Urban Lead Poisoning and Medical Geology: An Unfinished Story

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ABSTRACT

The intersection between geological sciences and human health, termed *medical geology*, is gaining significant interest as we understand more completely coupled biogeochemical systems. An example of a medical geology problem largely considered solved is that of lead (Pb) poisoning. With aggressive removal of the major sources of Pb to the environment, including Pb-based paint, leaded gasoline, and lead pipes and solder, the number of children in the United States affected by Pb poisoning has been reduced by 80%, down to a current level of 2.2%. In contrast to this national average, however, about 15% of urban children exhibit blood Pb levels above what has been deemed "safe" (10 µg per deciliter); most of these are children of low socio-economic-status minority groups. We have analyzed the spatial relationship between Pb toxicity and metropolitan roadways in Indianapolis and conclude that Pb contamination in soils adjacent to roadways, the cumulative residue from the combustion of leaded gasoline, is being remobilized. Developing strategies to remove roadway Pb at the source is a matter of public health and social justice, and constitutes perhaps the final chapter in this particular story of medical geology.

INTRODUCTION

The industrial age has seen a number of technological advances that have had unforeseen environmental and human consequences. The awareness of the severe neurotoxicity of lead (Pb) in humans, for example, provoked a number of regulatory measures, including phase-out of Pb as additives to gasoline, paint, water pipes, and solder, which significantly reduced the human exposure to Pb. The end product of these actions? A reduction in Pb poisoning of children by 80% since the late 1970s—now <2.2% of U.S. children between the ages of one and five are considered Pb-poisoned (National Health and Nutrition Examination Survey [NHANES], 2003).

By all usual accounts, the recent turnaround in national health statistics related to Pb poisoning implies a seamless and uniform industrial and governmental response to this threat and denotes the end of Pb as a human health risk. Sadly, such is not the case—many urban areas still exhibit high Pb poisoning rates in children under age six (the most vulnerable age interval for Pb toxicity; Koller et al., 2004), reaching values up to 29% of the 0.5–5 yr old population in New Orleans, Louisiana (Rabito et al., 2003), and even higher overseas (e.g., 78% of school children in Johannesburg, South Africa are considered Pb-poisoned; Mathee et al. [2002]). Childhood Pb poisoning continues to be a major public health problem in the United States, particularly for low-income, urban, African-American children (Roberts et al., 2001). The emission control and public health strategies used in the past have not been successful at overcoming this urban poisoning remnant (Agency for Toxic Substances and Disease Registry [ATSDR], 2002), and until we fully understand the anthropogenic, geologic, and socioeconomic web that results in the poisoning of urban youth, this remains an unfinished story in the annals of medical geology.

In this paper, we introduce the historical perspective of Pb use, particularly in leaded gasoline, and the findings that Pb has significant health impacts for humans. But more importantly, we discuss how integrating geologic factors, like soil, Pb geochemistry and cycling, and soil moisture and resuspension, into public health practices may help to ultimately eliminate Pb poisoning as a human health concern.

HISTORY

Lead toxicity has been known for centuries, but it was not until the industrial revolution that this issue became a widespread problem. Lead is a soft and workable metal easily extracted from galena ore, characteristics that were widely exploited by preindustrial populations. The Romans developed the first large-scale quarrying and working operations for Pb, exploiting the newly conquered Iberian Peninsula and its rich metal deposits to produce finished Pb used in containers, water pipes, and as a Pb-salt preservative for wines (in which application the Pb becomes very bioavailable); evidence of the global impacts of this quarrying effort are seen in Greenland ice core records (Hong et al., 1994; Rosman et al., 1997).

By far the largest use of Pb has occurred in the industrial era, where two new applications of Pb were found in the twentieth century: Pb-based paints and tetraethyl/methyl additives to gasoline. Lead-based paints, which contain up to 15% Pb, are extremely durable and flexible, and their use expanded dramatically during the 1920s (Fig. 1). The production and use of Pb for gasoline additives was spurred by the need to control the explosion of gasoline in cylinders of internal combustion engines. Thomas Midgely, an engineer for General Motors and DuPont, perfected the formulation of Pb additives in the 1920s, but the peak in Pb use for this application follows the trend in automobile use in America, with a peak closer to 1970 (Fig. 1). Midgely (ironically, also the inventor of Freon®, the chlorofluorocarbon chemical implicated in stratospheric ozone loss) first developed an effective anti-knock additive using plant biomass–produced alcohol, but as this additive could be produced by any farmer and was not patentable, he was told to continue searching, eventually finding that adding ~2% Pb oxides to gasoline works well. An early warning sign went up when scores of workers were severely poisoned in the 1920s by Pb toxicity in plants producing tetraethyl Pb additives, although a multi-pronged industrial cover-up limited public awareness of this situation (Markowitz and Rosner, 2002). The

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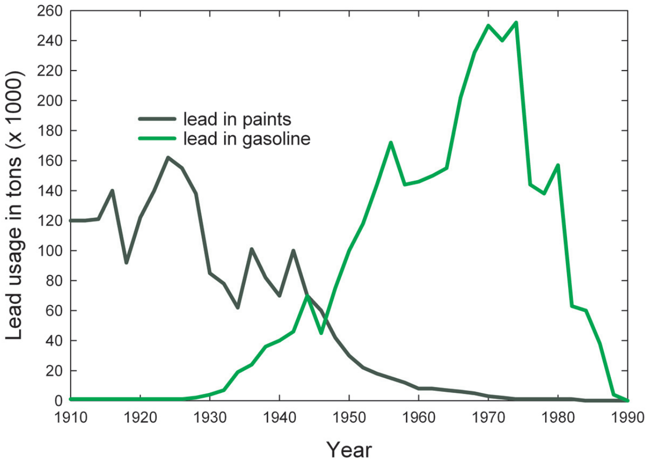

Figure 1. History of Pb usage in paints and gasoline during most of the twentieth century, showing the early dominance of Pb-based paints followed by the boom in transportation resulting in a high use of leaded gasoline (after Mielke, 1999). The decline after the mid-1970s was due to controls put into place to eliminate leaded gasoline.

dawn of the automobile age shelved concerns of the environmental impacts of tetraethyl Pb as affordable transportation dramatically altered the American landscape of the twentieth century.

Just how much the use of tetraethyl and other Pb impacted our environment began to be discerned in the 1950s in a laboratory at the California Institute of Technology. There, an isotope geochemist named Clair Patterson was carefully examining earth materials using new methods of mass spectrometry, with a goal of understanding the age of Earth (which, remarkably, he pinned at 4.55 Ga in 1963, nearly identical to modern estimates). He used radiogenic Pb isotopes for this work, and soon found that Pb isotopic ratios were excellent tools for fingerprinting source regions of sedimentary rocks and water bodies. One persistent problem he had in these efforts was the prevalence of contamination by anthropogenic Pb sources. Turning his considerable talents to this problem of contamination ended up being one of the great stories in medical geology. Patterson found that Pb resulting from human activity was everywhere, including water, soil, arctic ice, and most troubling, in people. Indeed, the development of Pb isotopic techniques has significantly enhanced our understanding of sources of additional Pb to the environment and cycling of Pb in soils (Deboudt et al., 1999; Sañudo-Wilhelmy and Gill, 1999; Kurkjian and Flegal, 2003) and in human tissues (Graziano et al., 1996; Gwiazda and Smith, 2000; Manton et al., 2000; Rothenberg et al., 2001). Showing an academic bravery just short of foolishness, Patterson not only published his troubling findings of Pb contamination and potential poisoning in humans in peer-reviewed scientific journals (e.g., Settle and Patterson, 1980), but he also raised the alarm to regulators, industries, and lawmakers, pointing out that the sources of this contaminant were clear and could be completely eliminated. After many well-documented attacks on his credibility, funding, and job by industry advocates (see Bill Bryson's 2003 book, *A Short History of Nearly Everything*, for an excellent recounting), he succeeded in convincing lawmakers to eliminate Pb use in pipes, solder, and finally, in 1986, gasoline. As a measure of the value that the geological community placed on these efforts, the Geochemical Society's Environmental Geochemistry Medal is named in honor of Patterson.

LEAD AND HUMAN HEALTH

In part due to Patterson's crusade, new sources of Pb to the environment have been virtually eliminated in the United States and are being reduced and/or eliminated in many other countries as well. The net impact of this elimination can best be measured from a human health standpoint by the concentration of Pb in blood serum samples (venous blood Pb level). A portion of the Pb ingested via soil or water and/or inhaled is absorbed in the intestine and incorporated in the body. Inhalation is a minor uptake pathway and ingestion via water has largely been reduced with the replacement of Pb water pipes and water tanks with non-Pb alternatives. However, Pb in soil and dust continues to be a major source of exposure (Koller et al., 2004). Based on clinical trials, the portion of ingested Pb that is taken up in the body is typically less than 5% for adults, whereas it is as high as 50% for children due to their less-developed gastrointestinal pathway (Ziegler et al., 1978; Maddaloni et al., 1998).

Due to similar charges and ionic radii, Pb is utilized in biological processes much like Ca, including as a critical component of converting the electrical neural signal into a chemical signal and as a component of hydroxyapatite in the production of bone material. When engaged in the former process, Pb does not function as a neurotransmitter, effectively creating permanent neural differentiation defects resulting in mental retardation, learning disorders, and attention deficit hyperactivity disorder (ADHD). Because of their high ingestion efficiency and the rapid neural differentiation during early brain and nervous system development, children are especially vulnerable to the permanent effects of Pb poisoning. When Pb is incorporated in bone material, the bone becomes a long-term source of Pb to the biological system—bone is regenerated on monthly to yearly timescales, leaking additional Pb into the system. For this reason, children treated by medical interventions like blood chelation may continue exhibiting toxic levels of Pb in their blood (Roberts et al., 2001). In summary, persistent elevated Pb concentration in children can create a cascade of severe and permanent mental, behavioral, and physiological problems.

The health standards for Pb levels in blood have been revised steadily downward over the years as medical research has determined toxicological effects of Pb even in low quantities. The U.S. Centers for Disease Control and Prevention (CDC) in 1991 chose 10 µg/dL as an initial screening level for Pb in children's blood, although some research suggests that levels even lower than this can cause some toxicological effects (Bernard, 2003; Brown and Meehan, 2004). The persistent presence of Pb in children is a public health issue of a first order. As noted earlier, as a U.S. national average, 2.2% of children under the age of 6 exhibit blood Pb levels above this screening level, although this value is often above 15% among urban youth. In a summary from a national health survey, Brody et al. (1994) state "the exposure to Pb at levels that may adversely affect the health of children remains a problem especially for those who are minority, urban, and from low-income families. Strategies to identify the most vulnerable risk groups are necessary to further reduce Pb exposure in the United States." Factors affecting children in this socioeconomic class include poor nutrition with the potential for pica behavior (a subconscious desire to ingest soil and dust to overcome nutritional deficits), inadequate pediatric health care, poor home maintenance with a high percentage of rental housing, a significant proportion of urban housing with high dust and dirt exposure, and relatively low awareness of the links between health and behavior.

In this paper, we use the city of Indianapolis, Indiana, a typical older midwestern United States city, to explore in detail the continuing sources and the pathways for exposure that face urban youth. Indianapolis is the 12th largest city in the country, with diversity reflecting the national average (25% African-American and Hispanic), a significant proportion of pre-1940s housing (with Pb-based paint use), and a large interstate transportation connection downtown with a clear history of leaded gasoline use. Additionally, Indianapolis has excellent public health records from which to extract the distribution of Pb-poisoned children. Combining information about point sources of environmental contamination, a sampling technique designed to determine more diffuse sources of soil Pb, seasonality studies, and public health data, we demonstrate the ongoing impact that past Pb contamination has on the population, and provide several recommendations for determining and predicting Pb contamination and poisoning.

METHODS

All soil samples used in this study were collected from amalgamated sampling techniques (a 10 m grid with pooled surface samples of the upper 5 cm of soil). Samples were sieved to 63 microns to minimize the effect of grain size variations in Pb concentration. Dried soils were ashed at 550 °C and digested for 2 h in warm (90 °C) 3N trace metal grade hydrochloric acid. Supernatants were diluted with ultra-pure water (Milli-Q) and analyzed via inductively coupled plasma–atomic-emission spectrometry. All digestions were run with National Institute of Standards and Technology (NIST) soil standards for reference. Replicates were also run for all analyses, with typical analytical reproducibility of ~2%. Additional details and results for a number of other trace metals can be found in Laidlaw (2001).

ROADWAY SOURCES OF Pb

The aerosolized combustion products (containing Pb) from the burning of leaded gasoline in internal combustion engines initially deposit within ~50 m of a roadway if no obstructions are present (Fig. 2). The fate of deposited Pb then depends on the conditions of the depositional area. Although intersections of busy streets may have received over one metric ton of Pb per year (Mielke et al., 1997), their impervious surfaces lead to continual runoff of Pb-enriched particulates down storm drains (and from there into treatment plants or directly into rivers). If the particulate Pb is deposited instead on a grassy fringe, like a front yard or park, the Pb can be effectively retained. In such a setting, the insolubility of Pb leads to surface peaks in Pb concentration of soils (Fig. 3); in relatively undisturbed soils, this surface Pb enrichment may be the product of decades of Pb deposition from gasoline and may reach levels above 1000 ppm (Mielke, 1999; Mielke et al. 2003).

The roadway Pb generally is partitioned into the highly bioavailable carbonate, iron, and manganese hydroxide soil fractions, while the natural Pb in soils is speciated in the residual, or non-bioavailable fractions (Chlopecka et al., 1996; Lee et al., 1997). Lead is associated with the smallest particles, the clay grain size fraction in urban soils (Dong et al., 1984). Therefore, dust originating from urban soils contaminated by anthropogenic Pb is more toxic than naturally occurring dust and is more potent and concentrated than would be expected from simple measurements of the Pb content of the soil (Young et al., 2002).

DIFFUSE SOIL Pb AND CHILDREN'S HEALTH—A CASE STUDY FROM INDIANAPOLIS

The original sources of Pb to the environment were distinct sources, including Pb-based paints, gasoline-emitted Pb, and Pb emitted from smelters. As detailed above, Pb does not originally deposit far from its source, and its geochemical characteristics promote rapid sequestration onto surface soil particulates (usually via surface complexation of Pb and Pb oxides with soil organic matter). But an analysis of many urban areas reveals that these point sources have, to some extent at least, been redistributed to produce regions of Pb enrichment. Several factors can lead

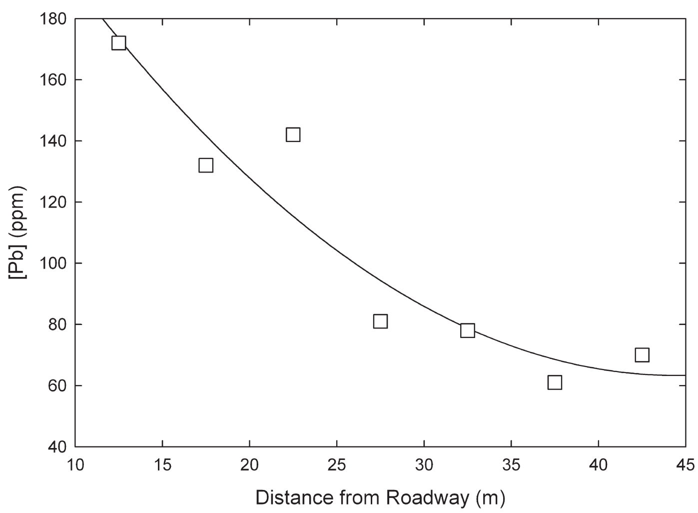

Figure 2. The exponential decay of Pb in surface soils as a function of distance from a roadway source along a suburban street in Indianapolis, Indiana (Kessler Boulevard). This curve is typical of the roadway effect, showing both the rapid deposition of Pb in exhaust particulates from the combustion of leaded gasoline and the persistence of this Pb in surface soils (leaded gasoline use stopped ~20 yr ago). A second-order regression fits data the best, yielding a correlation coefficient (r^2) of 0.902. Symbol size is larger than error bars on both axes.

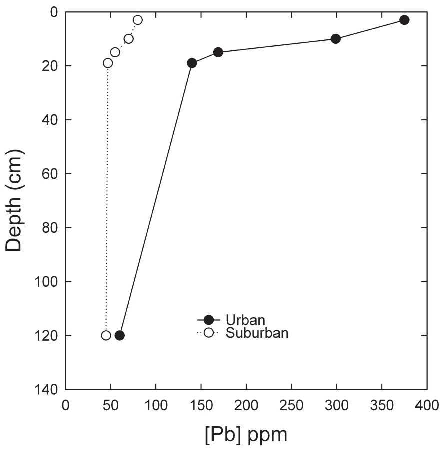

Figure 3. Concentration of Pb as a function of depth from two soil cores in Indianapolis, displaying the surface peak in both an urban and suburban settings far from direct sources of Pb deposition (e.g., painted structures or roads). This plot shows a soil background level of 50 ppm Pb (consistent with geological materials) and the surface retention of Pb, but also displays the ambient diffuse soil Pb enrichment in urban versus suburban areas. Sampling locations are in Laidlaw (2001).

to redistribution of Pb-enriched particles and soil—this issue will be addressed more completely in the next section—but the recurrence of a general urban enrichment of soil Pb has been documented in many regions (e.g., Mielke et al., 1983), and the potential impacts of this urban contamination were presaged by the classic quote by Clair Patterson (NAS, 1980), "Sometime in the near future it probably will be shown that the older urban areas of the United States have been rendered more or less uninhabitable by the millions of tons of poisonous industrial Pb residues that have accumulated in cities during the past century." To explore this generalized urban enrichment, termed *diffuse soil Pb*, and evidence of its potential human health impact, we first show the pattern of diffuse soil Pb in Indianapolis, then the link between soil Pb and children's blood Pb levels.

One of the characteristics of Pb distribution in the surface soils of cities is a distinct decrease in concentration from the city center to suburban surroundings (Mielke, 1999), a legacy both of Pb deposition, redistribution, and smearing of original point sources, and less Pb deposition in newer suburban neighborhoods due to recent Pb controls. This urban-suburban gradient can be illustrated by examining diffuse soil Pb along an urban roadway transect (Washington Street) versus one in the suburbs (East Kessler Blvd.) of Indianapolis. Washington Street, the route of the National Road (U.S. 40) in Indianapolis, experiences high local traffic loads and is bordered by very old urban neighborhoods. In contrast, the suburban East Kessler Boulevard was developed from a country road to a suburban thoroughfare in the 1970s, during a time when the use of leaded gasoline was declining significantly (Fig. 1). In the reference year 1980 (the official phase-out of leaded gas was 1986, although most vehicles were running on unleaded fuel by 1981), East Kessler Boulevard experienced a relatively high daily traffic load, but only ~50% that of Washington Street at the westernmost intersection. A comparison of the Pb loading from roadway sources along these two streets reveals three main factors of roadway Pb deposition. First, the decrease in Pb concentration away from the roadway is manifest in both higher and lower traffic volume settings (Fig. 4). Second, although leaded gasoline use spanned a relatively short time along the suburban roadway, the legacy of this deposited roadway Pb remains, attesting to the immobility of Pb after deposition. Finally and most critically, the urban roadway example shows both the impact of the long-term Pb loading from leaded gasoline close to the roadway as well as the diffuse soil Pb that blankets urban regions (Fig. 4). In other words, even at distances from the roadway beyond where direct Pb deposition occurs (and far away from structures using Pb-based paint), the background level for Pb is significantly higher in the urban transect (~500 ppm) than in the suburban transect (~60 ppm). This urban-suburban gradient is one overriding factor affecting the amount of Pb loading to individuals, a factor that we will next assess on a larger scale and with respect to human health.

Children's Blood Pb Levels and Diffuse Soil Pb

In many urban areas of older cities, large segments of children below the age of six have venous blood Pb levels exceeding the action level of 10 µg/dL (e.g., Mielke, 1999)—such is the case in Indianapolis. The actual distribution of blood Pb levels exceeding action limits is getting more difficult to obtain due to privacy issues, but in the past, blood Pb values could be collected from health department records down to the level of a street address, providing an outstanding way to examine the environmental factors in human health. The address-level distribution of blood Pb levels exceeding action limits in Indianapolis from 1992 to 1994 is informative. Much of the higher blood Pb values are concentrated in urban areas, particularly downtown. In contrast, very

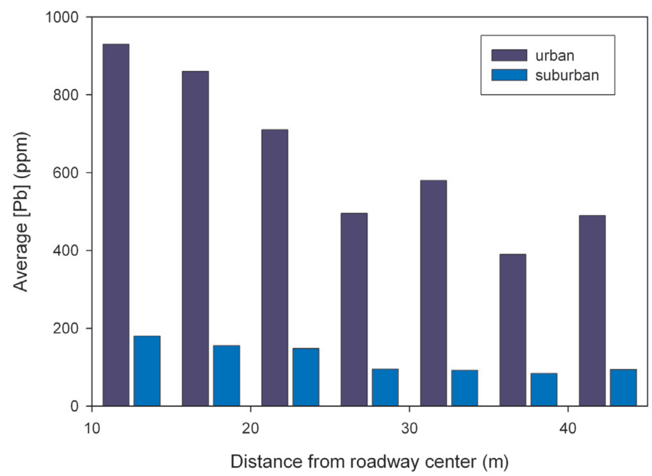

Figure 4. Average Pb concentrations in surface soil as a function of distance from the roadway using the urban Washington Street and suburban East Kessler Boulevard transects. The decrease away from the roadway source is apparent, but more importantly, there are significantly higher values in the urban transect, even at distances up to 42.5 m from the road center, beyond the range of direct deposition of Pb particulates from the combustion of leaded gasoline. Additionally, the significant near-roadway loading of surface soils in the urban transect is reflective of higher daily traffic volumes and the much greater duration of the urban roadway as an important traffic artery.

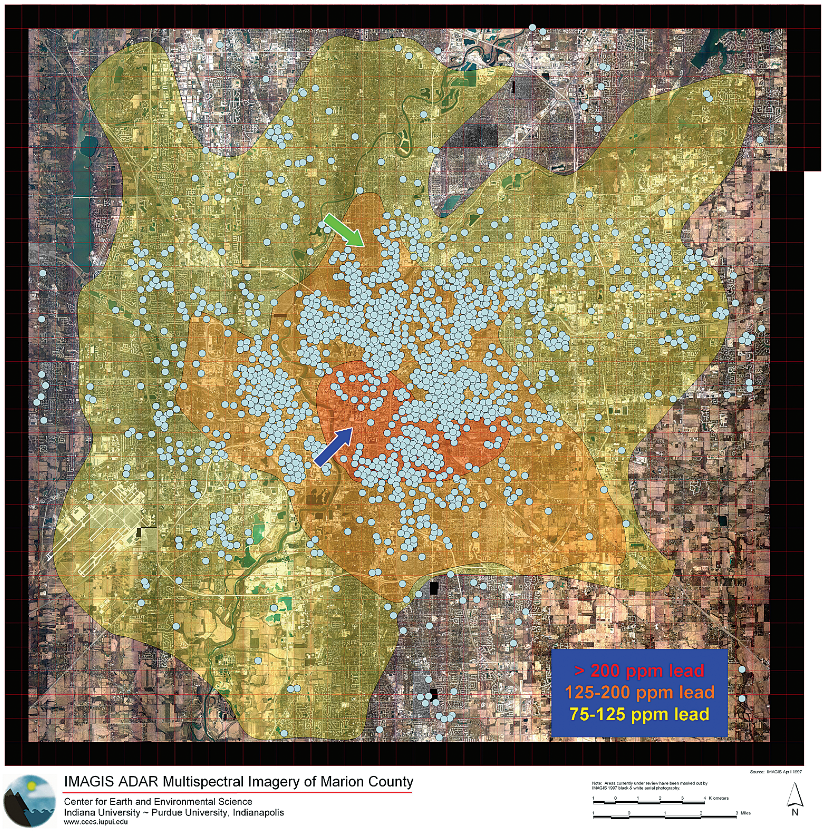

Figure 5. Satellite infrared image of Indianapolis, central Indiana (the boundaries are the Marion County borders—the city of Indianapolis officially extended its boundaries to those of the county in 1970). The concentration of diffuse soil Pb in surface soils of Indianapolis (colored regions) displays a characteristic pattern of urban enrichment trending toward background values in suburban and agricultural regions. The overprint of high diffuse soil Pb presented here corresponds roughly to the distribution of elevated blood Pb levels in children, displayed as circles for the distribution of children's venous blood samples exhibiting Pb concentrations above the level of concern (10 µg/dL) from 1992 to 1994 in Indianapolis. Most elevated blood samples are from the downtown region (significant overlap of multiple positive results occur in this region), with some additional scattered positive results ranging toward the older suburban development to the west and the east. These trends in positive samples are not dominantly controlled by population density, as the northern corridor and northeast portion of Indianapolis have population densities similar to those in the central urban region. The arrows point to regions with high diffuse soil Pb but low incidence of Pb poisoning, at apparent odds with the direct link between soils and blood. As with all epidemiological processes, a number of factors act as filters between potential exposure and toxicology, like socioeconomic status, age, population distribution, etc. In the case of the blue arrow, the lack of Pb poisoning is due to the lack of habitations in this industrial corridor, while the green arrow highlights a main street that displays a socioeconomic divide between poverty-line neighborhoods in the near-urban area and upper-middle and upper-class neighborhoods in the northern suburban area.

few incidences of blood Pb poisoning are found in the newer suburban areas to the west, north, south, and northeast sides of the city (Fig. 5). Because these are individual blood Pb data, population density plays some role in the distribution; for example, rural farmlands on the city outskirts have few incidences. But based on the 1999–2000 U.S. Census (Laidlaw, 2001), the population density per census tract in the newer suburban areas with few blood Pb poisoning incidences is comparable to the urban and near-urban areas with a high incidence.

To explore the concept of diffuse soil Pb (i.e., Pb now present far away from its initial depositional area) and its potential role in affecting children's health (e.g., Lanphear et al., 1998), we carefully selected sampling locations throughout Indianapolis. Our sampling criteria included soil >50 m from roadways and from structures (which might have contributed Pb-based paint), and was augmented by aerial photographic records over Indianapolis from several time slices (1940, 1970). The purpose of these aerial photographs was to rule out the potential for inadvertently sampling soils from disturbed, excavated, or filled areas that might have surface Pb contents characteristic of artificial materials rather than ambient soil. As one can imagine in a rapidly developing urban area, these criteria narrowed acceptable sites to only ~100 distinct sites (because of tillage, even the agricultural sites were excluded). Many of the acceptable sites were in parks, cemeteries, and very large lawns. Analyses were also carried out to determine whether soil source material showed any inherent Pb variation. The soil in Marion County (the area surrounding and including Indianapolis) is glacial outwash, till, and alluvium with a variety of lithologies including limestone, shale, and

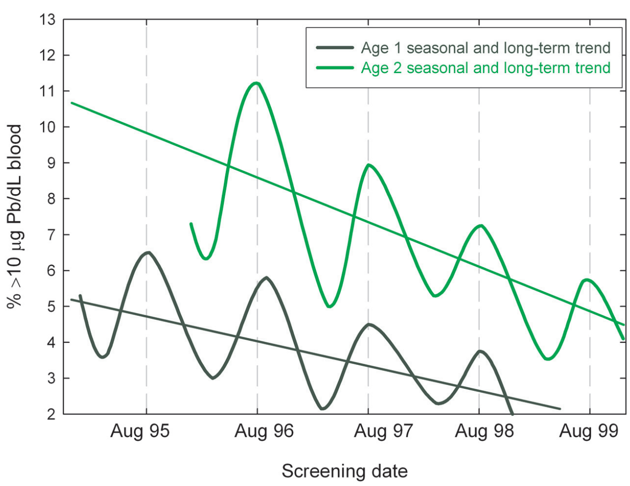

Figure 6. Seasonal patterns in children's blood Pb levels from New York State, showing summer peaks and a general decline from 1995 to 1999 (after Haley and Talbot, 2004). Note the generally higher levels of Pb poisoning in two-year-olds ("Age 2"), who are generally more mobile with consequently greater hand exposure to Pb-contaminated surfaces and more access to the outdoors.

granite. No trend was found between Pb content and soil composition across Marion County (Laidlaw, 2001), and thus we suggest that soil mineralogy is a minor control on the Pb distributions presented here.

In contrast to roadway and house-side soil sampling, which might exhibit Pb concentrations above 1000 ppm, the highest soil Pb concentrations in our study were below 500 ppm. The lowest Pb concentrations averaged ~50 ppm, which is a typical value for soils in this region based on a comparison to selected rural sites (Fig. 3; Laidlaw, 2001) and which we consider here the geological background value. As expected, the highest soil Pb concentrations were centered directly over the old urban and industrial areas of Indianapolis (Fig. 5), where the diffuse soil Pb content averaged ~200 ppm. Beyond this central hot spot, Pb concentrations decreased systematically toward the suburban outskirts of the city, ultimately falling to background values in the rural fringes of the city (Fig. 5). The central peak is consistent with the long history of Pb use in the downtown area, but the generally high values even away from point sources support the argument of a redistribution of Pb over time. This is a common feature of urban Pb distribution (e.g., Mielke, 1999), and it is likely related to the wind-driven redistribution of fine Pb-enriched particulates in a statistically consistent pattern (e.g., a two-dimensional exponential decay curve) over decades.

Combining the distribution of soil Pb with that of children's blood Pb poisoning reveals several important characteristics of diffuse soil Pb as a potential contributor to children's health problems. First, the similarity in the distribution of elevated soil and blood Pb values downtown reveals the potential for diffuse soil Pb to be an additional and important factor in children's blood Pb levels. Second, population patterns definitely have some influence on the health distribution data. For example, some areas downtown have perhaps the highest concentration of diffuse soil Pb but surprisingly few incidences of Pb poisoning (blue arrow on Fig. 5); in this case, this is because this region is an industrial area with no housing. In another case, the lack of correlation between soil Pb and blood Pb corresponds with a very high socioeconomic status in a wealthy northside neighborhood (green arrow on Fig. 5).

Although many factors influence the relationship between geology and human health in the story of Pb, it is clear from the lack of closure on this issue that we do not yet understand all of the contributing factors. Furthermore, the generalized approach presented above provides a reference point for further work, but does not integrate health data and geologic data well, nor does it present clear recommendations that geologists can make to health specialists in further reducing this public health hazard beyond the incredibly costly and disruptive solution of removing all of the contaminated surface soil in urban areas and replacing it with clean fill. Several bridging efforts are now being pursued to help further medical geology in the context of eliminating childhood Pb poisoning. Beyond simply documenting Pb distribution and its public health implications, current research is also examining more closely Pb as a toxicological agent with predictable behavior. For example, isotopic techniques have been utilized to closely examine the entry mechanisms of Pb into the body and the cycling of Pb within the body (e.g., Maddaloni et al., 1998; Gwiazda and Smith, 2000), with a goal of pinpointing the source of Pb toxicity in individuals and thus more closely coupling prevention and treatment. Another new tool of promise in accurately assessing Pb poisoning is predictive modeling of children's blood Pb levels using climatologic data.

CLIMATIC FACTORS AND A BLOOD Pb PREDICTIVE MODEL FOR HEALTH CARE RESEARCH

Several studies have identified a seasonal trend in blood Pb levels, with average monthly blood Pb levels of children from urban areas increasing significantly in summer months (Rabinowitz and Needleman, 1982; Hwang and Wang, 1990; Johnson et al., 1996; Mielke and Reagan, 1998; Yiin et al., 2000; Johnson and Bretsch, 2002; Haley and Talbot, 2004), perhaps partly due to increased exposure to Pb-based paint on window sills and through increased contact with soils containing Pb during the summer. A positive in this trend is that, overall, children's blood Pb values continued to decrease through the 1990s, but the seasonal trend in values seen in comprehensive studies is still a striking feature (Fig. 6). Summer increases of children's blood Pb levels were so prominent over many years in Syracuse, New York, that the researchers concluded that the phenomena was probably caused by the interaction between climate and soils (Johnson et al., 1996; Johnson and Bretsch, 2002), leading to enhanced dust Pb loading to children. An intriguing alternative hypothesis for blood Pb seasonality is internal, whereby bone material is increasingly recycled during summer months, releasing stored Pb to the blood stream (Rothenberg et al., 2001). Additionally, the increased amount of time that children spend outdoors in the summer when school is out may lead to increased exposure to Pb in soil.

To better constrain this possible climate–soil–human health link, we have been investigating in detail variations in children's blood Pb levels as a function of climate and soil factors in several urban areas. The ultimate goal of this effort is to develop a predictive model whereby a medical researcher can make an accurate diagnosis of Pb poisoning based on seasonal and weather-related factors as well as blood Pb level data. With a focus on Indianapolis (ongoing analyses are also being conducted in several other cities, with similar results as those presented here), we used a number of climatologically independent variables, including average monthly soil moisture, particulate matter <10 microns in size (PM10), wind speed, and temperature obtained from state and federal government data sources. We also used blood Pb databases obtained from local and state governmental sources and averaged them monthly (Fig. 7).

Based on this multiple regression model, and unpublished results from several other American cities, we believe that the seasonality in children's blood Pb levels (Fig. 7) is controlled by exposure to Pb dust originating from contaminated soils and suspended in the air when several weather-related environmental conditions are present:

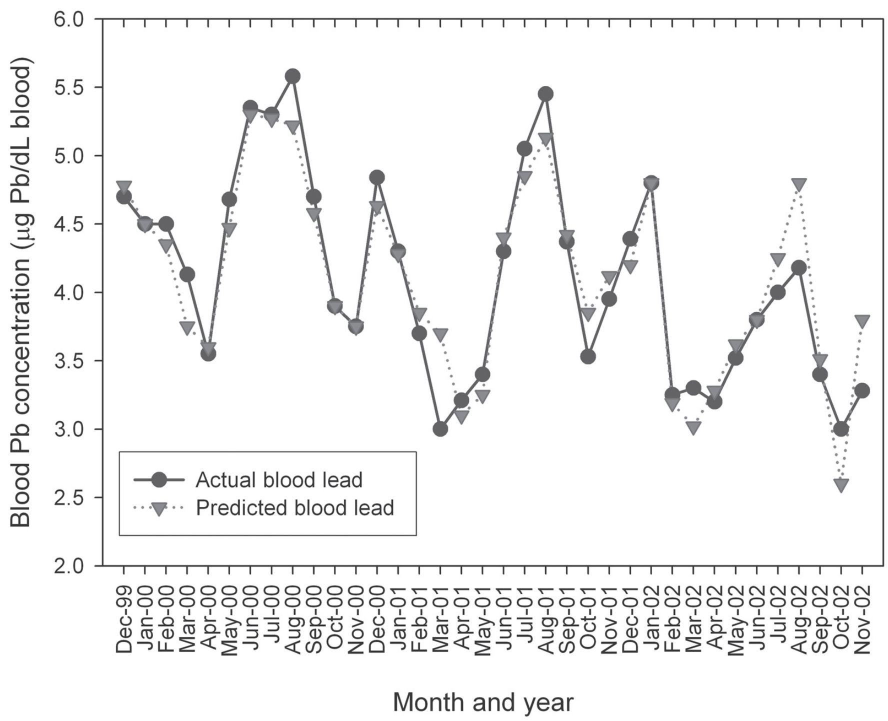

Figure 7. Best-fit model results to predict blood Pb levels (BLLs) in children from Indianapolis compared to actual monthly average BLLs. This type of effort can be used to better treat Pb poisoning from a public health perspective by providing clinicians with predicted trends of BLLs (functionally calculated as a percent deviation from the mean) at a given blood sampling event, allowing them to calculate the potential increase or decrease with time given normal exposure. Twelve separate multiple linear regression models, not presented in this paper, were modeled and differed only in the dependent variable. The independent variables for each model consisted of soil moisture, wind speed, particulate matter <10 microns in size (PM10), temperature, atmospheric Pb, interaction variables, and monthly dummy variables (M1 to M11). The time period of the regression consisted of 36 months between December 1999 and November 2002. The dependent variables for the models included monthly child blood Pb data from (1) a variety of subregions in Indianapolis, (2) a variety of BLLs, and (3) a variety of ages (i.e., 0–1.0, 1.01–2.0, 2.01–3.0, 3.01–4, 4.01–5, and 5.01–7.0 yr). The blood Pb database totals during this time interval included a monthly child blood Pb data set of 15,969 children. The outcome variable, children's average monthly city blood Pb concentration, was regressed against the average monthly independent variables soil moisture, PM10, wind speed, temperature, interaction variables, and monthly dummy variables using backward elimination procedures. The dominant wind direction in Indianapolis is east-southeast (Laidlaw, 2001), but in our initial analysis, wind direction had no predictive application for blood Pb values. This model indicates that the variables or interaction variables including soil moisture, wind speed, PM10, temperature, and the monthly dummy variables for March through September explain 87% of the variation in the response variable, monthly average child BLL concentration (correlation coefficient, r^2, = 0.87; number of individuals = 15,969).

high temperature, low soil moisture, and elevated atmospheric PM10. When temperature is high and evapotranspiration is maximized, soil moisture becomes low, and the generation of soil dust is maximized. Under these combined weather conditions, Pb-enriched PM10 dust disperses in the urban environment and is manifest by elevated Pb dust loading. In this case, exposure is via increased dust loads in homes and on contact surfaces, with ingestion as the uptake mechanism. Although further work using detailed tracking of Pb, possibly involving Pb isotopic studies as outlined above, may help to elucidate the connection between seasonality and blood Pb values, we argue that the ability of geochemical and meteorological factors to predict blood Pb supports our supposition that external loading and exposure drives much of the blood Pb concentrations.

In addition to the development of hypotheses related to the incorporation of Pb into children's systems, a promising result of these modeling analyses is the ability to predict toxicity in a given population. In other words, through easily collected atmospheric and soil data, a health researcher can determine the expected variation in blood Pb levels of the general population and, if performed in more detail using the subset of children's age, the expected variation in a given young patient. This is particularly important when attempting to treat blood Pb poisoning using discrete venous sampling events—a "safe" level measured in the spring under conditions of high soil moisture could become a poisonous level in the same patient just several months later when atmospheric conditions increase ambient Pb loading.

CONCLUSIONS AND RECOMMENDATIONS

The controls placed on the use of Pb have been incredibly successful in lowering the general loading of Pb to the environment and have resulted in impressive and positive human health benefits. Nevertheless, we continue to be faced with the legacy of Pb deposition, particularly in urban environments. As a result of this environmental and geological situation, over 400,000 children in the United States between the ages of one and five are still poisoned by Pb (NHANES, 2003), many of them from lower socioeconomic minority households. In this paper, we highlighted the persistence of Pb in surface soils as a potential route for the continued poisoning of urban youth, with socioeconomic status being a large contributor to the problem in areas with high ambient soil Pb. Although education and remediation seems to show continuing health benefits, it is likely that we will have to adopt another strategy, including soil Pb and soil dust exposure, to get over the final hurdle and eradicate Pb poisoning in this country. This strategy might include funded programs focused on aggressive landscaping of urban soils that are implicated in Pb poisoning, including mulching, geotextile barriers, dilution of soil Pb with added clean top soil, or construction projects like decking installation to remove children and their homes from exposure to Pb-enriched dust and soils. By collecting data and designing studies that more directly inform the health sciences community, particularly with the application of spatially-referenced studies and Pb isotopic techniques, researchers in the field of medical geology may have an important part to play in improving the short and long-term health of urban youth.

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