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Epidemiological Transitions and the Changing Face of Medical Geology

INTRODUCTION

Medical geology is defined as the study of the relationship between the geosphere and human health. Two recent books in this rapidly expanding field (1, 2) focus on current issues that generally involve exposure to toxic elements or compounds of direct geogenic origin, such as arsenic, mercury, and asbestos. A detailed understanding of these issues ultimately leads to scientifically based recommendations for public health interventions that decrease human morbidity and mortality. However, the relationship between our geological environment and our health antedates current public health practice by at least 200 000 years, when the first modern humans appeared.

Since that emergence of *Homo sapiens* in Africa, our species has undergone three epidemiological transitions, major changes in the pattern of our disease burden that result from steps in cultural evolution. Thus the advents of agriculture, industrialization, and globalization have led to the emergence of new diseases as well to the disappearance of others. It is the aim of this paper to trace the changing role of medical geology through these epidemiological transitions, thereby providing, for the first time, a historical perspective on the importance of this field.

HUNTER-GATHERERS BEFORE THE EPIDEMIOLOGICAL TRANSITIONS

As hunter-gatherers, humans moved around in small family groups and were (still are in places) dependent primarily on the direct availability of unmodified environmental resources. Thus the major determinant of the disease burden was resource dearth, which could lead to hardship (lack of tools), exposure (lack of shelter or fuel), famine (lack of food), and local extinction (lack of healthy mates). Stone tools were vitally important for processing other resources, so much so that their availability could influence settlement, migration, and lifestyle. A good illustration of this is the dependence of early Aboriginal Australians on Eocene chert used in the manufacture of knives and scrapers.

When Aborigines first settled the Swan Coastal Plain on the southwest coast of Western Australia some 50 000 years ago, sea levels were lower, and there were exposed outcrops of Eocene chert to the west (3). This rock is ideal for producing cutting edges because of its choncoidal fracture pattern, and there were no other rocks in the area showing this fracture pattern to the same degree. As their chert quarries were submerged by rising sea levels late in the Pleistocene, chert artifacts became smaller and smaller because of an increasing dependence on the reuse of discarded chert artifacts. These finally disappeared from the local archaeological record about 5000 years ago, when the local Aborigines either succumbed through hardship or moved east, presumably driven by a need for a more suitable geological environment (3). In effect, this is an example of a geologically determined local extinction, an adverse health outcome that is clearly at the extreme of the disease burden spectrum to which our hunter-gatherer ancestors were subject.

As a further example, mineral resources were also a key determinant of colonization success in the peopling of the Caribbean Islands. The first inhabitants were of both Central American (Casimiroids, using the Cuban countercurrent to reach Cuba and Hispaniola from the Yucatan peninsula about 4000 BC) and South American origin (Ortoiroids, using the south equatorial current to reach Puerto Rico from [then mainland] Trinidad about 2000 BC) (4). Culturally, both these peoples were preceramic and had only coarse stone tools; they lacked the knowledge of clays to produce pottery, and they did not have access to chert for the production of fine points and sharp edges. The Tainos—the dominant Indian group at the time of Columbus—on the other hand, had both pottery (improving food storage capability and reducing vulnerability to hurricanes) and chert (improving weapons, and found only in Antigua and Puerto Rico). These mineral resources had made it possible for the ancestors of the Tainos, migrating (invading) up the Antilles from Venezuela from about 500 BC, to supplant the preexisting Indian populations in what has been called the "First Repeopling" of the Caribbean (4). (The "Second Repeopling," from 1492, was also significantly influenced by mineral resources, namely steel and gold, as readers of Diamond (5) will know.) Inevitably, the population health consequences for the supplanted peoples were disastrous.

By nature of the archaeological record upon which they are based, neither the Aborigine nor the Taino example provides a sense of the frequency and severity with which periodic famine would have affected health. Notwithstanding the dependence on mineral resources for food gathering, hunting, and storage, periodic famine is likely to have been the single most direct determinant of hunter-gatherer health and to have provided the drive in cultural evolution for the development of a more reliable approach to food availability. That new approach came in the form of agriculture.

FARMERS AND THE FIRST EPIDEMIOLOGICAL TRANSITION

With the more reliable food supplies provided by agricultural production, people were able to settle villages, towns, and later cities. Population size and density increased, as did the intensity of animal contact, setting the scene for infectious disease to take over as the major contributor to the human disease burden. This changing demographic and epidemiological picture is known as the first epidemiological transition. The new food supply and associated sociocultural changes unfortunately also brought health problems of their own, and it is these that relate more directly to medical geology.

Variety in the diet had now been lost, often accompanied by a deficiency in the trace elements that are essential to health. In heavily leached soils, for example, iodine is deficient because iodine salts are generally very soluble. Iodine-deficient crops grew on such soils, and populations dependent on them were in turn iodine deficient. In inland areas this effect was exacerbated by lack of dietary intake of iodine from ocean fish and sea salt. In childhood, iodine deficiency resulted in cretinism, an intellectually disabling condition involving thyroid hormone (the function of which is iodine dependent). In the European Alps, where meltwater leaches valley soils heavily, entire agricultural communities were affected by cretinism until the advent of improved food distribution and later iodized salt, both of which followed the industrial revolution. (For a recent review, see Fuge (6).)

In farming communities that remain largely dependent on local produce, other elemental deficiencies can also have direct impacts on health. Filip, one of the sailors on the ill-fated Swedish warship *Vasa* (sunk in 1628), was severely zinc deficient: he had a bone zinc content of only 10.5 ppm (<100 ppm is considered deficient), presumably the result of a diet excessively dependent on bread and porridge (7). This deficiency would arguably have predisposed him to prostate and other cancers, but it was the nature of public health issues in those days that he drowned clinging to the steering lever instead, aged only 20. There are many other examples, including selenium deficiency (8). Interestingly, though, our newfound dependence on agricultural production also introduced the possibility of exposure to some potentially toxic elements at above background levels. In a complex interplay between geology, culture, politics, and health, it is likely, for example, that Viking-age Icelandic farmers suffered adverse effects from ingesting the leachates of volcanic ash deposits.

Viking society was essentially a dispersed farming society (with a bit of raiding thrown in), and in 874 one Norwegian Viking farmer, Ingólfur Arnarson, established a homestead at Reykjavik. Many other settlers followed, often in an attempt to escape increasingly uncomfortable political conditions in Norway, most notably the centralization of power under Harald Fine-Hair (first king of a unified Norway, 890–942 AD). These farmers brought with them the skills and resources to reproduce their farming methods from Norway, including a strong tradition of dairying and grazing. Sheep did well and rapidly became the mainstay of the local economy, but these sheep also suffered from a strange disease that had never occurred in Norway: gaddur, an outgrowing of the teeth to the point of damaging the gums and cheeks of affected animals (Finnsson 1796, cited in Petursson et al. (9)). Gaddur was a sign of fluorosis, with severely affected animals also becoming stiff and lame as a result of joint involvement. These sheep had ingested fluoride-rich volcanic ash with either pasture or drinking water: Icelandic tephra can be particularly rich in fluoride, with calcium fluorosilicates ($CaSiF_6$) adsorbed onto very fine ash particles with long dispersal potential. It would be surprising if this geological hazard had not also affected the human population, and there are several suggestions in the Icelandic historical literature that this may have been the case. One of the greatest Saga heroes, Egil Skallagrimson, had bone overgrowth arguably consistent with skeletal fluorosis, and many Icelanders affected by the 1783 Laki eruption demonstrated similar bone disorders (10, 11). Whereas hunter-gatherers might simply have moved on from ash-laden environments, farmers tied to their pastures and water supplies were left with little option but to ingest these geogenic toxins.

INDUSTRIAL SOCIETIES AND THE SECOND EPIDEMIOLOGICAL TRANSITION

With industrialization came all the improvements in population health indicators associated with development: decreased child mortality, increased life expectancy, decreased birth rates and improved quality of life. These changes constitute the second epidemiological transition: an associated increase in the diseases of affluence, like cardiovascular disease and diabetes (which both result from inactivity and overnutrition). New technologies also led to the production of toxins at unprecedented rates, when for the first time in history human production sources exceeded ecological absorption sinks, and ecosystems as well as the people dependent upon them were poisoned. Nowhere was this more obvious than in air quality.

Although fossil fuel (coal, peat) combustion was already affecting respiratory health in indoor environments, the resultant pollutants had, until now, usually not been as pervasive or persistent in their impact on human communities. With the industrial revolution, coal was burned at an unprecedented rate, and respiratory health was affected by outdoor air quality for the first time. Exposure to coal-produced SO_2 and particulates (PM_{10}, $PM_{2.5}$) now became chronic, and asthma and chronic obstructive pulmonary disease (COPD) developed into significant public health problems for the first time in our cultural evolution. Pollutants reached concentrations and persistence times that allowed new compounds to form under the influence of sunlight—the new phenomenon of photochemical smog. Outdoor air pollution had overtaken indoor air quality as the dominant exposure environment to compounds detrimental to respiratory health, and people started dying. Weekly mortality rates doubled during the "pea soup" fogs of London in the 1950s, with over 4000 excess deaths during one severe atmospheric inversion event that lasted for over a week in 1952 (12). Although emission controls have reduced this disease burden in the developed world, coal-generated "pea soup" smog is now killing people in the industrial centers of India and China. Cars exacerbated this problem not only by using yet another fossil fuel, petroleum, to generate NO_x and O_3, but by volatilizing metals such as lead. Lead was first added to petroleum as an antiknocking agent in the 1920s, and vehicle emissions have been the major source of airborne lead pollution ever since. In London in the early 1980s, the emission of lead was close to 10 000 tonnes per annum, with human exposure resulting through food, water, dust and direct inhalation. Convincing epidemiological evidence has since demonstrated that blood lead levels as low as 10 μg (100 ml)$^{-1}$ can adversely affect children's IQ, and leaded petroleum is now banned or being phased out in most western countries.

Other metals were also dispersed and rendered bioavailable by industrial processes. In Minamata Bay, Japan, mercury of industrial origin bioaccumulated in local food chains. Produce from the bay poisoned the nervous systems of people in local fishing communities, resulting in a disease that now bears that bay's name. In Bangladesh, wells driven into arsenic-laden rock strata are poisoning millions through the drinking water supply, creating one of the biggest public health engineering disasters in history. We will revisit this example below, and these and other geogenic toxins will also be discussed in more detail by later presenters in the symposium.

Less direct (but arguably as important) geological effects of industrialization can be seen at the global scale. Mechanized agricultural overproduction has led to desertification, producing vast sources of globally dispersed dusts that may pose a significant pathogen dispersal risk (13). Soil salinization has led disease-carrying coastal mosquitoes to spread inland, increasing the risk of arbovirus infections in populations not previously exposed to these species (14). Global environments (including geological environments) are being altered at an unprecedented rate, and it has been argued that such changes are contributing to what will be the third epidemiological transition (15).

GLOBALIZATION AND THE THIRD EPIDEMIOLOGICAL TRANSITION

If large populations continue to overexploit environmental resources at the current (or at an accelerating) rate, it is inevitable that ecosystems will increasingly fail to provide those services upon which the health of human populations depends. Many would argue that the emergence and reemergence of some diseases is already a reflection of nonsustainable resource use (16), and new disease outbreaks have been interpreted as bioindicators of ecosystem disruption (17). The changes in disease burden associated with the disruption of health-sustaining ecosystem services have been described as the third epidemiological transition (18), and because geochemical cycles underlie most ecosystem services, an understanding of medical geology is again integral to solving environmental health problems during (and after) this transition.

The ongoing impacts of infectious disease are still actively discussed in both the popular and scientific media, and there is an increasing realization that geological factors underlie the current emergence and reemergence of many of these (19). Lyme disease for example, a debilitating infection with the tick-borne pathogen *Borrelia,* has recently emerged as a major public health problem in the United States. The vector ticks, *Ixodes scapularis,* are present on alfisol-type soils of sandy or loam-sand textures overlying sedimentary rock, and are absent from areas with acidic soils of low fertility and a clay soil texture with Precambrian bedrock (20). Ecosystem disruptions resulting from human overexploitation or resources have led to Lyme disease becoming an "emerging infectious disease" only in areas with the former soil type. Many other human pathogens are either directly or indirectly dependent on soil ecology (21), and therefore also have the potential to emerge or reemerge as public health problems in areas where anthropogenic disruptions to soil ecology take place.

The mass poisoning of people on the Indian subcontinent by arsenic-laden drinking water is another example of disease emergence as a result of human overexploitation of environmental resources. The nonsustainable use of surface water and abstraction of groundwater, ultimately a result of population pressure, led to the inappropriate sinking of new wells into geologically unsuitable strata. Shallow aquifers in alluvial and deltaic sediments now deliver drinking water to tens of millions of people through millions of domestic bores, over half of which exceed the World Health Organization (WHO) arsenic guideline of 10 μg L^{-1} (22). With the causal relationship between skin changes (hyperkeratosis, squamous cell carcinoma, basal cell carcinoma) and arsenic exposure now well established (23), it is clear that the nonsustainable use of geological resources is already contributing significantly to the global disease burden—a disease burden that is becoming increasingly consistent with the changes expected from a third epidemiological transition.

The creation of a global geochemical database has been proposed as one means of providing a frame of reference on which to base interpretations of change and recommendations for the sustainable use of the Earth's land surface (24). Medical geology could, in this context, inform land use planning on the broadest scale, including mining, agriculture, and waste disposal. On this broadest planning scale, there is also a relationship between fossil fuel use, global warming, and increases in climate-related morbidity and mortality—arguably the greatest challenge that will face environmental health practitioners for several generations to come (25, 26).

CONCLUSION

Before the first epidemiological transition, a Neolithic medical geologist might have analyzed the health gain attributable to the discovery and use of particular geological resources. In agricultural and later industrial societies, medical geologists (albeit using different labels) made recommendations about maximizing soil yields and minimizing toxic pollution and human exposure. The medical geologist of the future will be a multidisciplinarian, able to span a breadth of geological (basic, applied, environmental), medical (clinical, epidemiological, sociological), and political sciences. As an emerging science, medical geology will provide a strong collaborative framework to start addressing environmental health problems including those that may arise from the third epidemiological transition will throw at us.

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