular and peripheral vascular disease, developmental anomalies, neurologic and neurobehavioural disorders, diabetes, hearing loss, portal fibrosis, hematologic disorders (anemia, leukopenia and eosinophilia) and cancers. Significantly higher standardized mortality rates and cumulative mortality rates for cancers of the skin, lung, liver, urinary bladder, kidney, and colon occur in many areas polluted with arsenic (Centeno et al., 2002a; Centeno et al., 2002b; Tchounwou et al., 2003; Fig. 3).

In Bangladesh, India, China, Taiwan, Vietnam, Mexico, and elsewhere, high levels of arsenic in drinking water have caused serious health problems for many millions of people (Kinniburgh and Smedley, 2001). Geoscientists from several countries are working with

FIGURE 2 | **Photos demonstrating cases with severe muscular abnormalities of extremities (A) and hands (B) associated with selenium deficiency in China (Kashin-Beck disease). These photographs were taken by Prof. Dr. Wang Zhilun (China) a leading researcher on selenium deficiency disorders.**

public health officials to seek solutions to these problems. By studying the geological and hydrological environment, geoscientists are trying to determine the source rocks from which the arsenic is being leached into the ground water. They are also trying to determine the conditions under which the arsenic is being mobilized. For example, the arsenic might be desorbed and dissolved from iron oxide minerals by anerobic (oxygen-deficient) groundwater, or it might be derived from the dissolution of arsenic-bearing sulfide minerals such as pyrite by oxygenated waters (Smedley and Kinniburgh, 2005). Understanding the mechanisms by which arsenic is mobilized will permit the public health officials around the world to identify aquifers that may pose a threat to their communities.

In China, geoscientists are working with the medical community to seek solutions to arsenic and fluorine poisoning caused by the residential burning of mineralized coal and briquettes. Chronic arsenic poisoning affects at least 3,000 people in Guizhou Province, P.R. China (Finkelman et al., 1999). Those affected exhibit typical symptoms of arsenic poisoning including hyperpigmentation (flushed appearance, freckles), hyperkeratosis (scaly lesions on the skin, generally concentrated on the hands and feet), and Bowen's disease (dark, horny, precancerous lesions of the skin (see Fig. 3). Chili peppers dried over open coal-burning stoves may be a principal vehicle for the arsenic poisoning. Fresh chili peppers contain less than one part per million (ppm) arsenic. In contrast, chili peppers dried over hig-harsenic coal fires in this region may contain more than 500 ppm arsenic. Significant amounts of arsenic may also occur in other foods dried over the high-arsenic coal fires. Additional sources of arsenic include ingestion of dust (samples of Guizhou kitchen dust contained as much as 3,000 ppm arsenic), and inhalation of indoor air polluted by arsenic from coal combustion. In Guizhou Province, the relatively low arsenic content of drinking water does not appear to make it as important a route of ingestion as in other parts of the world, such as Bangladesh.

Chemical and mineralogical characterization of the arsenic-bearing coal samples from this region of China (Belkin et al., 1997) indicates arsenic concentrations as high as 35,000 ppm! By contrast, typical coals from around the world have less than 20 ppm arsenic (Swaine, 1990). Although there are a wide variety of arsenic-bearing minerals in the coals from Guizhou Province, much of the arsenic is bound to the organic component of these coals (Belkin et al., 1997). This is important for two reasons. First, because the arsenic is in the organic matrix and not in pyrite as is typical worldwide, traditional methods of reducing arsenic, such as physical removal of heavy minerals, primarily As-bearing pyrite, would not be effective. Second, because visually observable pyrite in the coal is not a reliable indicator of the arsenic content, villagers do not have a way of predicting the arsenic content of the coal that they mined or purchased. Consequently, a field test kit for arsenic was developed (Belkin et al., 2003). This kit permits the villagers analyze coal in the field and to identify dangerous high-arsenic coals as well as the safer low-arsenic coals.

Fluorine

Over-exposure to trace elements in geologic materials is responsible for toxicity effects in humans and animals. One of the most studied trace elements in this regard is fluorine. The fluoride ion (F^-) stimulates bone formation and also reduces dental caries at doses of at least 0.7 mg/L in drinking water. However, excess fluoride (>1 mg/L) exposure can cause fluorosis of the enamel (mottling of the teeth) and bone (skeletal fluorosis) (Edmunds and Smedley, 2005).

The health problems caused by fluorine volatilized during domestic coal use are far more extensive than those caused by arsenic. More than 10 million people in Guizhou Province and the surrounding areas suffer from various forms of fluorosis (Finkelman et al., 1999). Typical symptoms of fluorosis include mottling of tooth enamel (dental fluorosis) and various forms of skeletal fluorosis including osteosclerosis, limited movement of the joints, and outward manifestations such as knock-knees, bow legs, and spinal curvature. Fluorosis combined with nutritional deficiencies in children may produce severe bone deformation.

The etiology of fluorosis is similar to that of arseniasis in that the disease is derived from foods dried over coal-burning stoves. Adsorption of fluorine by corn dried over unvented ovens burning high (>200 ppm) fluorine coal is the probable cause of the extensive dental and skeletal fluorosis in southwest China. The problem is compounded by the use of clay as a binder for making briquettes. The clay used is a high-fluorine (mean value of 903 ppm) residue formed by intense leaching of a limestone substrate (Finkelman et al., 1999).

Other Medical Geology Issues

Geophagia

Geophagia (or geophagy) is also an area of concern in medical geology. Geophagia can be defined as the deliberate ingestion of soil, a practice that is common among members of the animal kingdom, including certain human populations. Soil may be eaten from the ground, but in many situations there is a cultural preference for soil from special sources such as termite mounds. Geophagia is considered by many nutritionists to be either a learned habitual response in which clays and soil minerals are specifically ingested to reduce the toxicity of various dietary components or as a built-in response to nutritional deficiencies resulting from a poor diet. Geophagy is attaining renewed and serious interest within the scientific research community.

Radon

Exposure to natural gases such as radon is potentially hazardous. Geologic materials are the most important factor controlling the source and distribution of radon. Relatively high levels of radon emissions are associated with specific types of bedrock and unconsolidated deposits, including some granites, phosphatic rocks, and shales rich in organic materials. The release of radon from rocks and soils is controlled largely by the types of minerals in which uranium and radium occur. Radon levels in outdoor air, indoor air, soil air, and ground water can be very different (Appleton, 2005). Radon released from rocks and soils is quickly diluted in the atmosphere. Concentrations in the open air are normally very low and probably do not present a hazard (Appleton, 2005). Radon that enters poorly ventilated buildings, caves, mines, and tunnels can reach dangerously high concentrations.

Naturally occurring organic compounds in drinking water

Balkan endemic nephropathy (BEN) is an irreversible kidney disease of unknown origin, geographically confined to several rural regions of Bosnia, Bulgaria, Croatia, Romania, and Serbia. The disease occurs only in rural villages located in tributary valleys of the lower Danube River. Several thousand people in the affected countries are currently suffering from BEN and thousands more will likely be diagnosed with BEN in the next few years (Orem et al., 1999).

Many factors have been proposed as etiological agents for BEN, including: bacteria and viruses, heavy metals, radioactive compounds, trace element imbalances in the soil, chromosomal aberrations, mycotoxins, plant toxins, and industrial pollution (Tatu et al., 1998). Recent field and laboratory investigations support an environmental etiology for the disease (Feder et al., 1991; Tatu et al., 1998; Orem et al., 1999). In this regard, there is a growing body of evidence suggesting the involvement of toxic organic compounds present in the drinking water of the endemic areas. These compounds are believed to be leached by groundwater from low rank Pliocene lignite deposits, and transported into shallow household wells or village springs (Orem et al., 1999). Analysis of well and spring water samples collected from BEN-endemic areas contain a greater number of aliphatic and aromatic compounds, in much higher concentrations (>10x), compared to water samples from nonendemic sites. Many of the organic compounds found in the endemic area water samples were also observed in water extracts of the Pliocene lignites, indicating a probable connection between the coal and organics in the water samples.

Villagers in the endemic areas use well and spring water almost exclusively for drinking and cooking, and are therefore potentially exposed to toxic organic compounds in the water. The levels of toxic organic compounds present appear to favor a relatively slow development of the disease over a period of at least 10 to 30 years. The frequent association of BEN with

FIGURE 3 | **Photos showing arsenic-induced lesions of the skin: Keratotic (ulceration) lesions of the foot (A), leg (B), and hands (C). Photos courtesy of Dr. Jose A. Centeno (A and B) and Prof. Dr. Baoshan Zheng, Institute of Geochemistry, China (C).**

upper urinary tract (urothelial) tumors suggests the action of both nephrotoxic and carcinogenic factors, possibly representing different classes of toxic organic substances derived from the Pliocene lignites (Tatu et al., 1998). Pliocene lignites are some of the youngest coals in the Balkans and are relatively unmetamorphosed in the endemic areas. They retain many of the complex organic compounds contained in the decaying plant precursors (Feder et al., 1991; Orem et al., 1999), and many kinds of potentially toxic organic compounds may be leached from them.

In the Pliocene lignite hypothesis for BEN etiology, other factors besides the presence of low rank coal must also be considered. The hypothesis also implies the following circumstances: the right hydrologic conditions for leaching and transport of the toxic organic compounds from the coal to the wells and springs, a rural population largely dependent on untreated well water, a population with a relatively long life span (BEN commonly becomes manifest in people in their 40s and 50s), a relatively settled population for long exposure to the source of nephrotoxic/carcinogenic substances, and a competent and established medical network for recognition of the problem and proper, systematic, diagnosis.

Consequently, BEN appears to be a multifactorial disease, with toxic organics from coal being one component in the disease etiology. The challenge to researchers is to integrate studies among disparate scientific disciplines (medicine, epidemiology, geology, hydrology, geochemistry) in order to develop an accurate model of the disease etiology of BEN.

Vector-borne diseases

A vector is an insect or other arthropod that actively transmits a pathogen from an infected reservoir host animal to another individual. Of all human diseases, vector-borne diseases are the ones most closely tied to geologic materials and processes. This is because the life-cycles of arthropods that transmit disease agents are directly influenced by soil type (which is determined by parent rock, climatic conditions, water availability, and other environmental factors). The ability and efficiency of vectors to transmit diseases to humans depends on environmental factors being met. Hence, when environmental conditions change, human disease patterns may be altered in response to changing distributions of suitable vector habitats (Haines et al., 1993). For instance, while somewhat controversial, there is evidence that if global warming occurs, tropical vector-borne diseases such as malaria may once again become prevalent in temperate regions such as North America and Europe (Patz and Reisen, 2001). Specific climate factors have been linked to reports of vector-borne diseases in humans, presumably resulting from vector life cycle requirements as well as to human activity patterns (e.g., McCabe and Bunnell, 2004).

The rapid world-wide spread of the mosquito-borne West Nile fever illustrates how vulnerable the global human community is to substantial morbidity and mortality brought about by other life forms. By better understanding the effects of environmental parameters on vector and reservoir host distribution, public health preparedness and intervention strategies will likely improve. Tools of Medical Geology such as GIS (geographic information systems) can be effectively applied to increase knowledge of factors that might be conducive to outbreaks (Bunnell et al., 2005). For instance, a spatial analysis of vector distribution in the Middle Atlantic region of the USA revealed environmental parameters that may be used to prevent or minimize future ixodid tick-borne disease outbreaks, such as Lyme disease, Powassan fever and human anaplasmosis (Bunnell et al., 2003).

HEALTH BENEFITS OF GEOLOGIC MATERIAL

The reemerging field of Medical Geology is concerned with the impact of geologic materials and geologic processes on animal and human health. Most research has focused on health problems caused by an excess or deficiency of trace elements, exposure to ambient dust and other geologically related health problems, to which geoscience tools, techniques, or databases could be applied. Little attention has focused on the beneficial health effects of rocks, minerals, and geologic processes. These beneficial effects may have been recognized as long as 2 Ma ago (Abrahams, 2005) and include emotional, mental, and physical health benefits. Some of the earliest known medicines were derived from rocks and minerals. For thousands of years various clays were used as an antidote for poisons. Medicinal clays, “terra sigillata,” still in use today, may have been the first patented medicine. Many trace elements, rocks, and minerals are used today in a wide variety of pharmaceuticals and health care products. There is also a segment of society that believes in the curative and preventative properties of crystals (talismans and amulets). Metals and trace elements are used in some of today’s most sophisticated medical applications. Other recent examples of beneficial effects of geologic materials and processes include epidemiological studies in Japan that have identified a wide range of health problems (such as muscle and joint pain, hemorrhoids, burns, gout, etc.) that may be treated by one or more of nine chemically distinct types of hot springs, a study in China indicating that residential coal combustion may be mobilizing sufficient iodine to prevent iodine deficiency disease (Wang et al., 2004), and the 'sand baths' used to replenish essential nutrients in Portugal (Celso Gomes, pers. comm. 2004).

CONCLUSIONS

The objectives of Medical Geology are to identify harmful geologic agents, determine the conditions of exposure that promote deteriorating health conditions, and develop sound principles, strategies, programs and approaches necessary to eliminate or minimize health risks. Interaction and communication is necessary between the geoscience, biomedical, and public health communities to protect human health from the damaging effects of physical, chemical and biological agents in the environment. We recommend that Medical geology be included in higher education curricula so that students will be aware of the connection between geology and health and encouraged to pursue a career in Medical Geology. The rapidly emerging scientific discipline of Medical Geology holds promise for increasing our environmental health knowledge base, and contributing to substantial tangible improvements in the well-being of the global community.

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