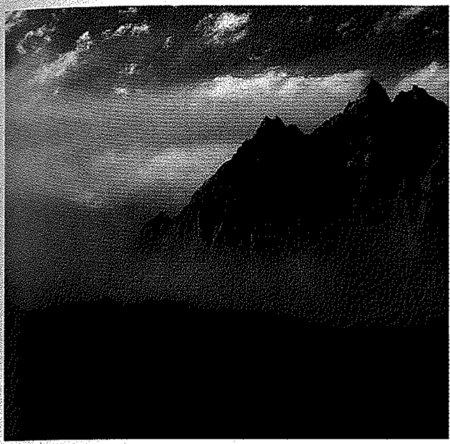

CHAPTER 18

NATURAL AEROSOLIC MINERAL DUSTS AND HUMAN HEALTH

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CONTENTS

I. INTRODUCTION

Fine atmospheric dust (including fine mineral aggregates, fibrous minerals, and fibrous organic materials) reaches concentrations in many parts of the world sufficient to constitute a major influence upon both human and animal health.

The visible effect of dust in the atmosphere has been noted in written records since at least 1150 BC in China, since ancient times in the Mediterranean, and over the North Atlantic to leeward of the Sahara since at least the eighteenth century. Written records of Saharan dust falls in western Europe became increasingly common from the mid-nineteenth century. Following the "dust bowl years" of the 1930s, awareness of soil-derived atmospheric dusts increased considerably in the United States, particularly after 1945. Understanding of the complex role of atmospheric dust as a factor influencing climate and climatic change has made notable progress in the past 20 years, although there is still much to learn (Houghton et al., 2001). In contrast, the impact of high concentrations of natural dust on human and animal health has received relatively little attention when compared to work on artificially generated particulates, smoke and gases.

Aerosols include gases, liquids, and solid particles suspended in the atmosphere for varying lengths of time. Solid aerosols include particles injected into the atmosphere, such as mineral dust and sea salt, and those that form within the atmosphere, notably sulfates. Natural and man-made fires, including extensive burning of vegetation, generate smoke plumes that are often carried several thousands of kilometers from their sources, which contributes to regional air pollution and adds to atmospheric health hazards. Biomass burning yields black carbon which, together with mineral dust, is monitored by ultraviolet and other sensors on Earth-orbiting satellites. This provides increasingly detailed information on the incidence and seasonality of aerosol plumes over both land and water surfaces. Emphasis here is given to the release, transportation, and deposition of mineral particulate aerosols derived from soils, sediments, and weathered rock surfaces and their impact on human health when in suspension in the atmosphere. The finer components (<10 μm) of respirable natural atmospheric dusts include single particles, aggregates of very fine mineral grains (notably

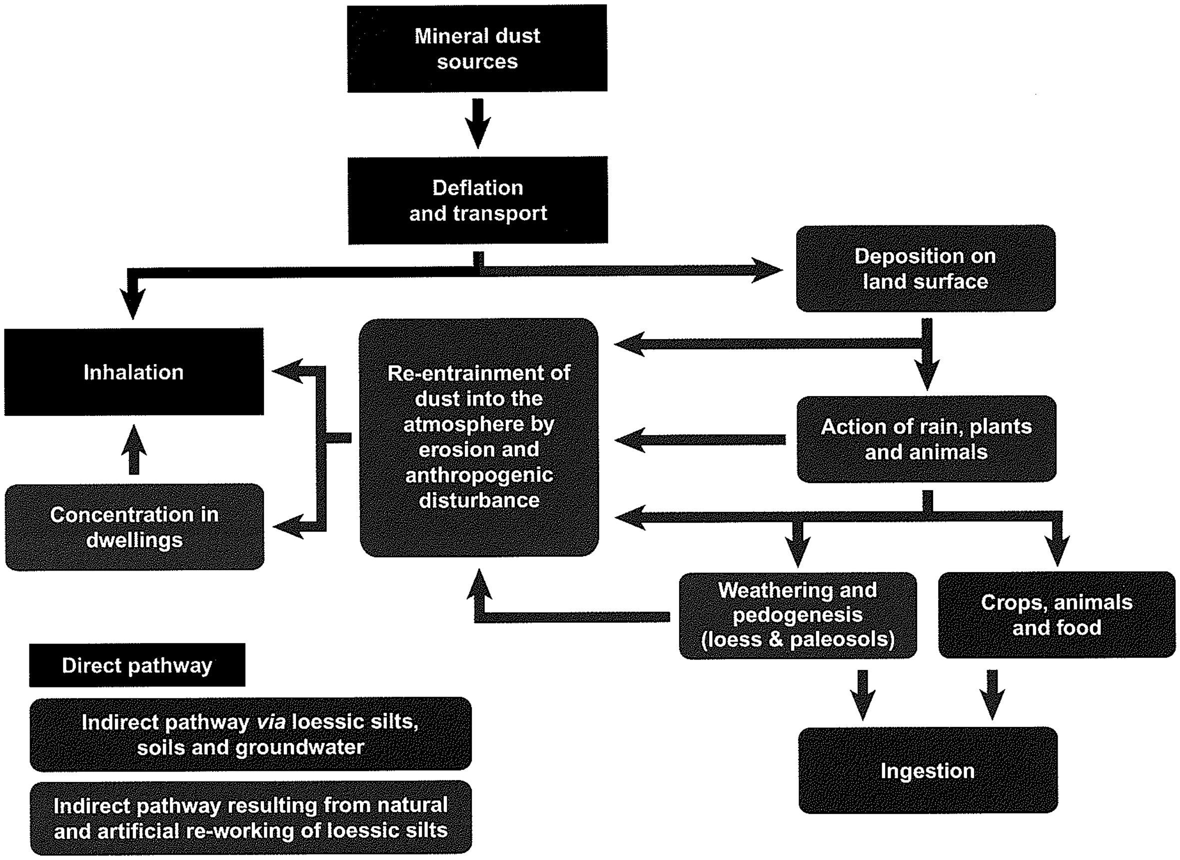

FIGURE 1 Some essential links in the direct and indirect pathways from dust sources to human inhalation and ingestion. Note: The wind-lain and variously weathered sediment known as loess commonly contains buried soils (paleosols) marking phases of relatively stable former land surfaces during the accumulation of the loess.

silica), fibrous minerals (e.g., the asbestos group), and fibrous organic materials.

Wind-borne dusts may affect human health by way of direct and indirect pathways. The elemental composition of dust, both when airborne and when accumulated on a land surface to form loess, can enhance the toxicity of the air breathed as well as that of the soil and the waters that drain through it. Inhaled dusts derived from fine-grained sediment sources such as seasonally dry rivers and dry lakebeds make up the direct pathway (Figure 1).

A significant indirect pathway arises from generation of respirable mineral dusts by both natural and human-induced re-working (erosion) of loess and loessic soils. A second indirect pathway (Figure 1), involving transfer and concentration of some toxic minerals by groundwater movement through thick loess accumulations, is not considered here. Some accumulations of mineral aerosols, including varying amounts of fine volcanic ash (tephra), contribute to the minerogenic dust in the atmosphere, which often endows surface sediments and soils with a distinctive mineralogy and chemistry (Section II.B). Large volumes of ash and dust have been emitted since 1995 during eruptions of the Soufrière Hills volcano on the island of Montserrat in the eastern Caribbean. The finer dusts contain up to 24% of cristobalite (a form of silica), which poses a potential health threat to local populations in conditions of prolonged eruption.

The detachment of mineral dust from the ground surface and its entrainment and subsequent transport by the wind are functions of several variables, which include the wind speed (both mean regional wind speed and the critical wind speed or threshold velocity required to dislodge particles), the degree of instability of the atmosphere, the size of the particles, the roughness and moisture content of the land surface, and the degree of particle exposure.

Source environments of mineral aerosol dusts are diverse, and some dust takeup by the atmosphere (the

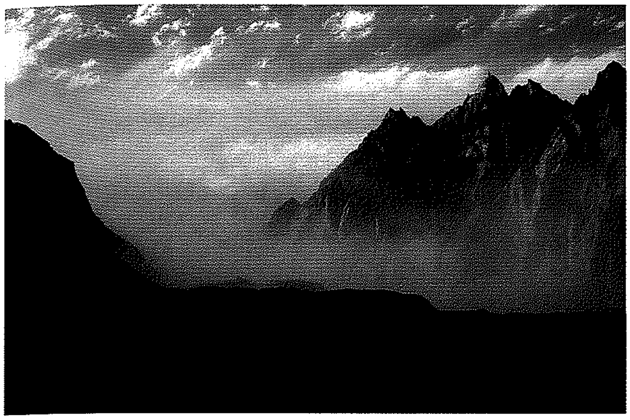

FIGURE 2 Dust storm in the upper Hunza valley, Karakoram Mountains, northern Pakistan, summer 1980. The thick pall is mixed fine sand and silts carried by a cold, dense, gravity-enhanced airflow (katabatic wind) from the 59-km long Batura Glacier (not visible from this viewpoint). Such glacially induced winds are frequent in summer in the dry mountains of High Asia, deflating the finer components of extensive, dried-out meltwater deposits that accumulate around glacier margins.

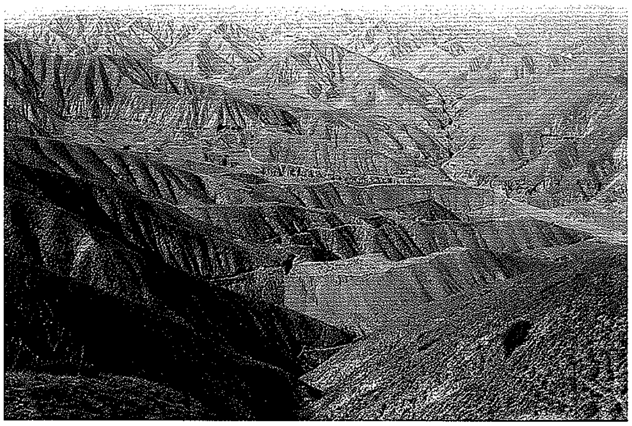

FIGURE 3 Bare, eroded slopes in thick (>200 m) loess of the subhumid Xining Basin, northwestern China.

process of deflation) is a natural phenomenon that occurs at some time in most terrestrial environments. However, certain types of landscape, notably the sparsely vegetated terrains characteristic of the world's drylands, are particularly susceptible to the massive deflation that accounts for most of the atmospheric dust plumes thought to have a bearing on human and animal health. Seasonally deposited fine water-lain sediments (notably the finer grades in the silt and clay range carried in typically turbid glacial melt waters: Figure 2), actively aggrading alluvial fan deposits, and fine lake sediments exposed in extensive basins by climatic desiccation are important examples of terrain types serving as atmospheric dust sources. Mineral particles are released by a variety of surface processes grouped together under the general heading of "weathering." These processes include breaking up of rock surfaces by the action of frost, salt, and chemical reactions and the biochemical complex of processes involved in soil formation; the latter accounts for the presence in some aerosol dust of plant fibers, phytoliths (biogenic opal), pollens, and spores. The silt-rich wind-lain deposits known as loess, which accumulated to great thickness after about 2.5 million years ago in Eurasia and the Americas, and particularly in central and eastern Asia (Derbyshire, 2001; Derbyshire et al., 2000), are readily eroded in certain circumstances, thus constituting a secondary source of minerogenic atmospheric dust (Figure 3).

Silt-sized particles, especially those in the ~10–50 μm range, are readily entrained by the wind from dry, unvegetated surfaces, but the clay-size (<2 μm) component of soils and sediments is not readily detached by the wind as individual particles because of the high interparticle cohesive forces typical of such colloidal materials. Entrainment of material finer than 2 μm usually occurs in association with the coarser (silt-sized) grains, and also in the form of coarse or medium silt-sized aggregates made up of variable mixtures of fine silt and clay-grade particles (Figure 4). Critical wind speeds for dust entrainment (threshold velocities) vary notably; those for the semi-arid/subhumid, silt-covered terrains of northern China being approximately twice those required to initiate dust storms in the Sahara (Wang et al., 2000).

Silicon, making up more than one-quarter of the elements in the Earth's crust, is highly reactive and readily combines with oxygen to form free silica (SiO_2), the most common form of which is quartz. SiO_2 dominates the composition of dust from North Africa (60.95%) and China (60.26%). These values closely match the world mean (59.9%) and its average content in the world's rocks (58.98%). Silicon also combines with other elements in addition to oxygen to form the dominant mineral group known as the silicate family, which includes the group of fibrous amphibole minerals grouped together under the general term asbestos. In the finest (<2 μm) fractions of many dryland surface sediments and soils, quartz is an important, and sometimes a dominant mineral, ranging in type from lithic fragments to biogenic opal. Varying amounts of clay minerals (hydrous aluminous phyllosilicates) are also common (notably kaolinite, illite, chlorite, vermiculite,

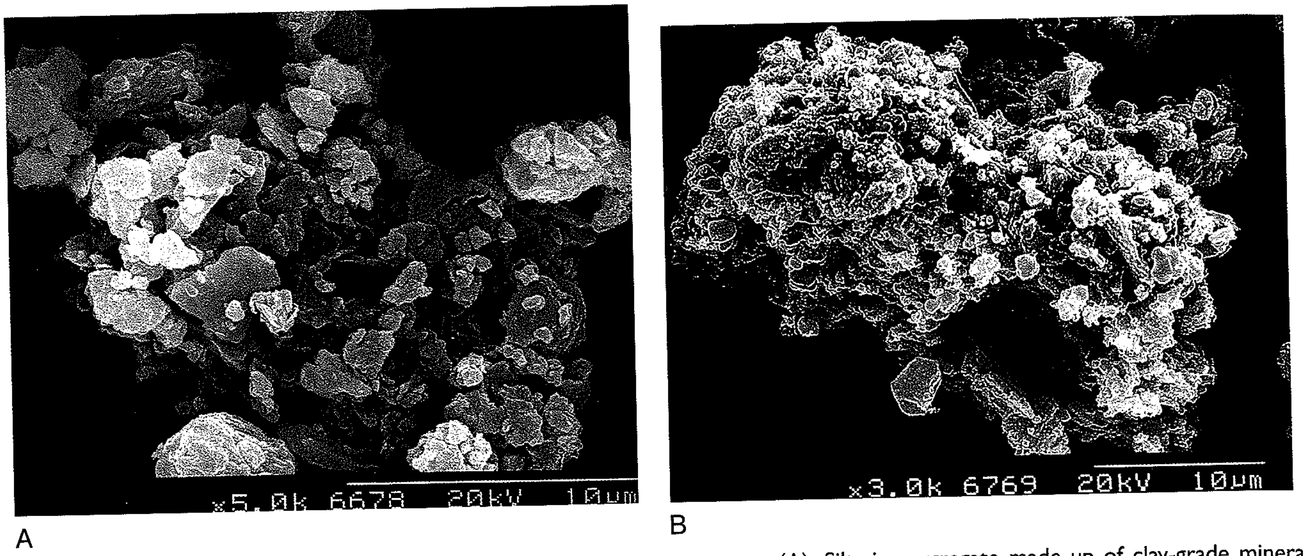

FIGURE 4 Scanning electron micrographs of windblown dust aggregates. (A): Silt size aggregate made up of clay-grade mineral particles, as commonly found in the young (Last Glacial) loess deposits of central and eastern Asia. (B): Silt size aggregate taken from the dust on a house beam in Ladakh. Elemental composition of such beam dust is dominated by silica, with lesser amounts of oxygen, aluminum, sulfur, potassium, calcium, and iron. Both scale bars = $10\,\mu m$.

smectite, and several mixed layer clays), with varying amounts of calcite, gypsum, and iron compounds.

The natural process by which substantial volumes of mineral dust are injected into the atmosphere is usually periodic, sometimes strongly seasonal, and mainly located in the subtropical arid and semi-arid regions. These potential dust sources cover about 30% of the total land area of the Earth. The dominant dust source regions lie in the northern hemisphere continents and include the subtropical and temperate deserts stretching from the Sahara of North Africa, through the Middle East and the northwest of the Indian subcontinent, and into central and eastern Asia. More modest sources of atmospheric dust have been identified in the Great Basin (United States) and in the Southern Hemisphere (the Lake Eyre Basin, Australia; central and northern Argentina; and a small part of southern Africa).

The relative contribution to global dust palls from these dominant source regions may have changed over recent geological time. For example, some sedimentary records from both the continents and the oceans indicate that rates of minerogenic dust accumulation during the last glacial maximum (about 20,000 years ago) were up to 10 times greater than at present (Kohfeld & Harrison, 2001). Such variable rates reflect changes in the location and size of dust source regions as glaciers waxed and waned, changing wind regimes (especially those associated with the monsoons) and climatically driven fluctuations in the hydrological cycle that affected surface conditions including vegetation cover. Considerable contrasts in dust accumulation, expressed as calculated dust fluxes (mass accumulation rates in $g/m^2/yr$; e.g., Derbyshire 2003), are beginning to emerge from studies of the Earth's loess deposits.

The process of entrainment and transport of mineral dusts varies from a local to a global scale. It is important to discriminate between source-proximal and source-distal dust plumes (Figure 5). In general, the size of particles entrained by the wind declines with transport distance. As a result, the proportion consisting of the respirable fractions (commonly regarded as $<10\,\mu m$) makes up an increasing proportion of the dust plume with distance from the source, although the absolute mass of the respirable fraction is greatest close to the source, as suggested by the colloquial term "desert lung" to describe pneumoconiosis in North Africa and the Middle East. High atmospheric dust concentrations show considerable variety in terms of their periodicity (from days to decades) and extent and proximity to sources, as well as in the percentage of the dust in the respirable range. In some regions of the world, extensive dust plumes have become an integral part of regional culture, and the washing out of the brown-to-red mineral particles by precipitation is known as "loess rain" in China, and "blood rain" in Mediterranean Europe and further north. These terms also draw attention to the contrast between yellow Chinese dust and the red dust of North Africa.

The concentration of mineral dust in the atmosphere (the atmospheric aerosol loading) is both a function of,

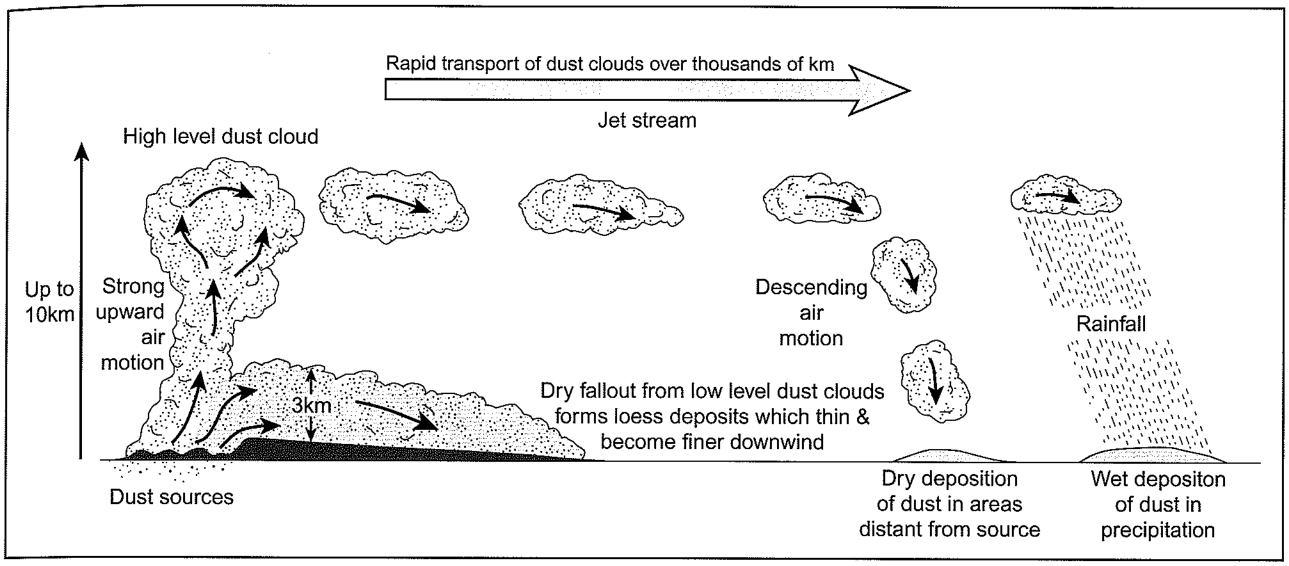

FIGURE 5 Sketch showing the two principal modes of aeolian dust transport and deposition, based on a transect from the Chinese drylands to the Loess Plateau and the North Pacific Ocean. Re-drafted from Pye and Zhou (1989).

and a factor influencing climatic change, as it affects physical and biogeochemical exchanges between atmosphere, land, and ocean. The presence of aerosols influences the chemistry of the troposphere including the proportion of ozone. Aspects of climate affected by atmospheric dust loading include the ability of dust to raise or lower air temperatures depending upon the differential effect of its particle size and chemistry, and upon the extent to which solar radiation is absorbed and scattered, which is an effect significantly modified by the amount, altitude, and thickness of any cloud cover. Deposition of dust may add notable volumes of certain nutrients to the world's oceans, including nitrates, ammonia, phosphates, and oxides of potassium and iron. It is considered that such inputs of iron to oceanic waters stimulate nitrogen fixation by plankton, thus enhancing productivity. The Sahara, commonly regarded as the world's greatest source of wind-transported mineral dust (Goudie & Middleton, 2001), has some influence on the nutrient dynamics and biogeochemical cycles of a region stretching from northern Europe to South America (Prospero, 1999) (Figure 6). In addition, it is claimed that Saharan dust storms sometimes transport bacteria and fungal spores that cause deterioration in Caribbean coral reefs (Shinn et al., 2000), events that have also been linked to reduced air quality and cases of asthma and other respiratory problems in residents of parts of the southeastern United States. Such an intimate relationship between aerosols and the global environment, taken together with the probability that human actions in the past century or so have progressively enhanced the atmospheric dust loading, has implications for future climatic change (Harrison et al., 2001). The effect of such changes upon human societies is likely to include some notable health impacts.

II. HEALTH-IMPACTING MINEROGENIC AEROSOLS

A. Dust Storms

The type, size, and extent of dust plumes raised during dust storm events are fundamental factors influencing the degree to which naturally occurring atmospheric dust impacts upon the health of human and animal populations. Dust storms may be generated by local vortexes, generally known as "dust devils" (or willy-willies in Australia). Dust devils are only a few meters in diameter and raise dust to heights of 100–200 m (exceptionally 1000 m) for periods of a few minutes to a few hours. Similarly low altitude, though more regionally extensive dust-carrying wind systems in northwest Africa, for example, arise from the relatively shallow northeasterly trade winds and by squall lines associated with northward incursions of equatorial air (the West African summer monsoon). These raise dust

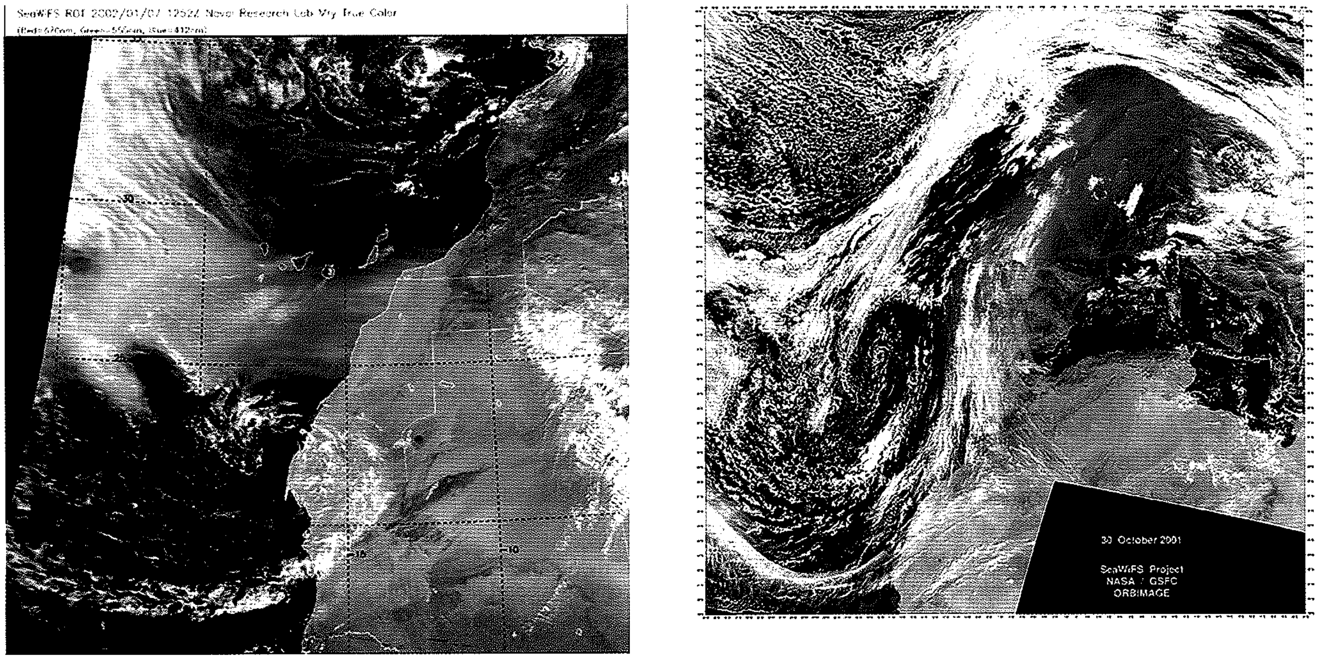

FIGURE 6 (Left): Outbreak of Saharan dust across the North Atlantic, January 2002. High pressure over and north of Morocco, with a depression centered off the West Sahara-Mauritania coast, indicates a strong easterly flow across the African coast and the Canary islands (center) and into the mid-Atlantic. A dense pall of dust, about 500 km wide, reduced visibility and enhanced sunset colors for several days in the southern Canaries and deposited red dust. (Right): African dust over western Europe, October 2001. High pressure over the Mediterranean basin and an extensive and vigorous depression west of North Africa and Spain (centered close to the island of Madeira) induced strong southerlies from Mauritania to Scandinavia. A high-level dust pall can be clearly seen running from off the Moroccan coast across western Iberia, the Bay of Biscay, western and central France, southern and central Great Britain, the Low Countries, North Germany, and Denmark. Both are NASA SeaWiFS images.

above the shallow trades and into the troposphere so that it crosses the Atlantic in winter as the dry northeasterly "harmattan." Such source-proximal transport involves a relatively high percentage of the coarser dusts (medium and coarse silts with some very fine sand), which are usually deposited at distances of only hundreds of kilometers downwind. Extensive regional atmospheric turbulence, however, arising from air mass frontal systems associated with the hemispherical wind regimes, notably the upper westerlies, carry the finer dust fractions at high levels within the troposphere. These source-distal events frequently transport terrestrial dust across oceans, including the Atlantic and Pacific, with deposition occurring some two or three weeks after initial entrainment (Pye, 1987).

An example of the relationship between landforms, surface sediments, and soils that are particularly susceptible to dust deflation and specific meteorological situations, on the one hand, and atmospheric dust loadings and their source-proximal and source-distal effects, on the other, are illustrated by a dust storm that occurred in northwest China in May 1993 (Derbyshire et al., 1998). The highest wind velocities and most severe damage and loss of human life were felt in the Hexi Corridor (Figure 7), a WNW-ESE topographical constriction between the mountains bordering the northeastern edge of the Tibetan Plateau (the Qilian Shan; in Chinese *shan* means mountains) and the Mongolian Plateau. The wider impact was felt in the provinces of Gansu, Ningxia, Inner Mongolia, Shaanxi, and Hebei, a region equal to the combined area of France and Spain.

The meteorological situation on May 4, 1993, was controlled by a large high-pressure system (the Siberian High) over western Eurasia, with a depression centered on the northern Urals but with a trough extending far to the south. The cold front associated with this trough extended to the northern edge of the Tian Shan range. The constriction between the Tian Shan and the Altai Shan ranges resulted in increasingly convergent, and hence accelerating, air flow toward the east. By the next day, the cold front had reached

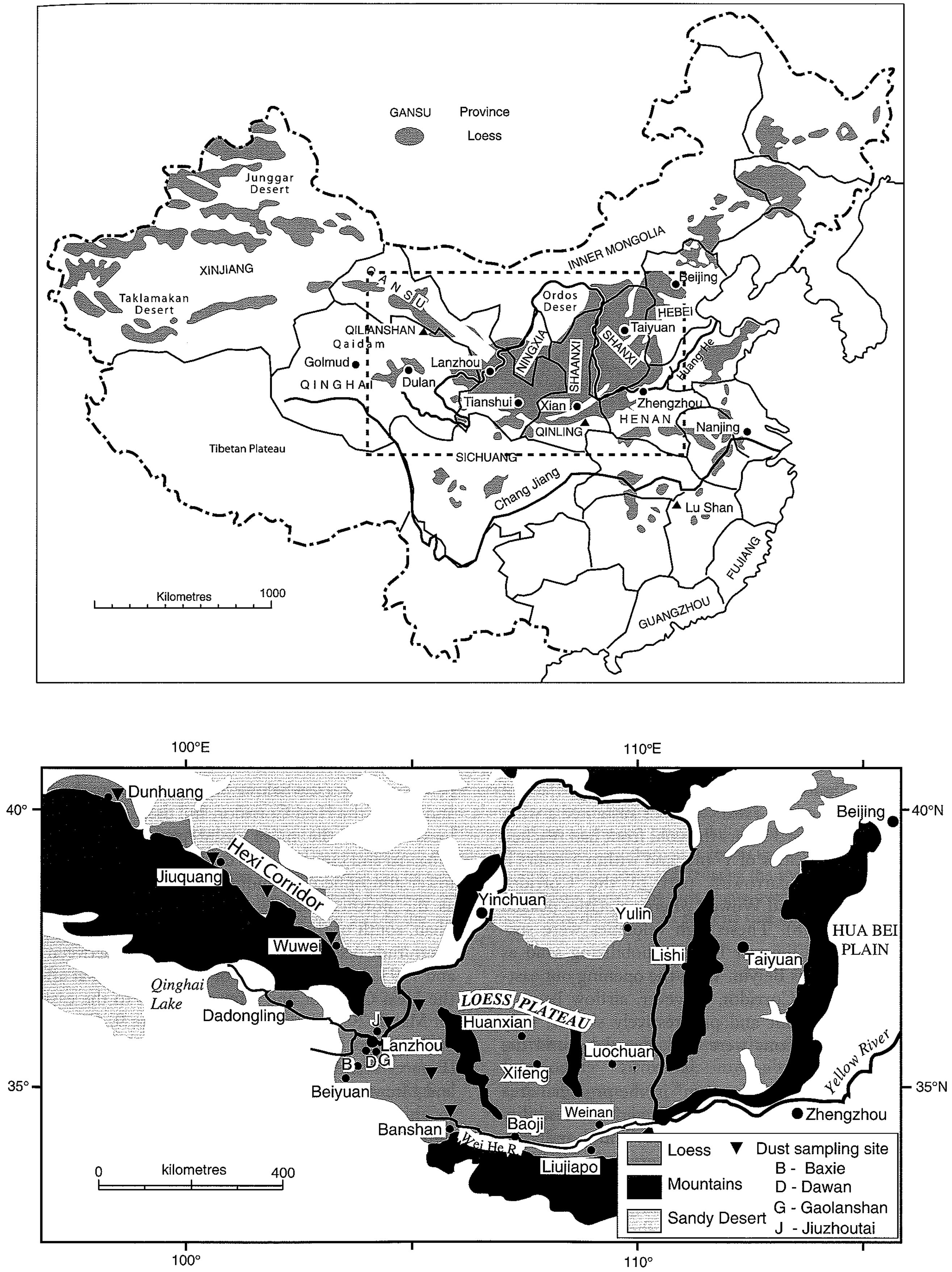

FIGURE 7 Upper: The Loess Plateau of North China in relation to the Hwang He (Yellow River) and the principal deserts. The box indicates area covered in lower half of the figure. Lower: Part of northern China, showing the Loess Plateau and the Hexi Corridor. See text. Re-drawn from Derbyshire et al. (1998).

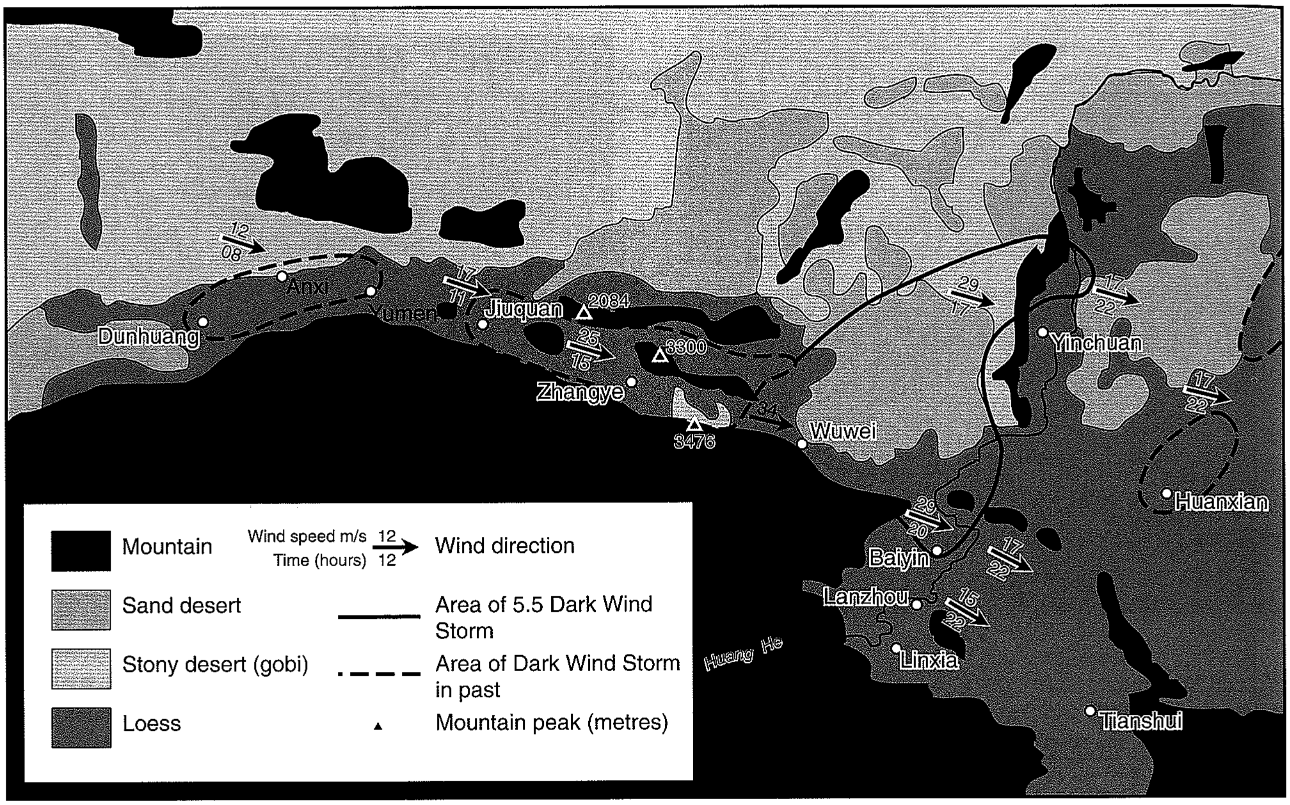

FIGURE 8 Terrain sediment cover types, dust storm zones, wind velocities, and timing (in hours) of the "dark storm" of May 5, 1993, in the Hexi Corridor and the western Loess Plateau, China. Data provided by the State Meteorological Service of China, and the Meteorological Bureau of Gansu Province. Re-drawn from Derbyshire et al. (1998).

Dunhuang (Figure 8), where the channeling effect of the western end of the Hexi Corridor sustained a wind velocity of 12 ms. In 3 hours the cold front had reached Jiuquan, with velocities of 17 ms, and within 5 hours it had reached the narrowest part of the Corridor (between Zhangye and Wuwei) where velocities peaked at 34 ms (Figure 8). These high velocities were sustained across the Tengger Desert, mobilizing sand as well as dust as far as Beiyin. With the opening out eastward of the Hexi Corridor, however, airflow became increasingly divergent and progressively slower; only the finer dust fractions were transported beyond the North China plain.

The effect of this "dark storm" in the proximal area of the Hexi Corridor was extremely serious. Visibility declined below 10 m in full daylight, and the depressed temperatures created severe frosts (minima −6.6°C) with some local snowfalls. The direct effects included 380 people and 120,000 farm animals killed and damage to about 3300 km^2 of crops. The particulate aerosol concentrations reached the "extensive dust pall" category (see below, Section II.D) in the center and east of the Hexi Corridor, and there was widespread loess rain in the more distal provinces to the east (Shaanxi and Hebei). The coarser suspension load in the lower atmosphere, including coarse silts, reached as far as the northern slopes of the 3700-m high Qinling Shan, south of the city of Xi'an. Five storms of similar magnitude occurred in the Hexi Corridor between 1952 and 1993. A satellite image of a dust storm that affected the Hexi Corridor and a broad region to the east of it on March 29, 2002, is shown as Figure 9. Comparison of this image with the regional details of the 1993 event (Figures 7 and 8) shows it to be very similar in source and extent, if not in destructive power.

This Hexi Corridor case study is an example of dust impact from a proximal source with the bulk of the visible dust pall consisting of relatively coarse silt particles in the lower few kilometers of the atmosphere. However, the finer components of such palls, traveling at higher levels, are known to be carried great distances across the Pacific Ocean. Such "distal source–high

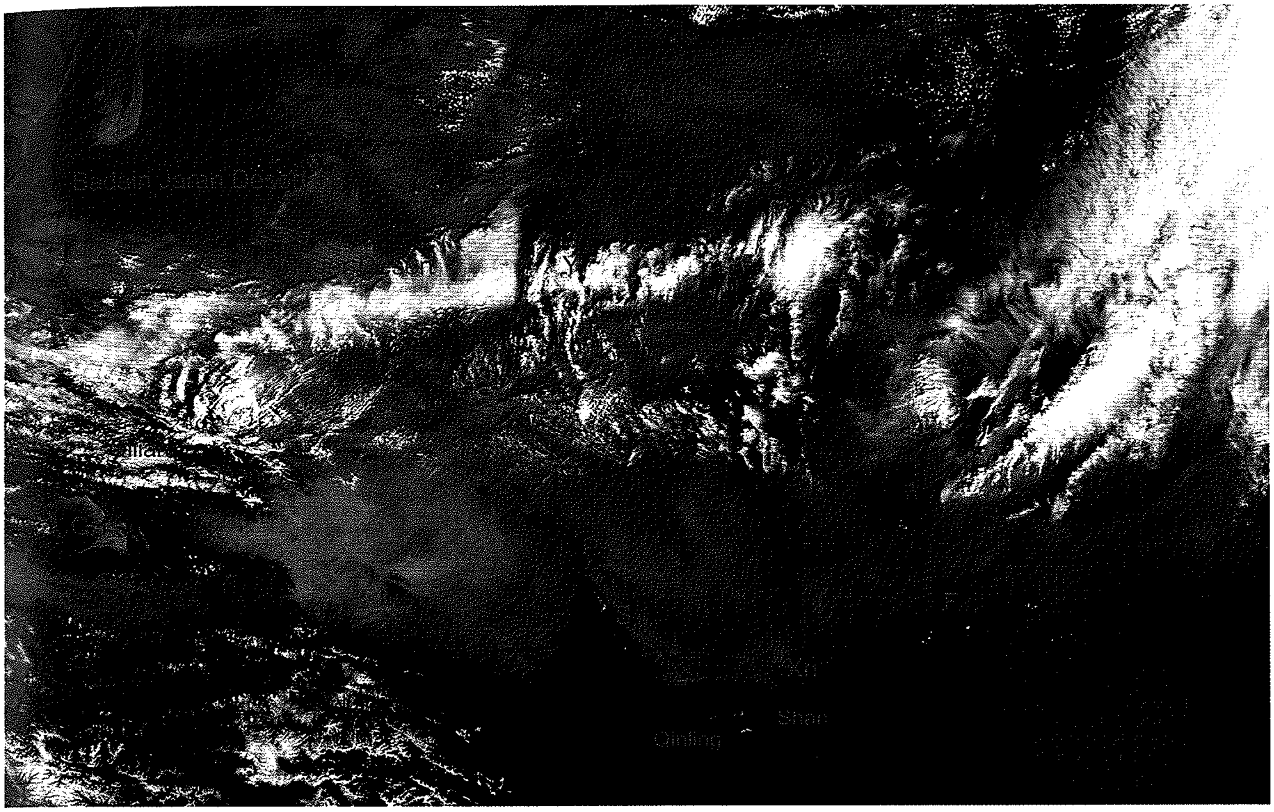

FIGURE 9 Part of a Terra Satellite image, using the MODIS sensor, taken on March 29, 2002, and showing a dust storm generated by winds from the west-northwest over northwest China. (For comparative location, compare with Figures 7 and 8). The air over the Badain Jaran and Tengger deserts is clear of dust, as it is over the Mu Us Desert (to the north of which can be seen the big bend of the Yellow River). However, the dust thickens rapidly with proximity to the cold-weather-front and the alluvial-fan-covered Hexi Corridor on the northern side of the Qilian Shan. The Xining Basin (X = city of Xining, just to the east of Qinghai Lake; QH) generates its own pulse of dust, but not the adjacent Qaidam or Gonghe basins in this case. Lanzhou city (L), near the outlet of the Hexi Corridor, has a thick dust pall over it as well as its own locally generated pollution cloud. The dense dust plume is split by the NNW-SSE aligned Liupan Shan (L-P-S). East of this mountain range, the plume completely covers the twin basins of the Jing and Luo rivers (draining the central and southern part of the Loess Plateau). This part of the plume just covers the city of Xi'an (Xn); its pollution pall is more modest than that of Lanzhou. The southeastern margin of the plume is very sharp as it comes up against the ~3700 m high Qinling Shan (on which several snow-covered areas can be seen). The plume extends eastward, crossing the sharp bend of the Yellow River at Fenglingdu (75 km west of the Sanmenxia Reservoir on the lower Yellow River). The dust plume over the green farmlands of Henan and Hebei provinces in the southeastern part of the image is much more diffuse, which suggests that it may be the product of a pre-frontal trough.

altitude–finer dust" systems have aroused considerable recent interest because they can be tracked using orbital imagery backed up by study of synoptic meteorological charts. One such example of a distal dust source of global significance is the Tarim Basin, a region that probably has the highest mean annual number of "dust days" in China. The Taklamakan Desert, occupying most of the Tarim Basin, is predominantly a sandy desert, but loess accumulations are found along extensive parts of its windward (southern and western) mountain rim, which shows that the Tarim also has a functioning "proximal, low altitude–coarser dust" system (Figure 10).

Steep atmospheric pressure gradients associated with extensive Siberian–Mongolian ridges of high pressure, most notably between late winter and early summer, strengthen the easterlies around the southern flank of the seasonal high pressure cell over the Taklamakan Desert. This air flow is then subject to vigorous uplift as it comes up against the western Kunlun, the Pamir,

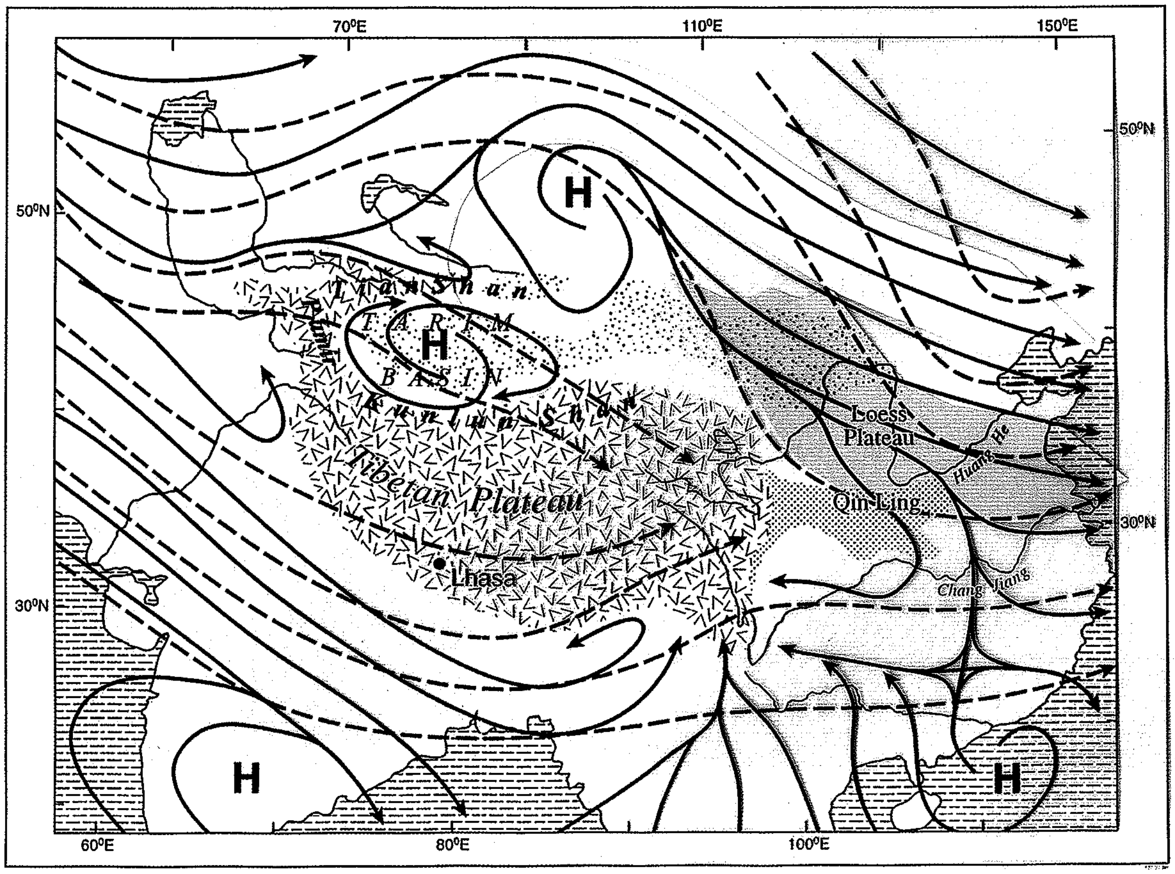

FIGURE 10 Relationship between generalized winter-spring pressure systems over central and eastern Asia, the major orographic features, the two dominant dust source regions, and the associated principal atmospheric dust pathways. The deserts, alluvial fans, and dry lake basins to the north and west of the Loess Plateau provide both source-proximal, coarser silts to the Loess Plateau, with much finer material being carried at higher atmospheric levels across the east China plain, and the Pacific Ocean and beyond (pink arrow). The Tarim Basin surrounded by high mountains (the Tian Shan, the Pamir, and the Kunlun Shan) concentrates fine sediments largely derived from glacial meltwater rivers and alluvial fans. These are re-worked by winds blowing from north of east to be deposited as loessic silts on the northern flanks of the Kunlun Shan. At over 5000 m above sea level, this may be the highest loess in the world (from Sun, 2002b). Finer dusts are lifted above this level and enter the westerly jet stream to be carried great distances, sometimes as far as Europe (yellow arrow).

and the western Tian Shan ranges, all of which have peaks around 7000 m above sea level. Current opinion (e.g., Sun, 2002a) is that the finest fractions of the Tarim dust cloud are uplifted into the upper troposphere to be carried northeastward across Outer Mongolia, eastern Siberia, and across the Pacific Ocean (Figure 10). Fine Chinese airborne dust is commonly recorded in western North America, and it is known to reach the eastern United States from time to time. This airborne dust was recorded over the Atlantic Ocean on April 20, 2001, and has recently been discovered in the French Alps, a distance from source of about 20,000 km (Grousset et al., 2003). Preservation of mineral dust from both of the principal Chinese source regions in the Greenland ice cores confirms that the "distal–high level–fine dust" pathways are long established, persistent, and also of global scale.

B. Dust Sources

Interest in the detection, tracking, and measurement of distal (regional and global scale) mineral dust in the atmosphere has been greatly stimulated by the increasing availability of images and other data provided by Earth-orbiting satellites. Aerosol optical thickness (AOT), as estimated using the advanced very high resolution radiometer (AVHRR) of the United States' National Oceanic and Atmospheric Administration (NOAA), is based on backscatter radiation measurements made at an effective wavelength of 0.63 μm. In general, high AOT values indicate high atmospheric dust concentrations. However, because the AOT algorithm requires the surface below the dust plume to have a low and constant albedo, AOT can be estimated in this way only over the oceans. This restriction is generally true of satellite sensors operating in the visible spectrum. The situation was greatly improved by the advent, in 1980, of the total ozone mapping spectrometer (TOMS). This is used to detect absorbing aerosols based on the spectral contrast at 340 and 380 nm in the upwelling ultraviolet (UV) spectrum. TOMS is sensitive to a range of UV-absorbing aerosols such as mineral dust, volcanic ash, and black carbon from fossil-fuel combustion sources and biomass burning. The UV surface reflectivity is typically low and nearly constant over both land and water, which allows TOMS to detect aerosols over both continents and oceans. The UV spectral contrast is used in a non-quantitative way as an absorbing aerosol index (AAI). The temporal and spatial variability of this TOMS AAI has been matched to types of absorbing aerosols, as well as to known sources such as individual volcanic eruptions, forest fires, and large-scale dust events. The global distribution of the occurrence frequency of relatively high TOMS AAI values (January and July 1980–1992) is shown in Figure 11 (Prospero et al., 2002) (see also Chapter 27, this volume).

This image contains one huge, dominant area with high AOT values extending westward of the North African coast and eastward from the Middle East, indicative of dust plumes from the world's premier atmospheric dust source region. The plume off the west coast of South Africa, in contrast, is attributed to biomass burning.

The irregular timing and the variety of sources contributing to dust storms, as well as the technical limitations of the different sensors in use, complicate the determination of the location and extent of individual dust source regions or areas around the globe. The common association of dust-raising conditions with the cloudy conditions generated by pressure troughs and air-mass fronts is a case in point. The TOMS system is most sensitive to aerosols in the middle and upper troposphere and above (distal dust) and least sensitive in the boundary layer where aerosol residence times are shorter (proximal dust). Aerosols below the altitude range of 1000–1500 m remain largely undetected. Thus, the source-proximal components of major destructive dust storms may not be detected on some visual imagery.

Despite such difficulties, the use of global distributions based on the month in the year that best represents the long-term (13 year) frequency of dust storm occurrence as indicated by TOMS AAI has yielded a map of major global dust sources that closely matches the information available from other types of observation (Prospero et al., 2002). The result (Figure 12) indicates sources in all continents except Europe and Antarctica. Most of the major sources are in surface depressions or adjacent to mountain fronts.

For example, the Ahaggar and Tibesti mountains in the Sahara are surrounded by what may be the greatest single regional dust source on Earth. There is a strong link between dust sources and extensive alluvial deposits, as well as ephemeral, saline, and dried out lakes throughout North Africa, the Middle East, the northwestern Indian subcontinent, Middle Asia (from the Caspian Sea to Kazakhstan), and across northwest China, as shown above (Section II.A). Sand dune deserts, as such, are not important consistent sources, although their sporadic drainage systems frequently provide abundant fine particles for deflation. There are many smaller, but important, sources outside these major regions. These include the Basin and Range province of the southwestern United States and northern Mexico; the Lake Eyre and Great Artesian Basin in Australia; Patagonia, the Andean footslopes in central Argentina, and the Altiplano of Bolivia and northern Argentina; and southern Africa. Secondary sources also include the major loess deposits, notably in parts of northern China. The "mountain deserts" of Iran and Pakistan, at the western end of the Himalayan tract, constitute an important regional dust source, notably in summer, which involves channeling of dust by down-valley (katabatic) winds (Figure 2).

The human impact, varying in both type and intensity of activity as well as in length of its history, further complicates assessment of "natural" dust sources. The major concentrations of fine-grained, poorly vegetated deposits that constitute important dust sources are those associated with floodplains, alluvial fans and lake depressions, and sites that are fed by seasonal perennial freshwater flows that also attract human communities and their animals. The dust sources in the Middle East include the Tigris-Euphrates basin where agriculture has been widespread on this rich alluvium for thousands

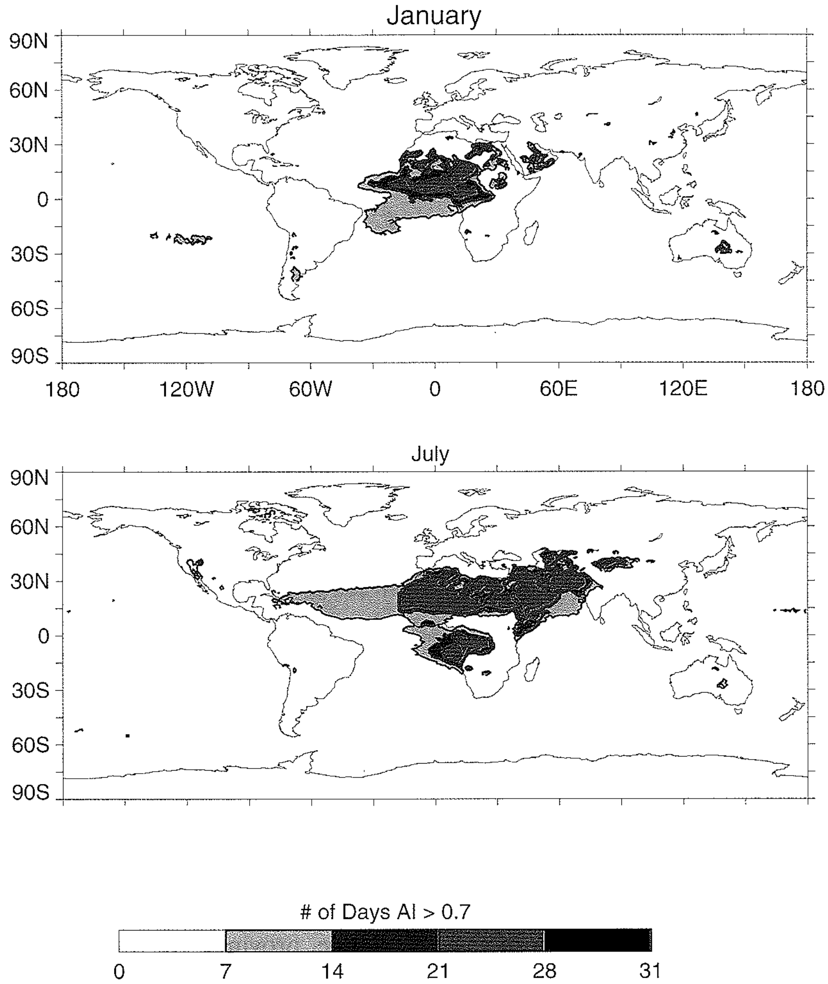

FIGURE 11 Global distribution of dust and smoke. Monthly frequency of TOMS absorbing aerosol product for January (top) and July from 1980 to 1992. Scale: number of days per month when the AAI equaled or exceeded 0.7. The large, dark area in southern Africa in July is a product of biomass burning, and there is also evidence of biomass burning in January just north of the Equator in Africa. Part of the plume over the Equatorial Atlantic is smoke. All other distributions shown are due to the presence of dust. After Prospero et al. (2002), with kind permission of the first author.

of years. There is also a long history of human use and interference with such water sources in the drylands of central Asia. Many small states and cities in western China have collapsed as a result of a failure of water supply due either to overuse or destruction of dams in warfare as well as severe periodic drought (Derbyshire et al., 2000). The present-day use of dung, wood, and, to a lesser extent, coal, as fuel sources in the drylands of western China is an important factor affecting the extent and composition of airborne dust.

The colonization, by sophisticated agricultural people, of the Loess Plateau of northern China, a mass of wind-deposited silt with an area >400,000 km^2 and an average thickness of 100 m, has had a notable impact. Locally dense populations practicing hand agriculture and their grazing animals have played a major role in accelerating river erosion and slope failure. Some commentators take the view that the Loess Plateau and the Mongolian steppe lands to the north of it can be regarded as a secondary source of atmospheric dust in present climatic conditions (Figure 13), although this view is being challenged (see Section II.C).

Northern India, another region with a dense human population, injects the products of the burning of dung, wood, and fossil fuels into the atmosphere to an extent that makes it difficult to estimate the natural component in atmospheric dust palls. The definition of the main dust sources is also complicated by widespread

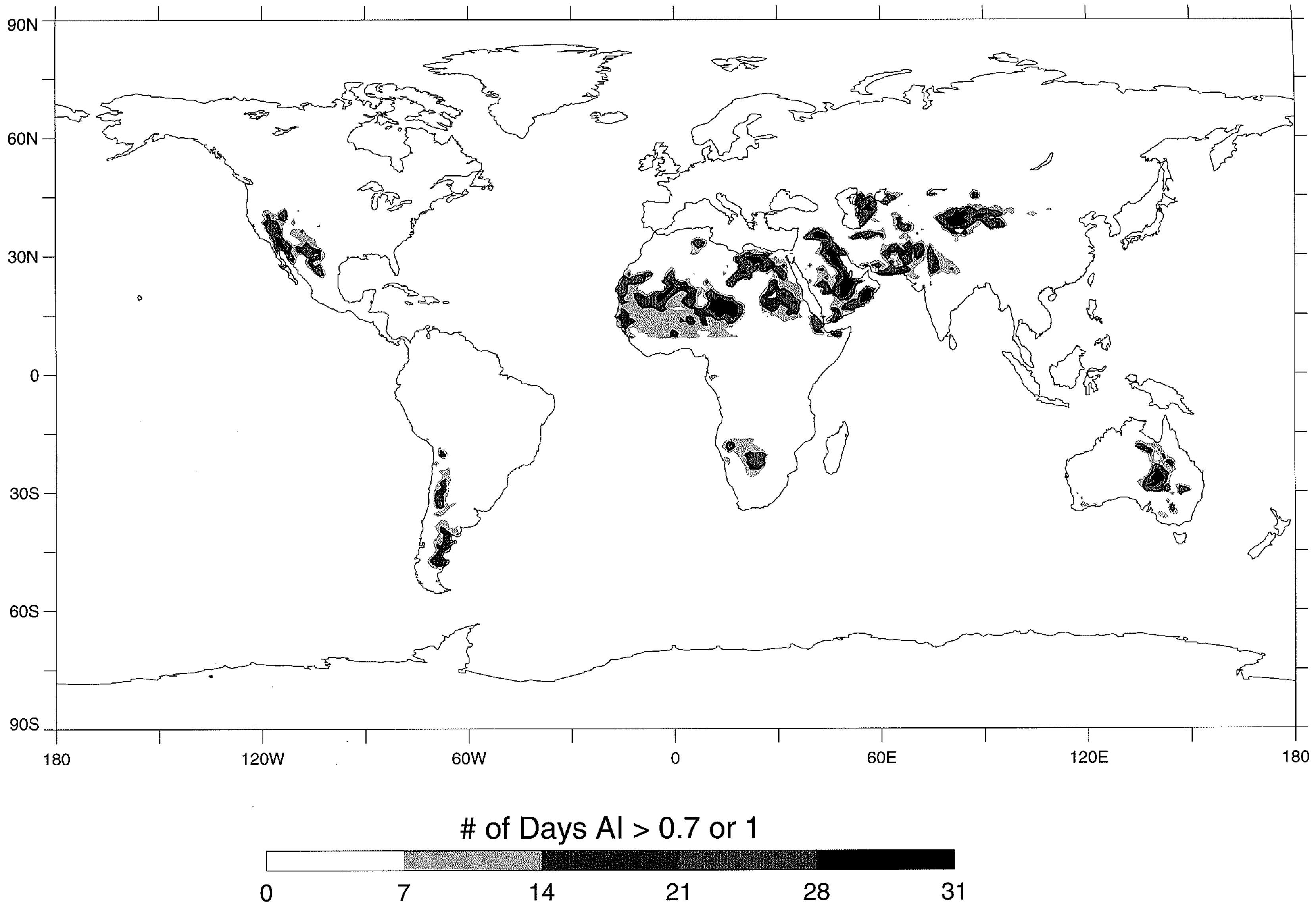

FIGURE 12 Global distribution of TOMS dust sources. This is a composite of selected monthly mean TOMS AAI frequency of occurrence distributions for specific regions using those months that best illustrate the configuration of specific dust sources. The distributions were computed using a threshold of 1.0 in the "global dust belt" (west African Saharan coast, through the Middle East, and central Asia to the Yellow Sea), and 0.7 elsewhere. After Prospero et al. (2002), with kind permission of the first author.

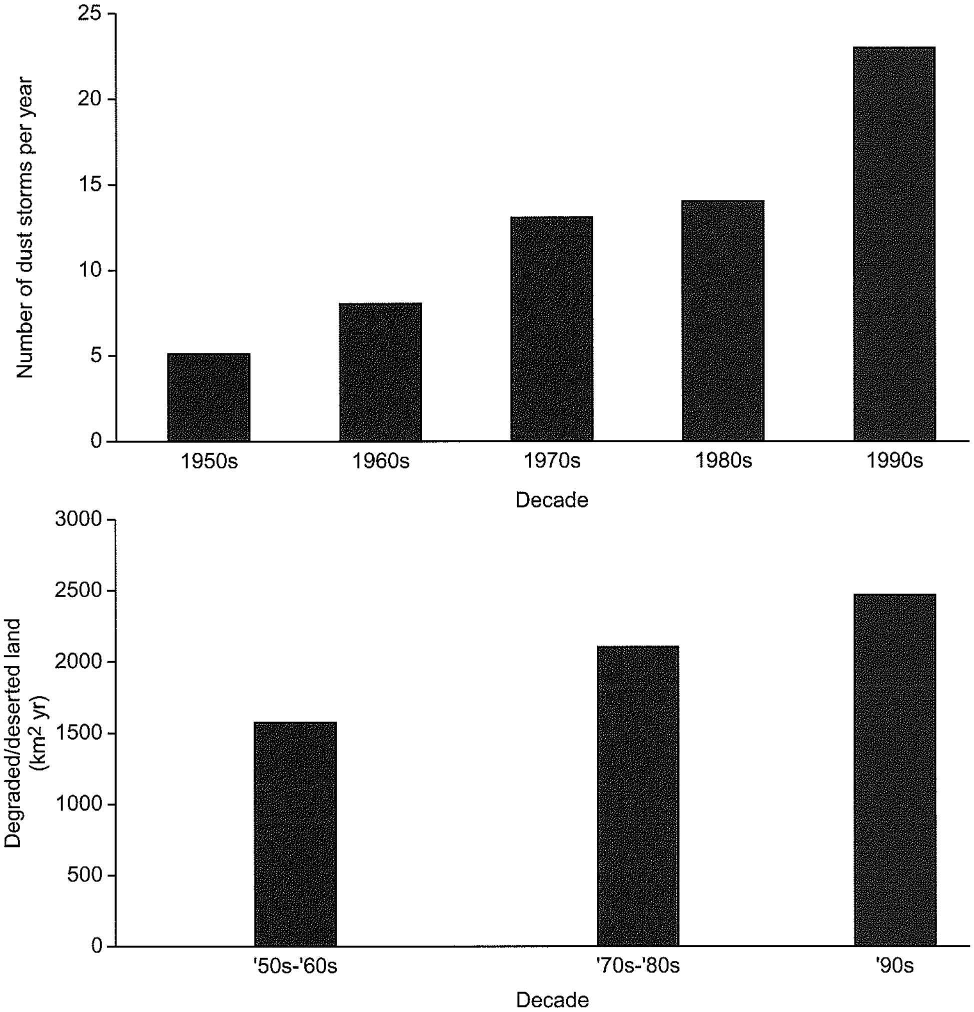

FIGURE 13 Graphs showing (top) the number of dust storms per year by decade, from the 1950s to the 1990s, in Beijing and (bottom) the annual rate of land degradation (in km^2 yr) in Inner Mongolia (lying northwest (windward) of Beijing). Data kindly supplied by Dr. Xingmin Meng from a Chinese-language Web site.

biomass burning in central and southern Africa. Land degradation arising from resettlement of quite large populations since the middle of the 20th century, and subsequent land clearing, agriculture, and/or animal grazing, has created new sources of dust in the Etosha Pan in Namibia (southern Africa; Bryant, 2003). This is also true of the Mongolian Plateau in eastern Asia. The recent history of human interference by damming rivers draining into the Caspian and Aral seas provides another such example. The diminution of the Aral Sea has become a classic case of the human generation of an atmospheric dust source, but smaller examples are known, such as Owens Lake in California in the United States (see Section III.B).

A number of studies have attempted to quantify global dust emissions, but estimates vary substantially, which reflects the evidently wide gap between modeling-based estimates and those based on the numerous available (but short-term) measurements. Equally diverse are estimates of the effect of land use and land use changes on the global atmospheric dust loading, which may be less than 20% (Prospero et al., 2002).

C. Dust Storm Frequencies

Dust storm frequency is usually measured by the annual number of "dust storm days," defined as a reduction of visibility by dust to less than 1 km for all or part of a day. Allowing for the fact that the number of ground observations is low, the location of measuring sites is extremely uneven, and the measurement record very short for many sites, the range of dust storm days per year values is wide with figures reaching about 80 in southwest Asia, >60 in Turkmenistan and the Karakum, >45 in Kazakhstan, >30 in the Tarim Basin, the Hexi Corridor, and the Loess Plateau (China), ~30 in parts of North Africa, ~20 in the Northwestern Indian subcontinent, and >15 in central Australia (Middleton et al., 1986).

Measured dust storm frequencies are open to different interpretations, however, even in some densely populated regions of the world. For example, the rise in frequency in North China in the second half of the twentieth century referred to above (Figure 13) is currently under review in the context of global warming. It is argued that, while increased desertification might be expected to result in more frequent dust storms, the recent decline in the number of dust storms in the Beijing region, indicated by some records, is consistent with the current warming trend, although the effects on total seasonal dust volumes of any such decline may be offset by an increase in the vigor of individual dust events. Certainly, higher mean temperatures over North China would be consistent with a generally weaker winter-spring monsoon and fewer outbreaks of cold, dense air from the northwest. Thus, although there is some observational evidence suggesting a negative correlation between the number of spring dust storms and mean temperatures over this large region, the case for decline is inconclusive. This may reflect the complex cause-and effect-relationships involved in dust storm analysis. Another more skeptical point of view is that governmental and public concern about dust storms is now much greater than it was in the social climate of the 1950s, 1960s, and 1970s.

D. Ambient Dust: Continental Concentrations

Dispersion of mineral aerosols during and following dust storms yields ambient atmospheric dust in the form of sets of discrete plumes and extensive regional sheets or palls. Discrete plumes, thought to derive from point sources, give rise to very high dust concentrations that include the coarsest particle fractions; such plumes persist for relatively short periods (hours to days). With increasing distance from source, atmospheric dust disperses as regional palls of finer particles in which the respirable fractions are dominant; these may persist for several days or longer.

Numerous measurements of ambient dust concentrations have been made, although most cover short periods only. In addition, the terrestrial sites concerned are very unevenly distributed. Both of these facts make it difficult to assess with any precision the terrestrial "dust climate" at a regional scale, as exemplified by the current controversial situation in North China mentioned above. Direct and regular measurement of dust concentration is rare or absent in many parts of the world. Most national meteorological services measure or estimate visibility. However, because visibility is a composite product of both atmospheric humidity and concentration of aerosols (both natural and anthropogenic), visibility estimates provide only a rough guide to dust concentrations (see below). Moreover, although satellite observations are very informative with respect to sources and transport paths in the troposphere, many dust events are not detected in this way (Section II.B). Further, the common assumption of global uniformity in the optical properties of dust is manifestly unrealistic. In regions in which frequent high concentrations of minerogenic dust constitute a health hazard for large human populations, such as northern China, existing data gathering is clearly inadequate, as indicated in the recent call within China for a nationwide state-owned network for the monitoring and analysis of atmospheric dust. Many of the existing measurements of atmospheric dust in continental locations are orders of magnitude greater than those obtained from measurements over the oceans. Maximum values of mineral dust cited in the literature for continental areas are around $10^5 \mu g m^{-3}$ (Pye, 1987), although concentrations may occasionally exceed this value in some parts of the world. The "normal background" lower atmosphere dust concentration in northwest China is $0.083 mg m^{-3}$, which reaches values of about $4 mg m^{-3}$ in "ordinary"

TABLE 1. Categories of Dust Concentration Used to Describe Chinese Dust Storm Events

Dust concentration ($mg m^3$)	*Description*
0.083	Normal background
0.356	"Detachment mode"
1.206	Extensive dust pall
3.955	Ordinary dust storm

From Chinese Meteorological Bureau.

dust storms (Table I). However, concentrations of 69 mg m^{-3} (April 1998) and 21.61 mg m^{-3} (April 2003) have recently been recorded, and an extreme value of 1016 mg m^{-3} occurred in May 1993 (Derbyshire et al., 1998).

Human settlement of continental drylands has undoubtedly served to enhance the frequency, magnitude, and impact on health of dust-entraining events and ambient dust levels. Activities such as arable farming, intensive grazing, industry, urbanization, and road and rail construction are frequently concentrated within natural dust source environments such as alluvial fans, river floodplains and terraces, and lake basin margins. Loess and silts deposited by rivers and lakes provide some of the most fertile and readily cultivated soils on Earth, as well as a widely used building material (known in parts of the Americas as adobe). Recent extension of agricultural activities along desert margins in several continents, and notably in Asia, has caused varying degrees of land degradation (often generalized as desertification). Hand cultivation and shallow plowing of such deposits certainly stimulates local dust palls, and dust concentrations in many adobe dwellings are often some orders of magnitude higher than those found in normal background conditions in regions such as Ladakh and northern China. In such situations, it is often difficult to discriminate between natural and anthropogenic dust, and so to attribute with any assurance human health effects exclusively to natural versus "occupational" dust events.

III. PATHOLOGICAL EFFECTS OF AEROSOL DUST

Inhalation of mineral aerosol particles, followed by deposition in human pulmonary alveoli, varies with a number of factors, but particle size and composition and certain lung functions are particularly important. Most coarse particles in minerogenic dust (diameter <100 µm) are abundant close to the dust sources, and they are deposited relatively quickly by both dry and wet depositional processes. Thick dust palls characteristic of locations relatively close to dust sources pose a number of hazards to human health and welfare, which include transport accidents, destruction of crops, and eye irritation. When inhaled, many of the larger dust particles are eventually rejected by expectoration. However, inhalation of large dust particles (>10 µm) may constitute a health risk if the mineralogy is toxic, regardless of where the grains lodge in the respiratory system. Of the finer dust particles (diameter <10 µm) that remain in suspension in the atmosphere for much longer periods (the respirable fraction), most between 10 and 5 µm become trapped in the upper respiratory tract and are ultimately removed by coughing. Particles finer than 5 µm frequently penetrate more deeply into the lungs to cause silicosis (Pendergrass, 1958), asbestosis, and other lung conditions. Recent studies suggest that about 75% of dust found in some Chinese post-mortem lung tissue is finer than 3 µm. Atmospheric dust finer than 2.5 µm is considered to be of particular importance with respect to community health, as in the PM standard of the United States' Environmental Protection Agency.* Ambient dust may also absorb harmful gases, disease-generating bacteria, and even carcinogenic hydrocarbon compounds. Recent work in China, for example, has shown that the denser the ambient dust, the higher the rates of chronic respiratory disease and associated death rates. Respiratory disease may also exacerbate cardiac problems (see also Chapter 23, this volume).

A. Pneumoconioses

The pneumoconioses, lung diseases that include silicosis and asbestosis, are a result of prolonged inhalation of fine minerogenic aerosol dust. The condition is best documented from studies of workers in certain industries in which high mineral concentrations are generated (occupational pneumoconiosis). Much less attention has been accorded to cases of pneumoconiosis arising from non-occupational exposure to ambient mineral dust; one recent exception is the "cleanup" campaign at Libby, Montana in the United States (see below). Studies based on occupational cases show both pneumoconioses to be insidious in the early stages but then progressively noticeable when exercising, thus the symptoms are sometimes attributed to a patient's aging (Wagner, 1997). Many symptoms are nonspecific in the absence of radiography, and this may constitute an important factor influencing diagnosis in some developing countries. Radiographic diagnosis of silicosis is made with confidence only after the appearance of silicotic nodules 2–5 mm in size. Continued dust exposure leads to an increase in nodular size and number so that they eventually cover much of the lung, and the nodules sometimes coalesce to form conglomerate shadows often called progressive massive fibrosis (Saiyed, 1999).

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*The PM (particulate matter) standard is based on the total mass of particles measuring 2.5 microns or less observed in a 24-hour period.

Some types of inhaled particulates are degraded by macrophages, but many are highly resistant to this process and persist in the lung cavity and lymph nodes. Some resistant particulates appear to cause no problems, but others stimulate fibroblastic cells to deposit collagen. In the case of asbestos, for example, detectable fibrosis appears only after a threshold number of particles have been retained (Bar-Ziv & Goldberg, 1974). Silica is a highly fibrogenic agent in lung tissue, and the reaction is very different from the granulomatous reaction to many other nondegradable grains; the fibrotic reaction has been associated with release of polysilicic acids. Fine-grained, sharply angular quartz grains are widely considered to enhance this process, although the precise nature of the pulmonary response to crystalline silica remains rather poorly known (Saiyed, 1999). Continued exposure to silica is thought to lead to increased rates of infection with pulmonary tuberculosis, a notable public health problem in many developing countries, with non-tuberculosis mycobacterial infection (involving intercellular bacterial parasites) also occurring. Many people with silicosis have been shown to be susceptible to tuberculosis (Snider, 1978), although present constraints on diagnosis, especially in poor and remote regions of the world, carry with them a continuing risk of confusing silicosis-related massive fibrosis with tuberculosis. Nevertheless, evidence exists that patients with silicosis carry a greater susceptibility to tuberculosis, and the World Health Organization (1997) has now listed crystalline silica as a human carcinogen. Silicosis has a number of deleterious effects upon the immune system. One important effect is a reduced ability of the macrophages to inhibit growth of tubercle bacilli. Some rheumatic, as well as chronic renal diseases also show higher than average incidence in individuals exposed to silica, and it is likely that such increased susceptibility of subjects to a suite of mycobacterial diseases is to some degree due to impaired function of macrophages in silicotic lungs (Snider, 1978).

A number of pathological conditions are associated with inhalation of asbestiform minerals. Asbestos is found in a wide variety of geological environments. For example, chrysotile is known to occur in hydrothermally altered ultramafic or carbonate rocks. Crocidolite is abundant in some metamorphosed iron formations, and may also occur as an authigenic mineral and as a hydrothermal alteration product in some carbonatite complexes. Although not covered by the term asbestos, the mineral erionite, a fibrous zeolite (group of hydrous aluminosilicates), is also known to cause asbestosis and related conditions as noted below (Section III.C). Natural release of asbestiform minerals from the host rock occurs by the processes of weathering and erosion, and the fibers are frequently concentrated by surface wash. In seasonally dry climates, such concentrations of fibers dry out and become susceptible to deflation. The health effects of asbestos inhalation include asbestosis, mesothelioma, and lung cancer. Some asbestos fibers penetrate body tissue and remain in the lungs, lung lining, and abdominal cavity. Radiographically visible fibrosis may take 15–20 years to appear following initial exposure (Wagner, 1997) (see also Chapter 22, this volume).

B. Case Studies of Non-Occupational Silicosis

Non-industrial deposition of silica in human lung tissue was first reported in three inhabitants of the Sahara Desert half a century ago. The autopsy results showed a high content of fine (<3 μm) silica dust, but there was no sign of typical silicotic lesions (Policard & Collet, 1952). Other findings from different parts of North Africa include radiological evidence of multiple micronodules in reticular disposition scattered throughout the lungs, and this is considered to be consistent with silicosis. A radiographic survey of 18 asymptomatic Bedouin females in the Negev Desert by Hirsch et al. (1974) found positive indicators in all patients who were aged between 26 and 70 years, with 9 cases in people older than 50. Histological examination showed varying amounts of dust-laden macrophages in a perivascular and peribronchial distribution, mainly in the middle and lower lungs. No typical silicotic nodules with collagenization were found, and a 3- to 5-year radiological followup study showed no evidence of progression. The fact that older patients made up the largest proportion of the sample group, and the lack of any progression toward formation of fibrotic conglomeration, suggested a benign condition called simple siliceous pneumoconiosis, which was possibly attributable to long periods of work within the confined environment of the home tent. In a larger study involving 54 cases, siliceous particles were found both free and in macrophages, and the incidence of fibrosis was shown to be age related with a progression more noted in women (13 out of 22) than in men (only 4 out of 32) (Bar-Ziv & Goldberg, 1974).

Such "desert lung syndrome" has a long history and was even found in ancient Egyptian mummies (Tapp et al., 1975). In the past half century it has also been recorded in Pakistani farmers, Californian farm workers, Ladakh villagers, people in the Thar Desert of Rajasthan, northwest India, and residents of northern

China as well as the cases mentioned above from the greater Saharan region.

A survey of two villages situated at altitudes between 3200 and 3500 m in the western Himalayas, situated only 15 km from Leh (the capital city of Ladakh), was undertaken by Norboo et al. (1991). There are no mines or industries in Ladakh, but dust storms are frequent between late winter and summer and there is characteristic local variability in their incidence in this high mountain environment. Radiographic evidence was taken from an equal number (23) of men and women between the ages of 50 and 62 years. Of these, 8 men and 16 women showed varying grades of silicosis, with important differences resulting from the higher dust concentrations at the lower village (at 3200 m) compared to the higher one (at 3500 m). Three cases of progressive massive fibrosis were found in the lower village, which suggested the likelihood that silicosis here causes appreciable morbidity. Later augmentation with necropsy lung tissue samples revealed heavy dust deposition with abundant hard, 1- to 3-mm nodules and a lymph node largely replaced by hyaline collagenous nodules, a classic feature of silicosis. More than 20% of the mineral dust extracted from the lung tissue consisted of quartz, bulk chemical analyses yielding 54% elemental silica, and 19.2% aluminum. A larger study (Saiyed et al., 1991), involving a total of 449 patients aged over 50 years (245 women, 204 men) from three different villages in the Leh vicinity, showed typical cases of pneumoconiosis associated with progressive massive fibrosis and egg-shell calcification of the bronchial glands (indicative of high concentrations of free silica) in 101 cases (22.5% of the population sampled). A close correlation was found between frequency of dust storms and number of cases of pneumoconiosis: the village with low dust storm frequency recorded only a 2.0% incidence, the one with moderate frequency showed that 20.1% of the sample population was affected, and the village with severe dust storm incidence revealed a 45.3% incidence of pneumoconiosis. The existence of such a high proportion of pneumoconiosis cases in the populations of such remote villages, with no possibility of exposure to the products of mining or industrial activity, is striking evidence of the role of minerogenic dust. Although there is little doubt that the burning of brushwood and dung in the adobe dwellings places the women at higher risk of developing pneumoconiosis, as clearly indicated by Norboo et al. (1991), Saiyed et al. (1991) found no clear differences in incidence between the sexes. Mineral dust found on the upper surfaces of wooden roof beams in houses built of loess in Ladakh is all finer than 15 μm, more than 25% by weight being <1 μm; the silica content is >60% (Figure 4B).

Several studies, both published and unpublished, have implied that the large number of people subject to the frequent dust storms characteristic of north China are potential silicosis cases. In one investigation 395 subjects (294 men and 101 women) from two communes in the middle of the Hexi Corridor, Gansu Province, were studied (mean dust concentration: 8.25–22.0 mg m^3), and 88 people (46 men and 42 women) were randomly chosen from a third commune with low dust storm exposure as a control group (mean dust concentration: 1.06–2.25 mg m^3). The incidence of silicosis was 7.09%, with no cases in the control group, but this rose to 21% in subjects over 40 years of age. There was no significant difference in incidence between the sexes, but comparative necropsy of the lungs of camels showed them to contain evidence of silicosis (Xu et al., 1993). In another, larger but unpublished radiological survey, involving 9591 residents in Gansu Province, a prevalence of 1.03% was found, which rose to 10% in subjects over 70 years old (Changqi Zou, personal communication).

In the past four decades, about half (36,000 km^2) of the former bed of the Aral Sea (western Uzbek Republic, middle Asia) has been exposed, providing a new and frequent source of fine dust (Figure 14). This situation has been exacerbated by the diversion, for irrigation purposes, of most of the waters of the two main rivers (Syr Darya and Amu Darya) that drain into the Aral Sea, adding to the regional desiccation. The fine-grained sediments (silts and clays) on the seabed are rich in agricultural chemicals, and they are readily deflated. Despite some reports of increasing respiratory illness in children, including some mention of interstitial lung disease in this region, there is little authoritative information about the link between the desiccation of the Aral Sea region and human health (Wiggs et al., 2003).

Owens Lake (California in the United States) was a shallow but perennial water body for most of the last million years, but diversion of water for use by the city of Los Angeles began in 1913 and, by 1926, the lake had dried up. The dry lakebed is now probably the greatest single source of respirable mineral dust particles in the United States. Palls of dust <10 μm in aerodynamic diameter occur on about 10 days per year across a wide area. With arsenic levels sometimes as high as 400 ng m^3 within air samples (Reid et al., 1994), and tests indicating high solubility of the arsenic in simulated lung fluids (G. Plumlee, personal communication), these events are viewed as a health hazard for residents of Owens valley (Reheis, 1997).

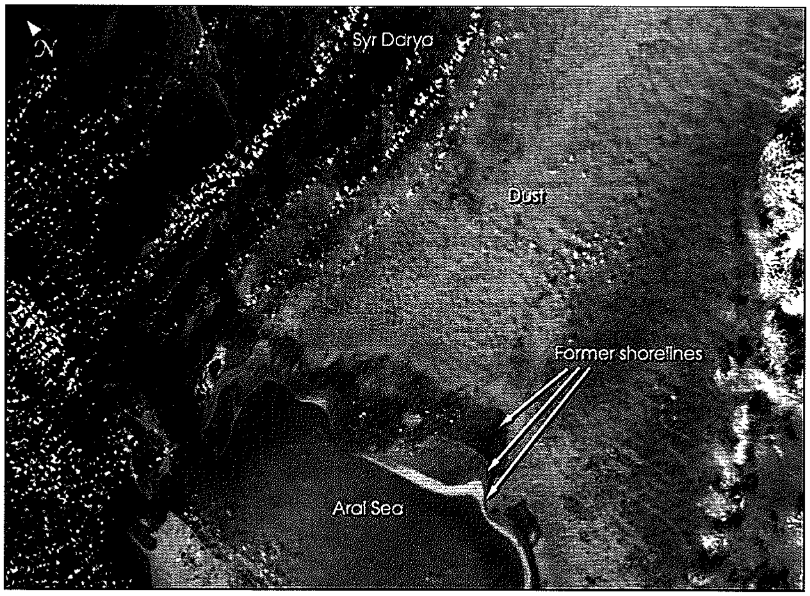

FIGURE 14 Orbital image of the Aral Sea area taken on June 30, 2001, from Space Station Alpha (Earth Sciences and Image Analysis Laboratory, Johnson Space Center). A major dust storm can be seen, driven by strong westerly winds. The sharp northern margin of the dust pall coincides with the Syr Darya River. This is beyond the area of exposed sea floor sediments, where soil moisture and vegetation cover impede deflation.

C. Case Studies of Non-Industrial Asbestosis

Asbestosis arises from inhalation of asbestos fibers, although conclusive risk assessment has been hampered because the microscopically detectable fibers make up only an insignificant proportion of the total dust burden in lung tissue (Eitner, 1988). Most studies of this interstitial lung disease have been concerned with the impact of asbestos on the health of workers in a wide range of occupations, including mining, manufacturing, and construction, as well as in users of the thousands of commercial products that contain asbestos primarily because of its insulating qualities. However, cases of non-occupational asbestosis have been reported in several countries in Europe and around the Mediterranean, including Czechoslovakia, Austria, Bulgaria, Greece, and Turkey.

In central Turkey, inhalation of agricultural soils rich in tremolite (a common fibrous amphibole found in contact-metamorphosed impure calcareous rocks) and erionite (most commonly arising from alteration of volcanic rocks) is responsible for an endemic malignant pleural mesothelioma. Incidence of this disease is specific to certain villages around which the soils contain one or both of these minerals.

Incidence of pleural plaques, associated with mesothelioma, was also found in residents of northern Corsica who had no history of occupational contact with asbestos. The percentage of 1721 subjects shown by radiographs to have bilateral pleural plaques was 3.7% for those born in northeastern Corsica compared to only 1.2% for those born in the northwest. The rocks of the northeast are rich in serpentine, asbestos, and chrysotile, but this region is separated from the northwest part of the island by a mountain barrier. A clear excess of subjects with bilateral plaques born in villages close to asbestos outcrops was shown (94.6% for affected subjects born in the northeast compared to only 5.4% of subjects born in unexposed villages; Boutin et al., 1986). Preliminary data indicated high levels of chrysotile fibers in the atmosphere, suggesting that incidence of the disease arises directly from inhalation, in an environment in which asbestos exposures and patients with plaques are juxtaposed.

In 1999, public concern led to investigation of a vermiculite mine in Libby, Montana, USA, following its closure in 1990 after more than a century of operation. It had been found that the vermiculite, a micaceous mineral widely used in the insulation of buildings, was contaminated with the tremolite-actinolite form of asbestos. In the alkalic intrusive complex at Libby, the amphiboles are a product of hydrothermal alteration of pyroxenites which also occur as hydrothermal veins cutting across the igneous rocks (G. Plumlee, personal communication). Investigations designed to determine the extent of the impact upon human health arising from occupational links as well as any non-occupational effects arising from activities such as gardening and use of unpaved roads included testing of more than 7000 people over 18 years old in the years 2000 and 2001. This involved interviews, medical history, chest x-ray, and lung function (spirometry) tests. The results showed that radiographic pleural and interstitial abnormalities were present in 51% of former mine workers. The risk of such abnormalities increased with age and with increasing length of residence in the Libby area. The odds of finding pleural abnormalities were stated to be 1.7–4.4 times greater (depending on age) in the case of former mine workers compared to residents with no mine connection, although the incidence of abnormalities in the latter group (3.8%) was higher than for groups within the United States with no known asbestos exposure (range 0.2%–2.3%; United States Environmental Protection Agency, 2003).

D. Tuberculosis

It has been suggested that the incidence of pulmonary tuberculosis in dryland environments may be linked to non-occupational silicosis. Sunlight and aridity are antipathetic to the tubercle bacilli and droplet transmission of pulmonary tuberculosis is favored by lack of sunlight, higher humidity, and overcrowding. However, data from the Thar Desert, India, presented by Mathur and Choudhary (1997), show a prevalence of tuberculosis in desert areas of Rajasthan about 25% higher than the non-desert parts. The presence of radiographically determined evidence of non-occupational silicosis in the desert people offers some support for the hypothesis that silicosis may be an important factor in the higher prevalence of tuberculosis in this desert.

IV. CONCLUSIONS

Aerosol mineral dusts affect human health as a result of inhalation and retention of the finest fractions derived directly from source sediments and indirectly from disturbance of surface layers of loess, a geological formation consisting primarily of wind-lain minerogenic dust. The geological and meteorological study of dust sources, sinks, transport, and geochemistry provides a foundation for improved understanding of the extent and magnitude of the impacts of natural minerogenic aerosols on human health.

The pathological effects of prolonged exposure to natural aerosol dust have been recognized in a general way since ancient times, but the number of modern studies of the pneumoconioses outside occupation-specific contexts remains small. The specific health effects of direct inhalation of high concentrations of fine minerogenic dusts, generated by natural deflation from loose, poorly bound soil surfaces, including those exposed by accelerated erosion of weak geological formations such as loess, thus remain rather poorly known and relatively little researched. Knowledge of many of the suspected linkages involved is incomplete, and so is inferential to varying degrees. The magnitude of the world's population affected by inhalation of fine mineral aerosols can only be estimated, although it is likely to number millions of people in the middle latitude desert zone especially across Eurasia between the eastern Mediterranean and the Yellow Sea. Given the progressive improvement and sensitivity of remotely sensed information derived from the several types of orbiting satellite platforms, there is a need for greater investment in improved "ground truth" systems. Obtaining the necessary data on the nature of the "dust climate" and degrees of dust exposure in susceptible environments requires the application of appropriate geological and meteorological methods of monitoring and analyzing dust. This should include regular, standardized measurement and collection and analysis of dust concentrations in the lower atmosphere as a routine component of the meteorological observation systems already operated by most countries. Systematic research programs designed to quantify the respiratory health status of people in the same environments but with contrasting dust exposure potential, and taking full account of other risk factors including those of anthropogenic origin (occupational conditions, cigarette smoking, lifestyle, etc.), will be needed to complement the environmental monitoring.

The impact of trace elements on human health by way of the indirect pathway through soils and groundwater, as found in the loess and loess-like sedimentary accumulations and associated soil types within and adjacent to the great dryland zones of the world, has received much more attention than the direct and indirect pathways considered here, as shown elsewhere in this volume.

Finally, some account of way of life must be considered as a factor in any assessment of the health impact of respirable mineral dust because it directly affects dust generation, re-suspension, and inhalation in many of the world's drylands. Loess and loessic alluvium are abundant and easily applied to building materials used widely in Asia; the predominantly flat-roofed dwellings require only small amounts of wood to complete them. Traditionally, many such houses use small interior kitchens for cooking in winter, with open fires and some primitive chimneys. Although the situation is now slowly changing, domestic burning of dried cattle-dung, wood, and (rarely) low-grade coal is still common, for example, in Ladakh and the Hexi Corridor in northwestern China. To the smoky atmosphere in such confined environments is added fine, re-suspended loessic dust raised by sweeping the dried loess floors. This is mixed with varying concentrations of cigarette smoke. Such high dust concentrations in the home place females at relatively higher risk than males. This may be further enhanced by additional exposure to field dust in areas, such as the tributary valleys of the Indus (northernmost Pakistan), in which females also play a primary role in cultivating the fine silty soils. Such complexity renders the design of a set of strategies for amelioration, if not prevention, a formidable task. It is yet another, perhaps unsung, addition to the challenges posed particularly by many countries in the developing world, with a bearing on the lives of many tens of millions of people.

SEE ALSO THE FOLLOWING CHAPTERS

Chapter 2 (Natural Distribution and Abundance of Elements) · Chapter 11 (Arsenic in Groundwater and the Environment) · Chapter 19 (The Ecology of Soil-Borne Human Pathogens) · Chapter 22 (Environmental Medicine) · Chapter 23 (Environmental Pathology)

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