

Health impacts of coal and coal use: possible solutions

Robert B. Finkelman^{a,*}, William Orem^a, Vincent Castranova^b,
Calin A. Tatu^c, Harvey E. Belkin^a, Baoshan Zheng^d, Harry E. Lerch^a,
Susan V. Maharaj^e, Anne L. Bates^a

^aU.S. Geological Survey, Mail Stop 956, Reston, VA 20192, USA

^bNational Institute for Occupational Safety and Health, Morgantown, WV 26505, USA

^cClinical Laboratory No. 1, County Hospital Timisoara, Str. L. Rebreanu 156, RO-1900 Timisoara,

Romania 2 Institute of Public Health, Arad, Romania

^dInstitute of Geochemistry, Guiyang, Guizhou Province, 550002, PR China

^eArmed Forces Institute of Pathology, Washington, DC 20306, USA

Accepted 30 January 2002

Abstract

Coal will be a dominant energy source in both developed and developing countries for at least the first half of the 21st century. Environmental problems associated with coal, before mining, during mining, in storage, during combustion, and postcombustion waste products are well known and are being addressed by ongoing research. The connection between potential environmental problems with human health is a fairly new field and requires the cooperation of both the geoscience and medical disciplines. Three research programs that illustrate this collaboration are described and used to present a range of human health problems that are potentially caused by coal. Domestic combustion of coal in China has, in some cases, severely affected human health. Both on a local and regional scale, human health has been adversely affected by coals containing arsenic, fluorine, selenium, and possibly, mercury. Balkan endemic nephropathy (BEN), an irreversible kidney disease of unknown origin, has been related to the proximity of Pliocene lignite deposits. The working hypothesis is that groundwater is leaching toxic organic compounds as it passes through the lignites and that these organics are then ingested by the local population contributing to this health problem. Human disease associated with coal mining mainly results from inhalation of particulate matter during the mining process. The disease is Coal Worker's Pneumoconiosis characterized by coal dust-induced lesions in the gas exchange regions of the lung; the coal worker's "black lung disease".

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Arsenism; Fluorosis; Black lung disease; Balkan endemic nephropathy

1. Introduction

For at least the first half of the 21st century, coal will continue to be a very important energy source

required to sustain the standard of living in the United States and in many other developed countries. In many developing countries such as China and India, coal will be relied upon as the primary source of energy needed to fuel industrialization and to improve the standard of living of these large and growing populations.

* Corresponding author.

E-mail address: rbf@usgs.gov (R.B. Finkelman).

It has long been recognized that there are environmental consequences from using this inexpensive, widespread energy source. Extensive research has been conducted and reports written about the environmental problems associated with coal mining, processing, and combustion and related problems such as acid mine drainage, acid rain, smog, and greenhouse gas emissions.

In contrast, there has been relatively little in the geoscience literature about the direct human health impacts of coal use. In this article, we describe some of the more common direct health impacts of coal and coal use. These direct health problems may be very severe (leading to death), widespread (affecting many millions of people), and complex (requiring a multidisciplinary research approach). Nevertheless, these health problems can be minimized or even prevented. We firmly believe that coal scientists have an important role to play in helping to identify possible solutions to these problems.

This paper will be divided into three parts. The first part will deal with the health impacts of coal combustion. The second part will describe a severe health problem believed to be caused or exacerbated by the organic moieties leached by water from coal aquifers. The third part describes the health problems caused by inhalation of coal dust. These three scenarios are not, of course, the only potential health problems caused by coal but are used here to illustrate the type of research necessary to define, study, and mitigate the relationship between coal and human health.

2. Health problems caused by coal combustion

In its report (U.S. Environmental Protection Agency, 2000) to Congress on the health impacts of coal-burning electric utilities, the U.S. Environmental Protection Agency concluded that, with the exception of mercury, there is no compelling evidence to indicate that emissions of trace elements or organic compounds cause human health problems. The health problems attributed to mercury are not due to direct exposure to emissions from coal-burning power plants but are due to methylation of the mercury and resultant amplification of mercury concentration as it moves up the food chain. The absence of detectable

health problems from coal combustion in the US is in part due to the fact that the coals burned in the US generally contain low to modest concentrations of potentially hazardous elements (Bragg et al., 1997). Moreover, the organic compounds of concern do not form, or are destroyed at the temperatures achieved by utility boilers and most US coal-burning utilities employ sophisticated pollution control systems that efficiently reduce the emissions of potentially hazardous substances.

Such is not the case in many developing countries, especially where coal is used for heating and cooking in homes. Residential use of coal can present serious human health problems because the coals are generally mined locally with little regard to their chemical composition and the coals are commonly burned in poorly vented or unvented stoves directly exposing residents to the emissions.

Several dramatic direct health problems attributed to residential coal use have been recognized in China and will be used here to illustrate this issue. China is the world's largest coal producer and coal consumer. Coal production has increased steadily during the past 25 years to nearly 1.4 billion metric tons in 1996 (Coleman, 1998). In contrast to most developed countries, such as the US, where residential coal use constitutes a small fraction of 1% of coal consumption, a substantial portion of China's coal is used for domestic energy needs. Florig (1997) estimates that more than 75% of China's primary energy needs are supplied by residential coal use. Coal stoves and small coal boilers provide more than 50% of the energy for urban households and 22% of rural households rely on coal (Florig, 1997). Considering that 70% of the population in China resides in rural areas, these data indicate that about 400 million people in China rely primarily on coal for their residential energy needs.

2.1. Health problems caused by trace element emissions

Wood had long been the primary source of energy in southwest China but by the early part of this century the forests were largely denuded and the residents were forced to seek other sources of fuel. In southwest Guizhou Province (Fig. 1), surface exposures of coal are plentiful and coal quickly became the primary fuel

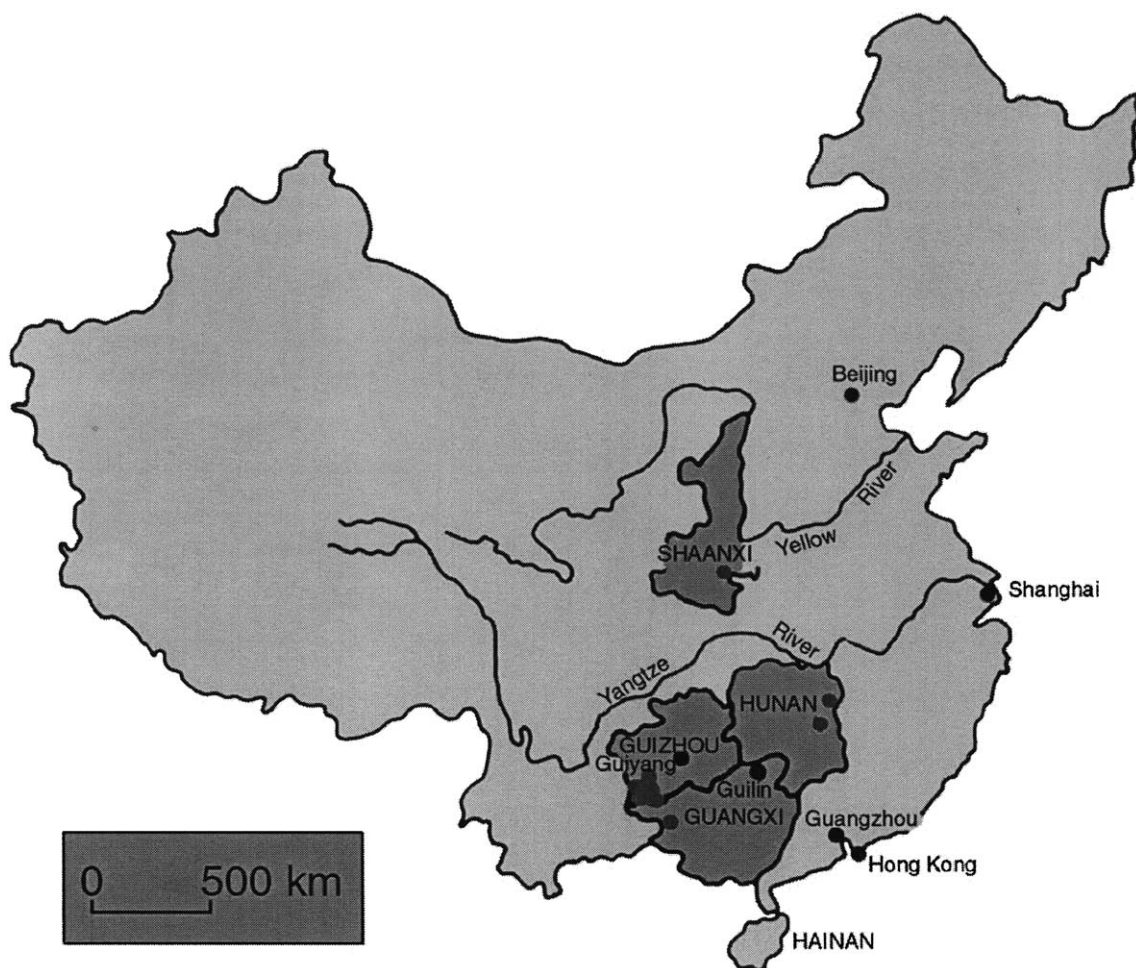


Fig. 1. Map of China indicating provinces in which there are reported health problems due to domestic coal combustion.

for residential use. Unfortunately, some of these coals have undergone mineralization, resulting in the enrichment of potentially toxic trace elements such as arsenic, fluorine, mercury, antimony, and thallium.

Burning the mineralized coals in unvented stoves volatilizes the toxic elements and exposes the local population to the toxic elements in the emissions. The situation is exacerbated by the practice of drying crops directly over the coal fires. In the autumn, it is commonly cool and damp in the higher elevations of Guizhou Province. It is common practice for the residents of this region to dry their corn and chili peppers directly over coal fire.

2.2. Arsenic

Chronic arsenic poisoning, which affects at least 3000 people in Guizhou Province, has been described by Zheng et al. (1996). 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), Bowen's disease (dark, horny, precancerous lesions of the skin), and squamous cell carcinoma (Fig. 2).

Zheng et al. (1996) have shown that chili peppers dried over open coal-burning stoves may be a principal vehicle for the arsenic poisoning. Fresh chili

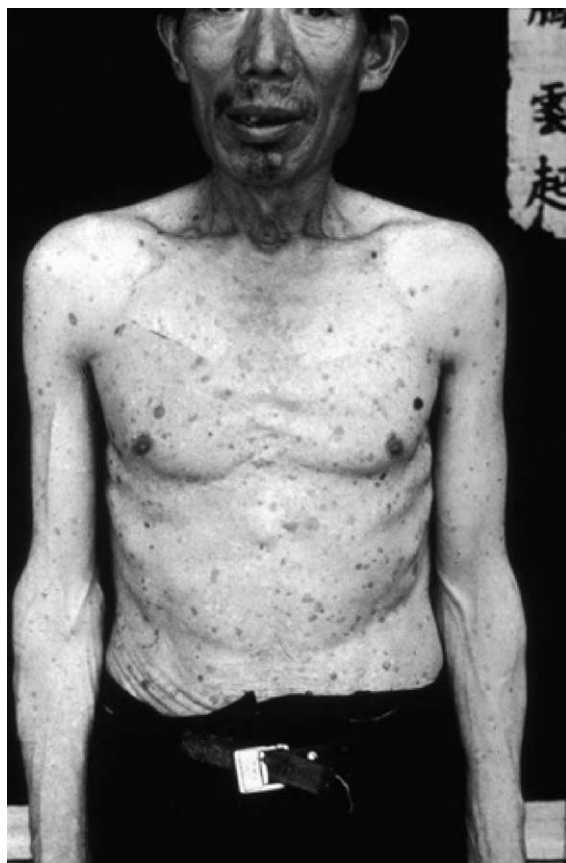


Fig. 2. Extensive scaly lesions (hyperkeratosis) are evident on the chest of a resident of this region. The dark spot over the left breast was diagnosed as Bowen's disease.

peppers have less than 1 ppm arsenic. In contrast, chili peppers dried over high-arsenic coal fires can have as much as 500 ppm arsenic. Significant amounts of arsenic may also come from other tainted foods, ingestion of dust (samples of kitchen dust contained as much as 3000 ppm arsenic), and from inhalation of indoor air polluted by arsenic derived from coal combustion. The arsenic content of drinking water samples was not considered to be a significant contributing factor.

Belkin et al. (1997a,b, 1998) and Ding et al. (2001) recently conducted detailed chemical and mineralogical characterization of the arsenic-bearing coal samples from this region. They analyzed about 25 coal samples collected from several locations within the Guizhou Province. Instrumental neutron activation

analyses of the coal indicate arsenic concentrations as high as 35,000 ppm! The magnitude of this concentration can be seen by comparison with US coals. The mean concentration for arsenic in nearly 10,000 US coal samples is approximately 22 ppm, with a maximum value of about 2000 ppm (Bragg et al., 1997).

Belkin et al. (1997b) examined polished blocks of the coal using a scanning electron microscope equipped with an energy-dispersive X-ray analyzer (SEM-EDS) and an electron microprobe (EMP). They observed a wide variety of As-bearing mineral phases in the coal samples. Pyrite was the most common sulfide, occurring as framboids, euhedral crystals, and irregular shapes. The range of As in pyrite determined by EMP analyses was from the detection limit (~ 100 ppm) in unaltered framboids to about 4.5 wt.% in grains adjacent to arsenopyrite crystals (Fig. 3a). Arsenopyrite occurred in a variety of habits, including large 150–250 μm crystals, narrow, 1–5 μm veins, and small crystals. Selenium contents in arsenopyrite were fairly uniform (0.15–0.2 wt.%). A third As-bearing sulfide, composed of As, Pb, and S, was present rarely.

Three samples from the same location had As concentrations in excess of 3 wt.% and were mineralogically unusual. Although they contained some small grains of As-bearing pyrite, the concentration of this phase was completely inadequate to account for the As abundance on a whole coal basis. However, in SEM back-scattered electron images, a distinct banding characterized by differing image brightness was easily observed. Some of this banding formed box-like arrangements but, in all cases, the bands appeared to have sharp edges. The bands ranged from a few micrometers to tens or hundreds of micrometers in thickness. SEM-EDS results showed that these bright bands were highly enriched in As. Semiquantitative analysis by SEM-EDS demonstrated that the bright bands contain As at levels ≈ 3 wt.% (Fig. 3b and c). Fe concentrations in the bands were low but were always present at levels from 0.2 to 0.4 wt.%, S was the only other major element found. Using an SEM, no discrete As-bearing phases were resolved in these bands at 50,000 \times magnification nor were they detected in thin fragments of one sample examined by an advanced field emission transmission electron microscope at magnifications of 1 million times.

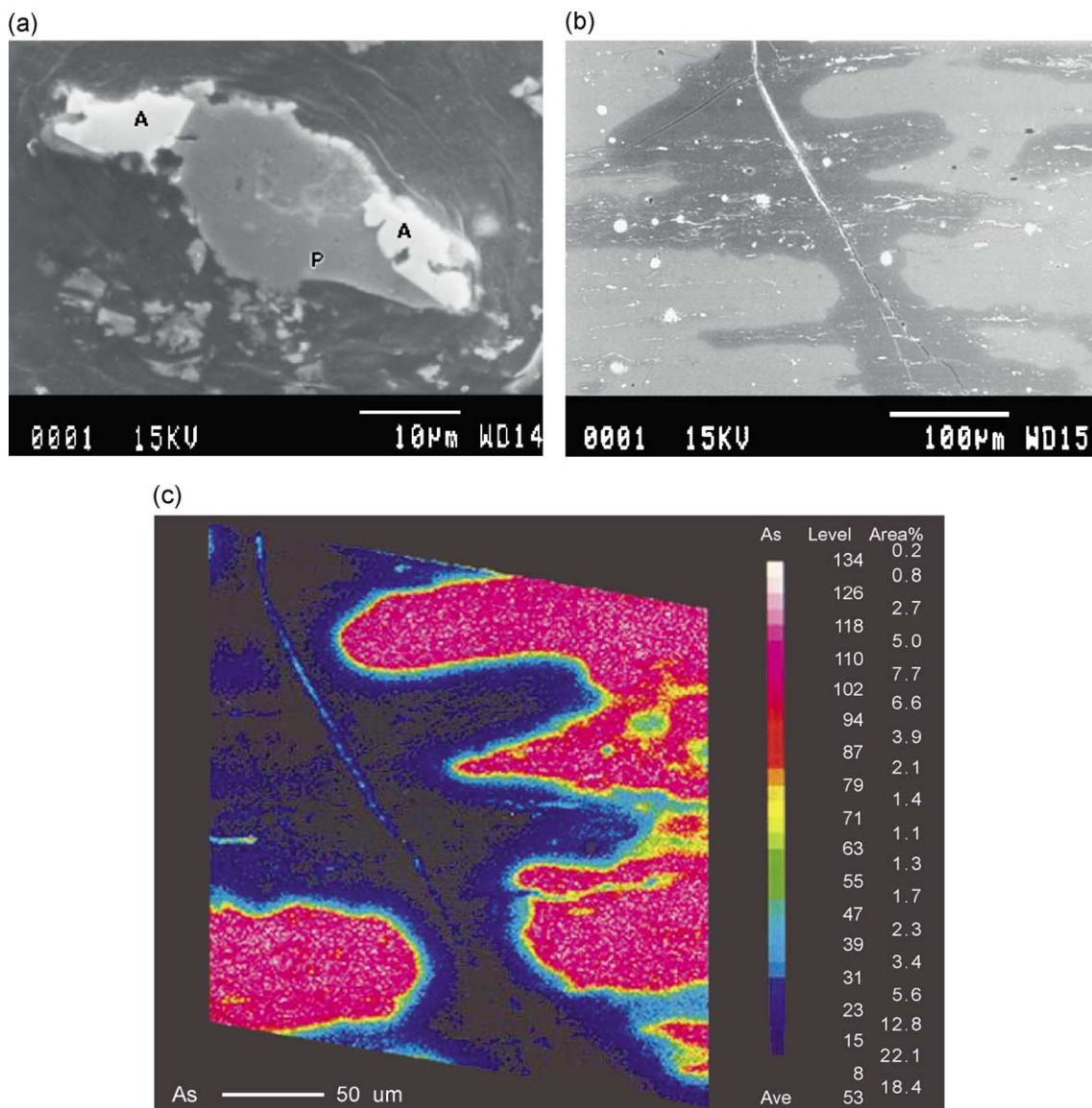


Fig. 3. (a) Scanning electron microscope (SEM) back-scattered electron image of polished coal showing a pyrite grain (P) and adjacent arsenopyrite crystals (A). (b) SEM back-scattered electron image of polished block of arsenic-rich coal. Dark areas are coal, bright areas are mainly pyrite, milky area is coal containing organically bound arsenate. Fluids moving through the fracture in the coal appears to have removed arsenic from the organic matrix. (c) X-ray map depicting the distribution of arsenic in the coal. Red areas are high concentrations, and blue areas are low concentrations. Compare distribution of arsenic to the outline of the milky area in C.

Thus, finely dispersed arsenopyrite, As-bearing pyrite, or any other As-phase was ruled out as the source of the As.

To define the nature of bonding in the arsenic-bearing phases, a reconnaissance study of two high-

energy X-rays from a synchrotron source (Huffman et al., 1994). Collection of diffraction spectrum intensity across the X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine struc-

ture (EXAFS) regions of an absorption spectrum can provide three-dimensional information on the electronic state and chemical coordination for each crystallographic site of the chosen element. Results from this work demonstrate that $\sim 100\%$ of the As in one sample is AsO_4^{3-} and that about 75% of the As in the other sample is AsO_4^{3-} with the balance (25%) as sulfide-bound As.

Mineralogical characterization of the coals from Guizhou Province may help elucidate the geologic process that created the high-arsenic coals and the relationship of the high-arsenic coals to the regional geology. Knowledge of these processes and relationships may help determine the regional distribution of these environmentally dangerous coals. Information on the arsenic mineralogy may also help us to anticipate the behavior of arsenic during coal combustion. Preliminary characterization of residual ash in coal-burning stoves indicates high retention of arsenic. Mineralogical characterization in conjunction with combustion tests may determine if one or more of the arsenic-bearing phases is primarily responsible for adsorption of arsenic on the chili peppers.

2.3. Fluorine

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 surrounding areas suffer from various forms of fluorosis (Zheng and Huang, 1989; Zhang and Cao, 1996) and it has also been reported from 13 other provinces, autonomous regions, and municipalities in China (Ando et al., 1998).

Typical signs 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 childhood, can result in severe bone deformation (Fig. 4).

The etiology of fluorosis is similar to that of arsenism in that the disease is derived from foods dried over coal-burning stoves. Zheng and Huang (1989) have demonstrated that 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 south-



Fig. 4. Bone deformation due to nutritional deficiency combined with exposure to high levels of fluorine from domestic coal combustion.

west China. The mode of occurrence of fluorine in the coal is unknown. 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. Ando et al. (1998) determined fluorine contents of coals from two mines (559 and 802 ppm) and in the associated soils (592 and 669 ppm). They estimated that 97% of the fluoride exposure came from food consumption and 2% from direct inhalation. Zhang and Cao (1996) report mean fluorine levels in coals from 11 regions in China to range from 203 to 1513 ppm with a maximum value of 3762 ppm.

2.4. Mercury

There is also considerable concern about the health effects of mercury and the proportion of anthropogenic mercury in the environment (EPA, 1998). So far, there is no direct evidence of health problems caused by mercury released from coal but there are circumstances where poisoning from mercury released from coal combustion may be occurring. Zhou and Liu (1985) reported on chronic thallium poisoning in Guizhou Province, China, where the source of the thallium poisoning appears to be from vegetables grown on a mercury/thallium-rich mining slag. Most symptoms, such as hair loss, are typical of thallium poisoning. However, loss of vision in several patients from this region was considered to be unique (Dart,

1996). Mineralogical analysis of the coal being used in the homes of people having visual impairment revealed abundant mercury minerals. Chemical analysis of a coal sample being used in Guizhou Province, China, indicates a mercury concentration of 55 ppm, which is about 200 times the average mercury concentration in US coals.

2.5. Selenium

Zheng et al. (1992) report nearly 500 cases of human selenosis in southwest China, which are attributed to the use of selenium-rich carbonaceous shales known locally as “stone coal.” The stone coals have as much as 8390 ppm selenium. This selenosis is attributed to the practice of using combustion ash as a soil amendment. This process introduced large amounts of selenium into the soil and resulted in selenium uptake by crops. Symptoms of selenium poisoning include hair and nail loss.

2.6. Radioactivity

Although there has been speculation that radioactivity from coal or coal combustion products presents a health hazard (Gabbard, 1993), no evidence has been offered to support this contention. Coals may concentrate uranium to a large degree (Swaine, 1990). However, these uraniumiferous coals are very rare and none are currently being used in the US. Data on nearly 10,000 US coal samples (Bragg et al., 1997) indicate that the concentrations of radioactive elements (uranium, thorium, and potassium) are generally no higher in these coal samples than they are in other common rocks and soil.

2.7. Organic compounds

Esophageal cancer is a common fatal cancer and the fourth leading cause of cancer death in China. Parts of Henan Province in north–central China have some of the highest rates of esophageal cancer in the world, with annual age-adjusted mortality rates of up to 169 per 100,000 and cumulative death rates of over 20% by age 75 for both sexes (Crowley et al., 1998). Coal combustion has been cited as one of the primary causes of the esophageal cancers in China but the dominant causative agents of the cancer remain

unclear. Polycyclic aromatic hydrocarbons (PAHs) released during unvented coal combustion in homes in China have been cited as the primary cause for the highly elevated incidence of lung cancer (Mumford et al., 1987). The PAH levels in homes burning “smokey” coal are so high that the resulting lung cancer mortality rate is five times the national average of China (Mumford et al., 1995).

2.8. Conclusions

Emissions of potentially hazardous air pollutants from utility coal combustion in the US may not present a threat to human health. Nevertheless, domestic coal use in developing countries has caused serious human health problems. Coal scientists and technologists are ideally positioned to help medical and public health specialists improve public health in these countries. A better knowledge of coal quality parameters may help to minimize some of the health problems caused by domestic coal use. Information on the concentrations and distributions of potentially toxic elements in coal may assist people dependent on local coal sources to avoid those areas of a coal deposit having undesirably high concentrations of toxic compounds. Information on the modes of occurrence of potentially toxic elements and the textural relations of the minerals and macerals in which they occur may help us to anticipate the behavior of the potentially toxic components during coal cleaning, combustion, weathering, and leaching. Coal characterization offers geoscientists opportunities to directly contribute to improve public health.

3. The Pliocene lignite hypothesis and the etiology of Balkan endemic nephropathy (BEN)

3.1. Introduction

Balkan endemic nephropathy is an irreversible kidney disease of unknown origin, geographically confined to several rural regions of Bosnia, Bulgaria, Croatia, Romania, and Serbia (Fig. 5). The disease occurs only in rural areas, in villages located in alluvial valleys of tributaries of the lower Danube River (Fig. 6). The first documentation of a disease resembling BEN was made almost six decades ago in regions

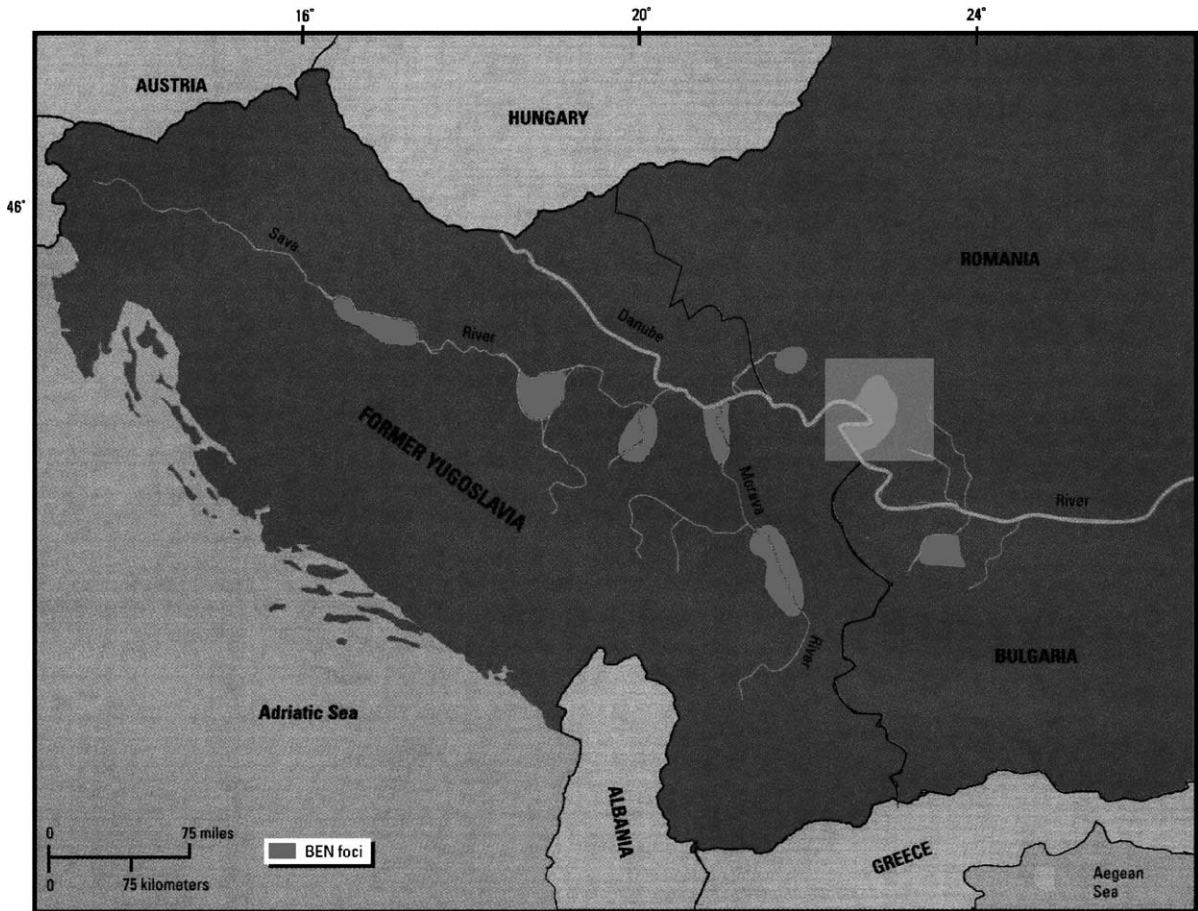


Fig. 5. Map showing the regions with clusters of villages having BEN, so-called endemic regions.

comprising the former Yugoslavia (Danilovic et al., 1957). Shortly thereafter, similar descriptions came from Bulgaria and Romania (Radovanovic et al., 2000; Ceovic et al., 1992; Craciun and Rosculescu, 1970). The distribution of BEN includes regions of central and southeastern Serbia, southwestern Romania, northwestern Bulgaria, southeastern Croatia, and parts of Bosnia and Kosovo. It is estimated that several thousand people in the affected countries are currently suffering from BEN and that thousands more will be diagnosed with BEN in the next few years. BEN has historically been perceived as much more than just a simple kidney disease, or even a simple medical problem, but as a major social and even political problem (Radovanovic et al., 2000). As a consequence, BEN has been a major research priority for

decades, involving multidisciplinary approaches and varied scientific disciplines, including: environmental medicine, microbiology, oncology, radiation biology, epidemiology, cytogenetics, geology, hydrogeology, and biogeochemistry. Despite these research efforts by regional and international scientific groups, BEN is still a medical enigma in many respects, and its etiology a matter of contradiction and controversy.

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, with a prime role played by the geological background of the



Fig. 6. Picture of an endemic village in southwestern Romania. Endemic villages are typically located in alluvial valleys, with a tributary of the Danube River usually running through the center of the villages. Coal deposits (Pliocene lignites) are located in the hills surrounding the villages, and are sometimes actively mined.

endemic settlements (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. The population of villages in the endemic areas uses well/spring water almost exclusively for drinking and cooking, and is therefore potentially exposed to any toxic organic compounds in the water. The presumably low levels of toxic organic compounds present would likely favor relatively slow development of the disease over a time interval of 10 to 30 years or more. The frequent association of BEN with 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.

3.2. The Pliocene lignite hypothesis of BEN etiology

The hypothesis relating BEN and the associated urothelial tumors to the close proximity of endemic

villages and Pliocene lignite deposits was originally formulated by Feder et al. (1991), based on research performed in the early 1990s in the countries of the former Yugoslavia. Field and geological investigations revealed that all endemic regions except one are in close proximity to *known* deposits of Pliocene lignites (Feder et al., 1991; Goldberg et al., 1994), as shown in Fig. 7. The reason for the one exception is unclear. This endemic area is in central Serbia and does have some nearby Pliocene lignite deposits, although not in as direct proximity as found in other endemic areas. This area of exception may have uncharacterized lignite deposits or may be hydrologically connected to nearby lignite beds, more work being needed to document the association. The hypothesis emerging from these observations is that groundwater leaches toxic organic compounds from these low rank coals, with subsequent transportation of organics to wells in the alluvial valleys below the lignite deposits. The inhabitants of the rural villages who rely on well water for drinking, cooking, and other purposes are, therefore, exposed to toxic organics for long periods of time. Although the concentrations of organic molecules in the well water may be low, long exposure and/or accumulation in body

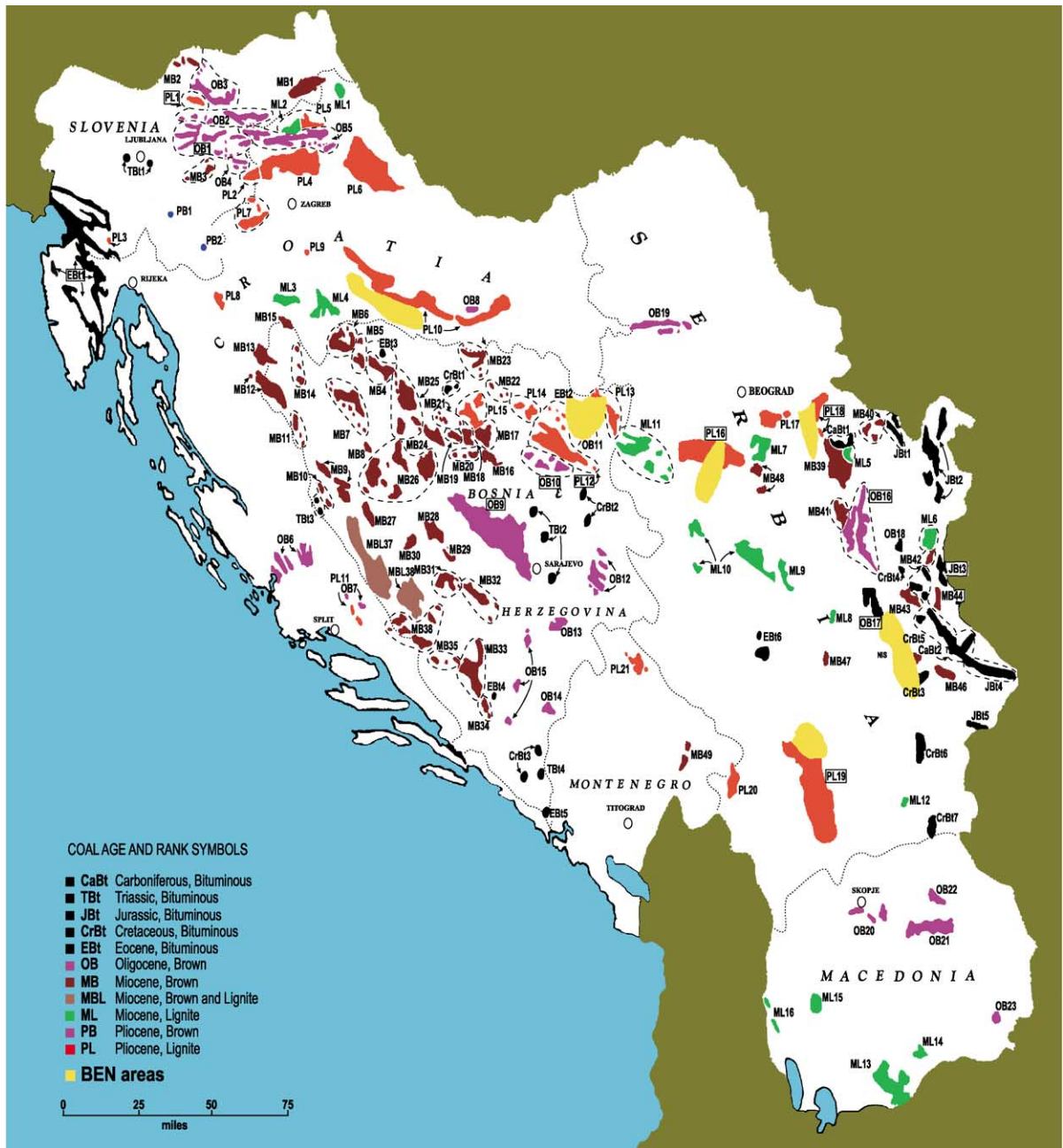


Fig. 7. Map showing the geographic correspondence between the occurrence of endemic villages and Pliocene lignite deposits for the former Yugoslavia. A similar correspondence has also been recently shown for Romania and Bulgaria.

tissues over time may lead to kidney lesions, the development of urothelial carcinomas in some individuals, and ultimately to full-blown BEN. Recently,

the close association of endemic villages and Pliocene lignite deposits has been documented for Romania and Bulgaria (Tatu et al., 2000).

3.3. *Why study BEN?*

BEN is a disease that causes suffering and death in the thousands of people currently afflicted with the disease, and looms in the future for the estimated 100,000 others who are living in the areas at risk for BEN. Finding the cause for this disease would be the first step in facilitating the development of methods for eliminating or minimizing exposure to the toxic substances that may be responsible for the onset of BEN. The eventual elimination of BEN is reason enough to study its root causes. Apart from this, BEN is a medical geology case study of the impact of toxic substances from coal on human health that can help establish closer working relationships between the geoscience and biomedical communities. The discrete and relatively small size of the endemic regions, the stable population, and the well-described clinical aspects of BEN make it especially useful as a model for other diseases that may be linked to toxic organic substances from coal. For example, in the USA, states with the highest incidence of urothelial tumors also have extensive low-rank coal deposits (although older and higher in rank than the Balkan lignites) and predominantly rural populations. A causal link between the occurrence of upper urinary tract cancers and toxic organics leached from coal cannot be completely excluded in this latter case, more geomedical research being needed to assess this connection. Coal deposits are present worldwide and several direct links between coal usage and combustion and disease in humans have been documented (Finkelman et al., 1999), but contamination of water by toxic organics and inorganics derived from coal could also have an impact on human health in susceptible population groups.

3.4. *Medical aspects of BEN*

BEN is a kidney disease characterized by slow progression to end-stage renal failure and terminal uremia. Clinically, BEN is a tubulo-interstitial nephropathy with a relatively nonspecific morphopathological aspect. In the advanced stages, kidneys are reduced in size symmetrically and may weigh 50 g or less (<1/3 normal kidney size). The disease progresses slowly with the occurrence of nonspecific symptoms (lassitude, fatigue, headache, weight loss,

reduced appetite, and pale skin), and specific signs of kidney damage (reduced tubular transport, intermittent proteinuria with low molecular weight proteins such as β 2-microglobulin, and a gradual rise in blood nitrogen) (Radonic and Radosevic, 1992). Although some symptoms seem to be specific for BEN, there is no clear-cut clinical or pathological definition that is solely sufficient for the diagnosis of this disease. Anemia (normocytic, normochromic, sometimes hypochromic and even of aplastic type) is one of the major symptoms of BEN, and it seems to develop well before other signs of the disease become manifest. Other medical and epidemiological features of the disease include: focal occurrence of the clinical cases, family aggregation without an obvious pattern of Mendelian genetic inheritance, a long subclinical incubation period followed by rapid onset of end-stage renal disease, residence of at least 10–20 years in one or more of the endemic villages, occurrence only in adults (age 30–50 being most heavily affected, while almost no children or individuals above 70 years develop the disease), a sex distribution (female/male) of $\sim 1.5/1$, no preferential disease pattern in different ethnic and religious groups in the region, restriction to a rural/farming population, presence of hypertension in only 20% of affected individuals, and a very high frequency of upper urinary tract carcinomas. The occurrence of upper urinary tract (uroepithelial) cancers in BEN is of particular interest. These tumors are rare in the general population, and their 100–200 times higher incidence in BEN patients (Ceovic et al., 1992) led to speculation that the two diseases could be causally related, or that the urinary tract tumors should be seen as a symptom, although inconstant, of BEN. BEN and carcinomas of the renal pelvises or ureters, however, sometimes may develop independently, the intriguing finding being their clustering in the BEN endemic regions.

BEN is a long-lasting disease, and once end-stage renal disease is diagnosed in BEN patients, the therapeutical approaches are only symptomatic. Hemodialysis combined with the other therapeutical interventions for patients with end-stage renal failure (e.g., low protein diet and drugs for correcting metabolic disorders and hypertension) is usually the only treatment available to BEN patients (Fig. 8). Kidney transplantation has been performed on a few individuals with BEN and no recurrence of the disease has



Fig. 8. A patient with BEN at a dialysis clinic in Romania.

been noted on the transplanted kidneys. Economic considerations, however, generally precludes kidney transplantation as a viable option for affected population. As a result, BEN patients in the end-stage renal disease phase face a poor quality of life from long-term dialysis, often contracting hepatitis as a result of treatment.

3.5. The Pliocene lignites linked to BEN

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. Macroscopically, the Pliocene lignites from the endemic areas are composed primarily of endured fossil wood. The ancient swamps that formed the Balkan Pliocene lignites developed about 3–5 million years ago in subtropical conditions, where rivers entered ancient seas in the Panonian and Dacian Basins of the Balkan Peninsula. Vegetation in these ancient swamps included cypress and sequoia trees, as well as smaller swamp plants characteristic of subtropical areas.

Although abundant, Pliocene coals have a restricted distribution. Besides the Balkans, Pliocene lignite deposits are found in Italy, Turkey, Greece, and Myanmar. Also, low-rank, unaltered coals such as the Pliocene lignites from the Balkans are distributed

worldwide (e.g., Australian brown coals, U.S. North Dakota and Gulf Coast lignites, Chinese lignites, etc.). In the Pliocene lignite hypothesis for BEN etiology, however, other factors besides the presence of low-rank coals must also be in play. The hypothesis also implies many or all of the following circumstances: the right hydrologic conditions for leaching and transport of the toxic organic compounds from the coal to the wells, 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. In underdeveloped nations such as Myanmar or rural regions in China, the average life span may be too short for a disease like BEN to emerge, and an established medical system may not exist for recognition of the disease. More developed nations such as the USA and Australia may supply treated water even to rural populations, eliminating the potential for exposure of the population to toxic organic substances. On the other hand, diseases like BEN may exist unrecognized. In the USA, for example, some of the highest incidences and deaths from urothelial cancer occur in North and South Dakota, rural states with extensive low-rank lignite deposits. Additional geologic, geochemical, and epidemiological work is needed to explore this potential environmental–medical problem. The linking of Pliocene lignites to BEN (Pliocene lignite hypothesis) is appealing in that it accounts for the *geographical restriction*, as well as for the epidemiological and clinical features of BEN. Much more work is needed, however, to solidify the Pliocene lignite hypothesis as a primary or contributing factor in the etiology of BEN.

3.6. Recent evidence supporting the Pliocene lignite hypothesis

The preliminary work (Feder et al., 1991; Finkelman et al., 1991) in the former Yugoslavia that led to the initial formulation of the Pliocene lignite hypothesis in BEN etiology was mentioned earlier. Additional work was conducted in 1993 (Orem et al., 1999) (1) to examine the chemical composition of

Pliocene lignites from the endemic areas, (2) to conduct laboratory leaching experiments on these coals, and (3) to determine the concentrations of aromatic compounds in well water from an endemic and a control village. Chemical analysis of Pliocene lignites from the endemic areas using ^{13}C nuclear magnetic resonance spectroscopy (NMR) showed the coals to be of very low rank (i.e., highly unaltered), with a high degree of organic functionality (e.g., methoxyl, phenolic, and O-bonded aliphatic hydrocarbon groups) (Orem et al., 1999). Lignite samples were leached with distilled water in the laboratory to simulate groundwater leaching of Pliocene lignites. The resulting aqueous extract had a distinct yellow tint, indicating the presence of dissolved organic substances, and ^{13}C NMR spectra of the dissolved organic matter showed it to have a high degree of condensed aromatic character consistent with polycyclic aromatic structures. Well water samples from two endemic villages and one control village in Yugoslavia were analyzed for dissolved aromatic compounds using GC/MS (Orem et al., 1999). A total of 14 compounds were identified in the samples, with concentrations at the low ppb level. With the exception of phenol, all the identified compounds were polycyclic aromatic hydrocarbons, some of which are human carcinogens. The presence of PAHs in well water suggests a possible source from coal, although other sources cannot be excluded. Concentrations of these compounds were higher in the well water from the endemic villages compared with the control village.

Additional research was conducted in the main Romanian endemic area (Drobeta Turnu Severin), located in southwest Romania during March and August 2000, jointly supported by the U.S. Geological Survey, NATO, and the Romanian Ministry of Health. Ten endemic locations and seven nonendemic sites in the area were visited for collection of well/spring water samples for analysis of dissolved organic and inorganic chemical species. In addition, Pliocene coal and water samples were collected from three Pliocene lignite mines located in the main Romanian endemic area. Villages for well water sampling were selected based on medical records showing their endemic character, obtained from the Drobeta Turnu Severin County Hospital (F. Margineanu, personal communication). Results from inorganic analysis of water samples showed no consistent

or significant differences for anions, nutrients, or the general inorganic parameters measured between endemic and nonendemic sites. Nitrate concentrations were elevated in most of the water samples, reaching values as high as 225 mg/l, and exceeding U.S. EPA guidelines for drinking water at all sites. Since no relevant difference was observed between the endemic and nonendemic sites for nitrate, however, it cannot be directly linked to BEN etiology. Concentrations of metals in the water samples were also generally similar at endemic and nonendemic sites, except for zinc, which appeared to be deficient at the endemic sites.

In contrast to the inorganic geochemistry, dissolved organic constituents in the well and spring water samples collected from the main Romanian BEN endemic area contain a greater number of different compounds (aliphatic and aromatic), and in much higher abundance ($>10\times$), compared with water samples from the nonendemic sites. Many of the organic compounds found in the endemic area water samples were also observed in water extracts of the Romanian Pliocene lignites, suggesting a possible connection between leachable organics from the coal and organics in the well water samples. The identification of the hundreds of individual compounds in the water samples analyzed by GC/MS is continuing. Preliminary assessment shows the presence of both aliphatic and aromatic compounds, rich in oxygen (hydroxy, phenol, methoxy, aldehyde, keto, carboxy, etc.) and nitrogen (amino) containing functional groups.

Based on the hypothesis that water is the carrier of the BEN-causing agent, we conducted laboratory extractions of different coals with polar solvents (methanol and water) as an experimental model for their natural bioavailability. Methanol extracts of Pliocene lignites from the endemic area have a geochemical signature distinct from that of higher rank coals, and characterized by a much higher number and abundance of organic compounds from GC/MS analysis (Tatu et al., 2000a,b). Water extracts of the Pliocene lignites from the endemic areas also appear to be distinct from water extracts of other lignites collected from areas in the Balkans with no incidence of BEN. The number and concentration of organic compounds in water extracts of the endemic area Pliocene lignites are unmatched by any lignites from nonendemic areas. The types of organic compounds present in the water

extracts of the endemic area lignites include aliphatic (mainly cycloalkanes/alkenes and steranic structures) and aromatic (mono- and polyaromatic terpanes, polycyclic aromatic hydrocarbons) structures. Many of these compounds have attached oxygen-based functional groups (hydroxy-, phenol-, keto-, methoxy-) and some of them contain heterocyclic nitrogen or amino groups, structural features that could make them nephrotoxic and carcinogenic. Very few of these components are encountered in the water extracts of lignite from the nonendemic areas. This difference could be due to distinctive coal-forming conditions during the last period of the Tertiary in the corresponding BEN endemic and nonendemic areas (see Tatu et al., 2000b).

All of the results discussed above support the Pliocene lignite hypothesis as a viable factor in the etiology of BEN. Work is continuing to add further evidence in support of this hypothesis, including clinical studies of the effects of water extracts of Pliocene coals on human cell cultures.

3.7. Conclusions

It may be that BEN is a multifactorial disease, with toxic organics from coal being one necessary factor 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 a reasoned conceptual model of the disease etiology of BEN.

4. Human disease associated with coal mining

The first discussion above concentrated on adverse health effects resulting from exposure to metals or dusts generated during the burning of coal. However, it has long been recognized that inhalation of dust generated during mining is associated with a lung disease unique to coal (Collis and Gilchrist, 1928; Heppleston, 1947). This disease is Coal Workers' Pneumoconiosis (CWP), which is defined by coal dust-induced lesions in the gas exchange regions of the lung. The Federal Coal Mine Health and Safety Act of 1969 legislatively has defined "black lung disease" to include not only CWP but also obstructive lung diseases, such as chronic bronchitis and emphy-

sema, as well as silicosis associated with an employment history in coal mines.

Data indicate a direct relationship between the mass of respirable coal mine dust inhaled and the incidence and severity of CWP (Walton et al., 1977; Hurley et al., 1982). The following chain of events has been proposed for the initiation and progression of CWP:

1. Inhaled coal dust concentrates at the bifurcations of the respiratory bronchioles.
2. Local inflammation results in the accumulation of phagocytic cells (alveolar macrophages) that scavenge coal dust particles, forming lung lesions known as coal macules.
3. With further exposure, coal macules enlarge to form coal nodules.
4. As the lesions condense, surrounding tissue is torn forming scar emphysema.
5. Connective tissue becomes associated with these lesions leading to progressive massive fibrosis (PMF).

4.1. Histological appearance of CWP

Coal Workers' Pneumoconiosis is categorized histologically according to severity as simple and complicated CWP (Kleinerman et al., 1978). Simple CWP is characterized by the formation of coal macules concentrated at the bifurcations of respiratory bronchioles mostly in the upper lung lobes. Coal macules are irregularly shaped lesions containing coal dust laden alveolar macrophages with a fine network of connective tissue (reticulin and collagen fibers). Coal macules range in size from 1 to 6 mm in diameter. With continued exposure, coal nodules develop which range in size from micronodules (<7 mm in diameter) to macronodules (8 mm–2 cm in diameter). Coal nodules have a centralized zone of concentric collagen fibers and are stellate in shape. Condensation of the lesion is associated with localized scar emphysema. The histological progression of CWP is demonstrated in Fig. 9.

Complicated CWP is also called progressive massive fibrosis. In PMF, fibrotic lesions become extensive forming coal dust laden lesions that are well demarcated, irregular, or rounded in shape, with collagen bundles. Dead cells are often found in the

center of these lesions. PMF lesions are 2 cm or greater in diameter and are often associated with vascular degeneration (Fig. 9).

CWP can also be associated with other pulmonary pathologies. Caplan's syndrome is characterized by pulmonary nodules that resemble classic subcutaneous rheumatoid nodules. They appear pale yellow with a granular central zone that contains dead cells and eosinophils. The pulmonary lesions of Caplan's syndrome are associated with circulating rheumatoid

factors (Caplan, 1953; Gough et al., 1955). Silicosis, a fibrotic disease associated with inhalation of crystalline silica, is often found in conjunction with CWP. The silicotic nodule is characterized by collagen arranged in a whorled fashion. Data indicate that in miners studied as part of the National Coal Workers' Autopsy Study from 1972 to 1996, 23% had pulmonary silicosis and 58% had lymph node silicosis (Green et al., 1998). The job categories of tunnel driller, roof bolter, and railway man are associated

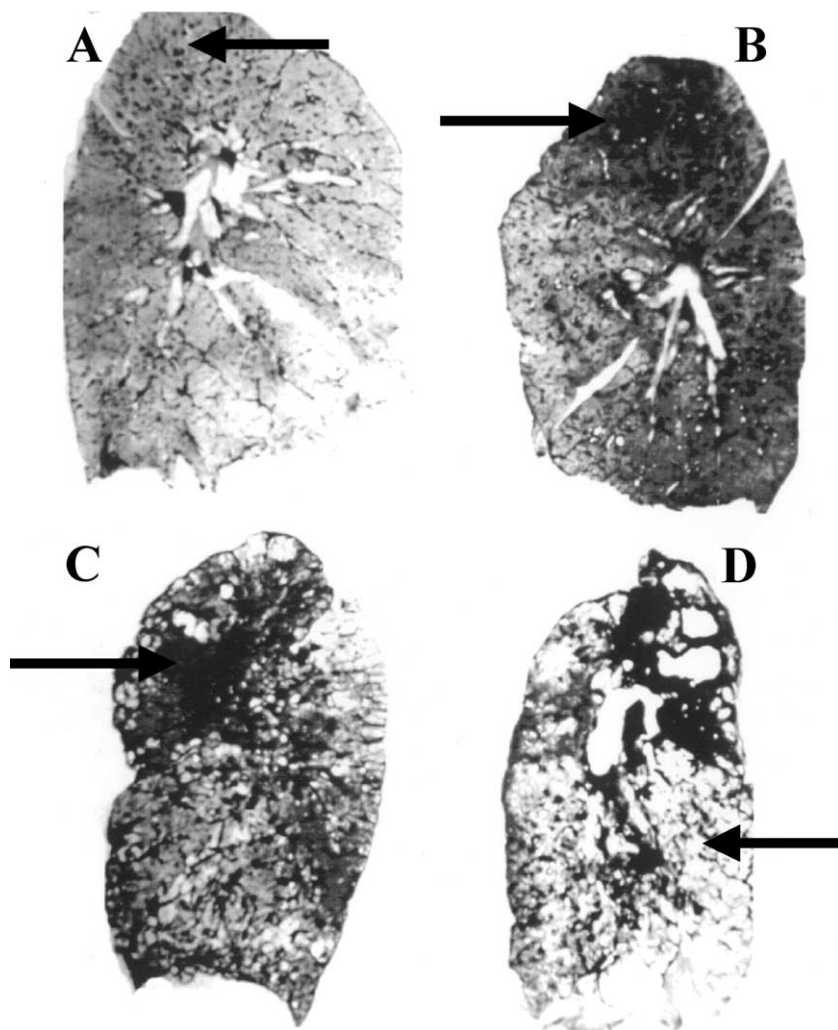


Fig. 9. Gough sections of lungs of coal miners, demonstrating the progression of CWP. Gough sections are thick sections of a whole lung lobe. (A) Coal macules (arrow) within relatively normal tissue. (B) Coal nodule (arrow) formation with increasing coal dust deposition in the lung. (C) Large fibrotic lesion (arrow) with areas of emphysema (lung tissue destruction). (D) Large areas of lung tissue destruction (emphysema) noted by the arrow.

with the highest incidence of silicosis (Green et al., 1989).

4.2. Radiographic appearance of CWP

Radiographically, CWP is classified according to the size, shape, and profusion of the lesions using standard reference films developed by the International Labor Organization (Vallyathan et al., 1996). In simple CWP, radiographic opacities range in size from 0.001 to 1.0 cm. With complicated CWP, there is an increase in the number and size of opacities with sizes of 1 cm or greater. Complicated CWP is categorized as more severe as PMF opacities enlarge. Profusion category is directly related with coal mine dust burden (Rossiter, 1972a,b). There is also a good correlation between pathologic grading of disease severity and X-ray category (Vallyathan et al., 1996). However, moderate to severe histologic changes must be present before a chest radiograph is judged to be abnormal.

4.3. Pulmonary function changes with CWP

Early stages of simple CWP are symptomless with little decline in lung function (Morgan and Lapp, 1976). Miners with simple CWP showed only a small decline in gas exchange that did not compromise arterial oxygen content (Musk et al., 1981). However, increases in residual volume, suggesting collapse of small airways due to focal emphysema, have been reported in simple CWP (Legg et al., 1983). As CWP progresses to the complicated form, irreversible airway obstruction, noted as a fall in dynamic lung volumes measuring air flow and a decrease in arterial oxygen upon exertion, has been reported (Lyons et al., 1974; Cockcroft et al, 1982; Musk et al., 1981). These progressive changes can eventually lead to pulmonary hypertension and cor pulmonale (Lapp and Parker, 1992).

4.4. Cancer in coal miners

Coal mining has not been associated with an elevated incidence of lung cancer (Rooke et al., 1979; Kuempel et al., 1995). However, coal miners have been reported to have a higher than normal incidence of stomach cancer (Enterline, 1964). It has been proposed that when coal dust is swallowed, it

mixes with nitrites in food and, under the acidic conditions in the stomach, becomes nitrosated. It is the nitrosation of coal-associated organic material that is thought to cause neoplastic changes (Ong et al., 1985).

4.5. Effect of coal mine dust composition on lung disease

The incidence of CWP is affected by coal rank. Normalizing for similar dust exposures, CWP is five times more prevalent in anthracite miners than for miners of lower rank coal (Bennett et al., 1979).

Coal workers from Pennsylvania mines have a higher incidence of CWP than coal miners from Utah. This difference in disease incidence has been attributed to a higher nickel content in Pennsylvania coal (Christian and Nelson, 1978). Others report that Pennsylvania coal has a higher content of surface available iron and generates more reactive oxygen species than Utah coal (Dalal et al., 1995).

Little correlation exists between silica content of coal dust from various mines in Germany and the prevalence of CWP (Robock and Reisner, 1982). Indeed, in Britain, CWP correlates with mass of respirable dust in the coal mines rather than with the silica content of the mine dust (Walton et al., 1977). However, animal studies link development of pulmonary fibrosis with the amount of silica added to coal dust samples (Ross et al., 1962). This apparent conflict was resolved by Wallace et al. (1994), who demonstrated that the extent to which silica particles were associated with a protective aluminosilicate coating varied with coal mine dust from various regions. The presence of this clay coating was associated with a lower incidence of CWP compared with mines where the silica particles in the coal mine dust were bare.

4.6. Conclusions

Inhalation of coal mine dust is associated with the development of pulmonary disease in miners. Although disease prevalence is directly related to the quantity of coal mine dust inhaled, mineralogical features can influence the pathogenicity of coal dust. These features include: the metal content of the coal, the coal rank, the silica content of the coal mine dust,

and whether the silica dust particles are bare or occluded with a clay coating. Geoscientists can contribute greatly to our understanding of compositional factors that affect the toxic potential of coal dust.

5. Concluding statement

The three research topics discussed above have addressed different relationships between coal and some particular etiology concerning human health. These differences illustrate various ways that coal can adversely affect human health. However, all the research efforts point out the critical necessity to acquire fundamental geological and geochemical data and that these data be applied beyond traditional uses to address global and/or local environmental coal issues. Coal geoscientists must be aware that the reliance on coal as a 21st century energy source will also bring the burden of understanding and mitigating environmental issues related to human health. We have the knowledge and tools and we can make a difference.

References

- Ando, M., Tadano, M., Asanuma, S., Matsushima, S., Wanatabe, T., Kondo, T., Sakurai, S., Ji, R., Liang, C., Cao, S., 1998. Health effects of indoor fluoride pollution from coal burning in China. *Environ. Health Perspect.* 106 (5), 239–244.
- Belkin, H.E., Zheng, B., Finkelman, R.B., 1997a. Geochemistry of coals causing arsenism in southwest China. 4th International Symposium on Environmental Geochemistry. U.S. Geological Survey Open-File Report 97-496. 10.
- Belkin, H.E., Zheng, B., Zhou, D., Finkelman, R.B., 1997b. Preliminary results on the geochemistry and mineralogy of arsenic in mineralized coals from endemic arsenosis areas in Guizhou Province, P.R. China. Fourteenth Annual International Pittsburgh Coal Conference. (CD-ROM).
- Belkin, H.E., Warwick, P., Zheng, B., Zhou, D., Finkelman, R.B., 1998. High arsenic coals related to sedimentary rock-hosted gold deposition in southwestern Guizhou Province, People's Republic of China. Fifteenth Annual International Pittsburgh Coal Conference. (CD-ROM).
- Bennett, J.G., Dick, J.A., Kaplan, Y.S., Shand, P.A., Shennan, D.H., Thomas, D.J., Washington, J.S., 1979. The relationship between coal rank and the prevalence of pneumoconiosis. *Br. J. Ind. Med.* 36, 206–210.
- Bragg, L.J., Oman, J.K., Tewalt, S.J., Oman, C.L., Rega, N.H., Washington, P.M., Finkelman, R.B., 1997. U.S. Geological Survey Coal Quality (COALQUAL) Database: Version 2.0. U.S. Geological Survey Open-File Report 97-134 (CD-ROM).
- Caplan, A., 1953. Certain unusual radiological appearances in chest of coal miners suffering from rheumatoid arthritis. *Thorax* 8, 29–37.
- Ceovic, S., Hrabar, A., Saric, M., 1992. Epidemiology of Balkan endemic nephropathy. *Food Chem. Toxicol.* 30, 183–188.
- Christian, R.T., Nelson, J.B., 1978. Coal: response of cultured mammalian cells corresponds to prevalence of coal workers' pneumoconiosis. *Environ. Res.* 15, 232–241.
- Cockcroft, A., Barry, G., Cotes, J.E., Lyons, J.P., 1982. Shape of small opacities and lung function in coal workers. *Thorax* 37, 365–369.
- Coleman, L.L., 1998. International Coal 1997 Edition. National Mining Association, Washington, DC.
- Collis, E.L., Gilchrist, J.C., 1928. Effects of dust upon coal trimmers. *J. Ind. Hyg. Toxicol.* 10, 101–109.
- Craciun, E., Rosculescu, I., 1970. On Danubian endemic familial nephropathy (Balkan nephropathy). *Am. J. Med.* 49, 774–779.
- Crowley, S.S., Orem, W.H., Roth, M.J., Finkelman, R.B., Scroggs, E.A., Willett, J., 1998. Possible relation between esophageal cancer and coal combustion in China: a preliminary study. Fifteenth Annual Meeting of the Society for Organic Petrology. Abstracts and Program, vol. 15, pp. 97–99.
- Dalal, N.S., Newman, J., Pack, D., Leonard, S., Vallyathan, V., 1995. Hydroxyl radical generation by coal mine dust: possible implication to coal workers' pneumoconiosis (CWP). *Free Radic. Biol.* 18, 11–20.
- Danilovic, V., Djuricic, M., Mokranjac, M., Stojimirovic, B., Zivojinovic, J., Stojakovic, P., 1957. Chronic nephritis caused by poisoning with lead via the digestive tract (flour). *Presse Med.* 65, 2039–2040 (in French).
- Dart, R., MD, 1996, personal communication.
- Ding, Z., Zheng, B., Zhang, J., Long, J., Belkin, H.E., Finkelman, R.B., Zhao, F., Chen, C., Zhou, D., Zhou, Y., 2001. Geological and geochemical characteristics of high arsenic coals from endemic arsenosis areas in southwestern Guizhou Province, China. *Appl. Geochem.* 16, 1353–1360.
- Enterline, P.E., 1964. Mortality rates among coal miners. *Am. J. Publ. Health* 54, 758–771.
- EPA (U.S. Environmental Protection Agency), 1998. Mercury study report to Congress: White paper (<http://www.epa.gov/oar/merwhite.html>), February 24, 1998.
- Feder, G.L., Radovanovic, Z., Finkelman, R.B., 1991. Relationship between weathered coal deposits and the etiology of Balkan endemic nephropathy. *Kidney Int.* 40 (Suppl. 34), S9–S11.
- Finkelman, R.B., Feder, G.L., Orem, W.H., Radovanovic, Z., 1991. Relation between low-rank coal deposits and Balkan endemic nephropathy. *Assoc. Geosci. Int. Dev. News* 65, 23.
- Finkelman, R.B., Belkin, H.E., Zheng, B., 1999. Health impacts of domestic coal use in China. *Proc. Natl. Acad. Sci. U. S. A.* 96, 3427–3431.
- Florig, H.K., 1997. China's air pollution risks. *Environ. Sci. Technol. News* 31 (6), 274A–279A.
- Gabbard, A., 1993. Coal combustion: nuclear resource or danger? *Oak Ridge Natl. Lab. Rev.* 3–4, 24–33.
- Goldberg, M.C., Feder, G.L., Radovanovic, Z., 1994. Correlation of

- Balkan endemic nephropathy with fluorescent organic compounds in shallow ground water. *Appl. Hydrogeol.* 2, 15–23.
- Gough, J., Rivers, E., Seal, R.M.E., 1955. Pathological studies of modified pneumoconiosis in coal miners with rheumatoid arthritis (Caplain's syndrome). *Thorax* 10, 9–18.
- Green, F.H.Y., Althouse, R., Weber, K.C., 1989. Prevalence of silicosis at death in underground coal miners. *Am. J. Ind. Med.* 16, 805–816.
- Green, F.H.Y., Althouse, R., Parker, J., Kahn, J., Weber, K.C., Vallyathan, V., 1998. Trends in the prevalence of coal workers' pneumoconiosis in US autopsied coal miners. In: Chiyotani, K., Hosoda, Y., Aizawa, H. (Eds.), *Advances in the Prevention of Occupational Respiratory Diseases*. Elsevier, New York, pp. 145–148.
- Heppleston, A.G., 1947. The essential lesion of pneumoconiosis in Welsh coal workers. *J. Pathol. Bacteriol.* 59, 453–460.
- Huffman, G.P., Huggins, F.E., Shah, N., Zhao, J., 1994. Speciation of arsenic and chromium in coal and combustion ash by XAFS spectroscopy. *Fuel Process. Technol.* 39 (1–3), 47–62.
- Hurley, J.F., Burns, J., Copland, L., Dodgson, J., Jacobsen, M., 1982. Coal workers' pneumoconiosis and exposure to dust at 10 British coal mines. *Br. J. Ind. Med.* 39, 120–127.
- Kleinerman, J., Green, F.H.Y., Harley, R., Lapp, N.L., Laqueur, W., Naeye, R.L., Pratt, P., Taylor, G., Wyatt, J., 1978. Pathology standards for coal workers' pneumoconiosis: report of the Pneumoconiosis Committee of the College of American Pathologists to the National Institute for Occupational Safety and Health. *Arch. Pathol. Lab. Med.* 103, 375–431.
- Kuempel, E.D., Stayner, L.T., Attfield, M.D., Bruncher, C.R., 1995. Exposure-response analysis of mortality among coal miners in the United States. *Am. J. Ind. Med.* 28, 167–184.
- Lapp, N.L., Parker, J.E., 1992. Coal workers' pneumoconiosis. *Occup. Lung Dis.* 13, 243–252.
- Legg, S.J., Cotes, J.E., Bevan, C., 1983. Lung mechanics in relation to radiographic category of coal workers' simple pneumoconiosis. *Br. J. Ind. Med.* 40, 20–33.
- Lyons, J.R., Ryder, R.C., Campbell, H., Clark, W.G., Gough, J., 1974. Significance of irregular opacities in the radiology of coal workers' pneumoconiosis. *Br. J. Ind. Med.* 31, 36–44.
- Morgan, W.K.C., Lapp, N.L.R., 1976. Respiratory disease in coal miners. *Am. Rev. Respir. Dis.* 113, 531–559.
- Mumford, J.L., He, X.Z., Chapman, R.S., Cao, S.R., Harris, D.B., Li, X.M., Xian, W.Z., Jiang, C.W., Xu, J.C., Chuang, J.C., Wilson, W.E., Cooke, M., 1987. Lung cancer and indoor air pollution in Xuan Wei, China. *Science* 235, 217–220.
- Mumford, J.L., Li, X., Hu, F., Lu, X.B., Chuang, J.C., 1995. Human exposure and dosimetry of polycyclic aromatic hydrocarbons in urine from Xuan Wei, China with high lung cancer mortality associated with exposure to unvented coal smoke. *Carcinogenesis* 16 (12), 3031–3036.
- Musk, A.W., Cotes, J.E., Bevan, C., Campbell, M.J., 1981. Relationship between type of simple coal workers' pneumoconiosis and lung function. A nine year follow-up study of subjects with small rounded opacities. *Br. J. Ind. Med.* 38, 313–320.
- Ong, T.M., Whong, W.Z., Ames, R.G., 1985. Gastric cancer in coal miners: an hypothesis of coal mine dust causation. *Med. Hypotheses* 12, 159–165.
- Orem, W.H., Feder, G.L., Finkelman, R.B., 1999. A possible link between Balkan endemic nephropathy and the leaching of toxic organic compounds from Pliocene lignites by groundwater. *Int. J. Coal Geol.* 40, 237–252.
- Radonic, M., Radosevic, Z., 1992. Clinical features of Balkan endemic nephropathy. *Food Chem. Toxicol.* 30, 189–192.
- Radovanovic, Z., Sindic, M., Polenakovic, M., Dukanovic, L., Petronic, V., 2000. Endemic Nephropathy. *Zavod za Udzbenike i Nastavna Sredstva, Beograd.*
- Robock, K., Reisner, M.T.R., 1982. Specific harmfulness of respirable dust from West Germany coal mines: I. Results of cell tests. *Ann. Occup. Hyg.* 26, 473–479.
- Rooke, G.B., Ward, F.G., Dempsey, A.N., Dowler, J.B., Whitaker, C.J., 1979. Carcinoma of the lung in Lancashire coal miners. *Thorax* 34, 229–233.
- Ross, H.F., King, E.J., Yogunathan, M., Naggelschmidt, G., 1962. Inhalation experiments with coal dust containing 5 percent, 10 percent, 20 percent, and 40 percent quartz. Tissue reactions in the lungs of rats. *Ann. Occup. Hyg.* 5, 149–161.
- Rossiter, C.E., 1972a. Relation between content and composition of coal workers' lungs and radiological appearances. *Br. J. Ind. Med.* 29, 31–44.
- Rossiter, C.E., 1972b. Relation between lung dust content to radiological changes in coal workers. *Ann. N.Y. Acad. Sci.* 200, 465–477.
- Swaine, D.J., 1990. *Trace Elements in Coal* Butterworth, London, 278 pp.
- Tatu, C.A., Orem, W.H., Finkelman, R.B., Feder, G.L., 1998. The etiology of Balkan endemic nephropathy: still more questions than answers. *Environ. Health Perspect.* 106, 689–700.
- Tatu, C.A., Orem, W.H., Feder, G.L., Finkelman, R.B., Szilagyi, D.N., Dumitrascu, V., Margineanu, F., Paunescu, V., 2000a. Additional support for the role of the Pliocene lignite derived organic compounds in the etiology of Balkan endemic nephropathy. *J. Med. Biochem* 4, 95–101.
- Tatu, C.A., Orem, W.H., Feder, G.L., Paunescu, V., Dumitrascu, V., Szilagyi, D.N., Finkelman, R.B., Margineanu, F., Schneider, F., 2000b. Balkan endemic nephropathy etiology: a link to the geological environment. *Central Eur. J. Occup. Environ. Med.* 6 (2), 138–150.
- U.S. Environmental Protection Agency, 2000. Unified Air Toxics Website: Electric Utility Steam Generating Units Hazardous Air Pollutant Emission Study. (<http://www.epa.gov/ttn/uatw/combust/utitox/utoxpg.html>) December 14, 2000.
- Vallyathan, V., Brower, P.S., Green, F.H.Y., Attfield, M.D., 1996. Radiographic and pathologic correlation of coal workers' pneumoconiosis. *Am. J. Respir. Crit. Care Med.* 154, 741–748.
- Wallace, W.E., Harrison, J.C., Grayson, R.L., Keane, M.E., Bolsaitis, P., Kennedy, R.D., Wearden, A.Q., Attfield, M.D., 1994. Aluminosilicate surface contamination of respirable quartz particles from coal mine dusts and from clay works dusts. *Ann. Occup. Hyg.* 38, 439–445.
- Walton, W.M., Dodgson, J., Hadden, G.G., Jacobsen, M., 1977. The effect of quartz and other non-coal dusts in coal workers' pneumoconiosis: Part 1. Epidemiological studies. In: Walton, W.H. (Ed.), *Inhaled Particles IV*. Pergamon, Oxford, pp. 669–700.

- Zhang, Y., Cao, S.R., 1996. Coal burning induced endemic fluorosis in China. *Fluoride* 29 (4), 207–211.
- Zheng, B., Huang, R., 1989. Human fluorosis and environmental geochemistry in southwest China. *Developments in Geoscience, Contributions to 28th International Geologic Congress*. Washington, D.C. Science Press, Beijing, China, pp. 171–176.
- Zheng, B., Hong, Y., Zhao, W., Zhou, H., Xia, W., Su, H., Mao, D., Yan, L., Thornton, I., 1992. The Se-rich carbonaceous siliceous rock and endemic selenosis in southwest Hubei, China. *Chin. Sci. Bull.* 37 (20), 1725–1729.
- Zheng, B., Yu, X., Zhand, J., Zhou, D., 1996. Environmental geochemistry of coal and endemic arsenism in southwest Guizhou, P.R. China. 30th Int. Geol. Congr. Abstr. 3, 410.
- Zhou, D., Liu, D., 1985. Chronic thallium poisoning in a rural area of Guizhou Province, China. *J. Environ. Health* 48 (1), 14–18.