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Geochemical Surveys in the United States in Relation to Health

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Geochemical surveys in the United States in relation to health

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Geochemical surveys in relation to health may be classified as having one, two or three dimensions. One-dimensional surveys examine relations between concentrations of elements such as Pb in soils and other media and burdens of the same elements in humans, at a given time. The spatial distributions of element concentrations are not investigated. The primary objective of two-dimensional surveys is to map the distributions of element concentrations, commonly according to stratified random sampling designs based on either conceptual landscape units or artificial sampling strata, but systematic sampling intervals have also been used. Political units have defined sample areas that coincide with the units used to accumulate epidemiological data. Element concentrations affected by point sources have also been mapped. Background values, location of natural or technological anomalies and the geographic scale of variation for several elements often are determined. Three-dimensional surveys result when two-dimensional surveys are repeated to detect environmental changes.

Introduction

Purpose

Geochemical surveys in the United States in relation to health probably do not differ significantly in essential character from geochemical surveys in other parts of the world. It may be, however, that geochemical activities in the United States, if viewed as a whole, have slightly different appearances because of idiosyncrasies in scientific, social, and political climates that lead to minor differences in research approaches, methodologies, and subject-matter emphasis compared with similar activities elsewhere. It is my purpose to describe the kinds of geochemical survey made in the United States so that an impression is available of (1) any special characteristics that efforts in the United States may have and (2) the status of geochemical surveys and health in the United States. I have approached the subject from the geochemical side and my knowledge of important contributions that may be geochemical in character, but reported directly to the medical profession, may not be complete. It is not my purpose to evaluate the significance of substantive relations between geochemistry and health, such as the effect of water hardness on heart conditions or the role that Cd may play in the aetiology of cancer.

Kinds of geochemical survey

The fundamental purpose of all geochemical surveys is to determine the occurrence of elements in environmental materials in a systematic way so that conclusions can be drawn regarding various concerns important to mankind. All kinds of geochemical survey are thus regarded as being potentially related to health.

In this context, the field of geochemistry must be interpreted to involve not only rocks but all kinds of materials in the environment with which man comes into contact. Soil, stream sediment, water, air, plant and animal foodstuff, and even house dust are all appropriate materials for geochemical study.

Geochemical surveys may be classified as having one, two or three dimensions (figure 1).

One-dimensional geochemical surveys consist of data on the composition of environmental constituents perceived to be related to some theme, which can be compared to the string on which beads are strung. Themes are provided by such things as a general interest in the geochemical inventory of an area, pollution sources such as smelters and other technological activities, and other topical studies. Some one-dimensional studies use two or more areas of contrasting character, such as urban and rural or near to and far from a smelter. Characteristically, data and relations are shown by tables and graphs.

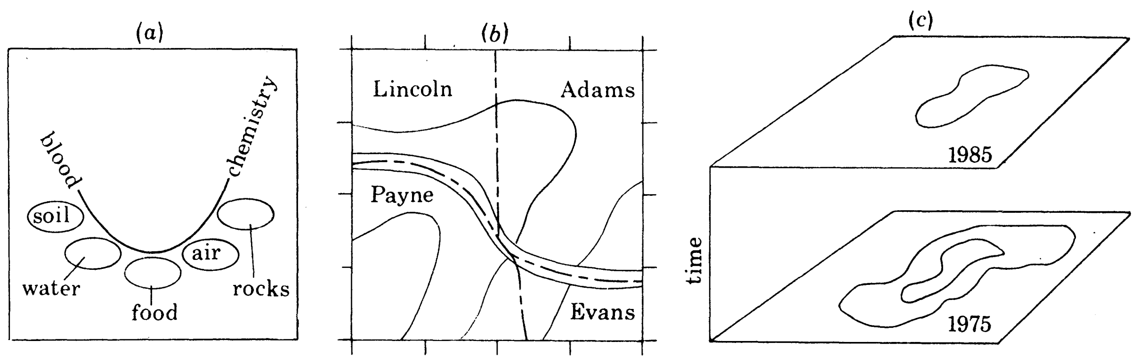

Figure 1. Kinds of geochemical survey. (*a*) One-dimensional survey on the theme of blood chemistry. (*b*) Two-dimensional survey showing natural sampling areas of conceptual units (areas bordered by smooth lines) and artificial sampling areas (named counties bordered by line convention or squares formed by joining tick marks). (*c*) Three-dimensional survey showing changes in a geochemical parameter with time.

A two-dimensional geochemical survey, in contrast, maps the spatial distributions of compositions of environmental constituents or health attributes. Systematic sampling or stratified random sampling, of either natural or artificial sampling strata, may be used. Natural sampling strata are conceptual units, or landscape units, that in aggregate make up the environment, such as rock formations and classified soils. Artificial strata are used mostly to obtain complete geographic coverage. States, provinces and counties are examples of artificial units that have a political origin; or an area may be divided by an arbitrary grid to give squares or quadrangles of convenient size. A good summary of stratified random sampling designs and procedures is given by Miesch (1976*b*). The need for sampling design in geochemical surveys related to health is discussed by Tourtelot & Miesch (1975).

Three-dimensional geochemical surveys map the distribution of the composition of environmental constituents at some time after a first determination to detect possible changes. Few such surveys have yet been made.

One-dimensional geochemical surveys

Environmental surveys

Environmental inventories and potential or observed health effects are the basic justification for one-dimensional environmental geochemical surveys.

In an environmental inventory, Seagle & Ehlman (1974) investigated the occurrence of metals in the water, bottom sediments and shellfish from four freshwater reservoirs in north Texas to study the partitioning of elements between components of a natural system. Solomon & Hartford (1976) found substantial amounts of Pb and Cd in dusts and soils in a small urban community. Vacuum sweepings from rugs in homes contained a maximum of 830 parts Pb/10^6 and 66 parts Cd/10^6. The maximum Pb content of rug dust from office hallways was 3380 parts/10^6 and from uncarpeted chemical laboratories was 11400 parts/10^6.

Much more ambitious one-dimensional background geochemical surveys are those that make up a comprehensive geochemical survey of the State of Missouri (Miesch 1976*a*). Tidball (1976), for instance, investigated the chemical variation of soils associated with several levels (suborders, subgroups and series) of the soil taxonomy. Variations between suborders were small. Variation between soil series, however, was much larger than variation within a given series. Consequently, maps based on the distribution of series might reasonably serve as geochemical maps for most elements. Erdman *et al.* (1976*b*) investigated variation in chemical composition of corn grains, soybean seeds, pasture grasses and associated soils based on sampling areas defined by vegetation-type areas. They found little variation between vegetation-type areas, most variation being within the areas and largely between the $7\frac{1}{2}'$ quadrangles that served as sampling localities.

Another ambitious geochemical survey is the inventory of Mo in nearly all components of the environment in parts of Colorado. The occurrence of Mo in source rocks, many of which contained more than average amounts of Mo in soil, water and vegetation, as well as the environmental effects of the largest Mo mining and milling operation in the world, all were investigated with emphasis on the processes of metal transport and accumulation. Experiments on the metabolic effects of Mo on animals and plants were also made. Runnels, *et al.* (1976) and Runnels *et al.* (1975) described the more strictly geochemical aspects of the investigations (see also Chappell & Petersen 1976).

The effects of Pb from automobile traffic on the composition of soils and plants along highways were pointed out by Cannon & Bowles (1962) and the reality of the effects are now common knowledge (see Lagerwerff & Specht 1970). Contamination by the road transport of lead-ore concentrates has been documented by Connor *et al.* (1971) and by Hemphill *et al.* (1974). Wixson & Bolter (1971) explored the distribution of Pb, Zn and Cu in streams in Missouri affected by mining operations as contrasted with the occurrence of these metals in unaffected streams selected as controls. Few hazardous concentrations of these metals were found by any of these investigators, but contamination was conspicuous.

Background studies around power-generating activities measured environmental effects of emissions from burning coal. Linear regression methods applied to sample data along traverses with logarithmically increasing intervals away from the power stations in Wyoming showed decreases in element concentrations in lichens (Gough & Erdman 1977), in sagebrush (Anderson & Keith 1976, 1977; Connor *et al.* 1976; Connor 1977), and in grass in New Mexico (Connor *et al.* 1976). Se and F commonly showed the most well defined trends away from the sources.

Background studies of the composition of native vegetation and soil have been made near two establishments processing phosphate rock for fertilizer in Idaho (Severson & Gough 1976; Gough and Severson 1976).

Combined environmental and health surveys

Metal smelters are potent sources of environmental contamination, and recognized health effects on both nearby animals and humans have prompted several detailed studies. The major

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purpose of the studies generally has been to assess the geochemistry of the environment around the smelter to determine the extent to which the smelter emissions to the air and soil are related to observed health conditions. Because smelter operations are the economic culmination of mining, significant industrial and commercial interests are involved. Consequently, smelter studies include a broad range of environmental constituents and present an abundance of data that cannot be reviewed in detail here.

Especially significant studies are those of the Helena Valley, Montana (soils, Miesch 1972; animals and vegetation, Gordon 1972; livestock, Lewis 1972; human hair, Hammer *et al.* 1972); of smelters in Missouri and California (Rabinowitz & Wetherill 1972, 1973; Rifkin & Ter Haar 1973); of a smelter in El Paso, Texas (Landrigan *et al.* 1975), and of smelter and mining operations in Kellogg, Idaho (Ragaini *et al.* 1977).

In general, results are similar. Pb, Cd and other metals typical of the individual smelter operation are found in largest amounts in samples within 1 km or so of the smelter. These large values decrease with distance away from the smelter, but effects of the smelters are detectable at distances of as much as 30 km. Metal concentrations in blood and other health effects of people and animals (where investigated) were found to correlate similarly with distance from the smelter and with the composition of environmental components. The survey at Kellogg, Idaho, was undertaken because two pre-school children had been treated for Pb poisoning; 90% of the children subsequently tested had abnormally high levels of Pb in their blood (Ragaini *et al.* 1977).

Health conditions have been studied in other, more generalized geochemical environments in which some health effect might be expected. Hammer *et al.* (1970) found that mean concentrations for As, Cd and Pb in hair of school children reflected community exposures in four cities judged to represent an exposure gradient from air but that means for Cu and Zn did not, perhaps because the exposure gradients for Cu and Zn were small compared with those for the other metals.

Blood lead levels in school children have been investigated in contrasting urban and suburban localities. Blood lead levels of children in Omaha, Nebraska, correlated best with Pb in local dustfall, soil and in exterior dirt trodden into the house, and the levels were higher in children from urban rather than suburban locales (Angle *et al.* 1974). In Newark, New Jersey, about 8% of the children living within 34 m of major urban roadways had blood Pb concentrations of more than 60 μg/100 ml, the lower limit that is suggestive of Pb poisoning (Caprio *et al.* 1974).

Shacklette *et al.* (1970, 1972) found that soils in Coastal Plain counties in Georgia selected for their very high cardiovascular death rates were deficient in trace elements compared with soils in counties in the mountainous Piedmont area of Georgia where death rates were very low. The compositions of garden vegetables, however, in these contrasting areas were not significantly different. No aetiological connections could be established.

Several diseases of animals have specific geochemical associations either with deficiencies or toxic excesses of metals such as Se, Mo and Cu in vegetation and associated soils (see, for example, Kubota & Allaway 1972). Concern for the relation between geochemistry and human health has been at least heightened by animal studies. A recent example of such studies is the recognition that metabolic disorders occurred in beef cattle in a pasture in Missouri that contained vegetation and soil having anomalous amounts of metals, particularly Mo, compared with expectable values elsewhere in the state (Ebens *et al.* 1973). The pasture was affected by sediment and

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soluble products derived from the spoil heap of an abandoned clay pit. The spoil heap contained pyrite and black shale that was rich in metals and that were the most obvious source of the anomalous amounts of metals in the pasture materials.

A number of geochemical studies in relation to epidemiology have been made in which both the geochemical and epidemiological data have been drawn from published work. These studies have particular value because they are preliminary evaluations of the possible interaction between environmental parameters and mortality, and thus serve as a background for considering further investigations.

Air pollution as reflected by the concentration of SO_2 in air is strongly correlated with total mortality in New York City according to Glasser & Greenburg (1971). Air pollution as represented by benzo(a)pyrene concentrations, and such indices as consumption of solid fuel and use of cigarettes is related by Carnow & Meier (1973) to deaths from pulmonary cancer. Cardiovascular death rates in 27 cities are strongly correlated with Cd in air (Carroll 1966).

The composition of water is a geochemical parameter that has long been considered in relation to health. Sauer *et al.* (1970) reported moderate negative correlations between death rates and drinking water compositions in 95 Metropolitan–State–Economic areas in the United States. Sauer (1974) considered trace elements in drinking water in 92 of these areas. Moderate negative correlations were found. The data bases for both mortality rates and water composition were extremely broad and generalized. The complications of the strictly geochemical approach were emphasized by statistical treatment of other kinds of variables in addition to the geochemical ones. For instance, among white females, the proportion not having changed residence within the preceding 5 years accounted for 62% of the total variation in cardiovascular–renal disease death rates whereas Mg in water accounted for only 2% of the variation (Sauer 1974).

In contrast to the multi-element approach of Sauer *et al.* (1970), Voors (1970) found negative correlations of atherosclerotic heart disease in some 100 largest cities with both Li and water hardness, which were themselves positively correlated. He described a pharmacological basis for a beneficial effect from Li.

On a much smaller scale, McDuffie *et al.* (1974) compared cardiovascular death rates and water hardness for three communities in New York State. The hardness of the water ranged from low to moderate and the death rates did not differ much; no correlation with water hardness was found.

Using published data, Klevay (1974) obtained a moderate correlation for humans between the Zn/Cu ratio in commercially available cow's milk and coronary heart disease in 47 cities. Milk composition accounted for about one-eighth of the variation in mortality. Shearer & Hadjimarkos (1975) obtained samples of human milk from 17 cities selected in large part on the basis of their location with respect to the adequacy of the Se content of forage crops as mapped by Kubota *et al.* (1967). With some exceptions, the Se content of human milk paralleled the gradient of Se in forage. This result is similar to that of Allaway *et al.* (1968) for Se in human blood.

One-dimensional geochemical surveys of the kinds reviewed no doubt will always amount to a significant part of the effort expended in combined geochemical and epidemiological surveys. Such surveys can be either broadly or sharply focused, they can be undertaken with a relatively small amount of laboratory work, or they can bring together available data from both geochemistry and epidemiology. This seeming simplicity, however, can lead to complexities in data quality, relevance and manipulation that are difficult to deal with, as discussed particularly by Carnow & Meier (1973) and Sauer (1974).

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Two-dimensional geochemical surveys

Environmental surveys

Two-dimensional geochemical surveys map the spatial distribution of geochemical parameters in an area and thus are distinctly different from one-dimensional surveys in design and nature of results, although kinds of problems involved and sampling media may be the same. In one type of two-dimensional survey, samples are collected at intervals that range from irregular to systematic.

Crecelius *et al.* (1975) explored the occurrence of As, Sb, Hg and other toxic metals in the sediments of Puget Sound, Washington. Their data, shown as values at sampling points, clearly implicated the cities and industrial establishments bordering the Sound as the major sources of toxic elements in the bottom sediments. Stoffers *et al.* (1977) explored the occurrence of Cu and other heavy metals in sediments in New Bedford harbour, Massachusetts. In addition to revealing the extent and intensity of urban and technological contamination, their data also indicated that the clay fraction of the sediments in the inner harbour contained about 3500 t of metals having a gross value of about $5M.

Two-dimensional mapping to outline the area affected by a point source of contamination was done effectively by McClenahen & Weidensaul (1977) in Ohio and by Huey (1972) in Montana. Relatively large fluoride concentrations in animal forage around a fluoride-emitting source in southeastern Ohio were of concern, and a two-dimensional monitoring system was planned. For various reasons, a single fluoride indicator was sought. Isopleths from linear regression models of the fluoride content of the leaves of the black locust tree closely predicted the distribution of fluoride in the crops.

The distribution of As, Cd, Pb and Zn in particulate fall-out around a smelter in the Helena Valley, Montana, were shown on choropleth maps by Huey (1972). The distributions of metal concentrations clearly pointed to the smelter as the source of the metals. Although the distribution for each metal reflected the expectable meteorological conditions around the smelter, the distribution was different for each metal.

Using a choropleth map showing the distribution of Cd, Pb and Zn in soil, Lagerwerff *et al.* (1972) and Lagerwerff & Brower (1974, 1975) explored many facets of the environmental effects of a smelter in southeastern Kansas. Klein & Russell (1973) made choropleth maps of metals around a power plant near Holland, Michigan, on the shores of Lake Michigan, based on grid sampling on land and irregular sampling offshore in the lake. The distribution of metal concentrations in the soil agreed well with meteorological data on land and with directions of currents in the lake. Choropleth maps of Cd greater than about 3 parts/10^6 in soil around a smelter in Amarillo, Texas, agreed closely with predominent wind directions and velocities (Blackmer *et al.* 1976). A diagonal grid was used by Bolter *et al.* (1972) to show effects around a smelting complex in Missouri; values were plotted on data points on a map. A similar method was used by Anderson & Smith (1977) to map the distribution of Hg in soil around a power plant in Illinois.

An environmental two-dimensional survey covering the United States as a whole is that of Shacklette and colleagues (Shacklette *et al.* 1971 *a*, *b*, 1973, 1974), in which about 900 samples of soils, regoliths and surficial materials were taken throughout the country at approximately 80 km intervals along but away from roads and highways. The concentration symbols for some elements on the maps, such as those for the alkali metals and alkaline earths, as well as those for Ti and Zr, showed regional patterns that are consistent with the general character of the soils and regoliths in the western United States as contrasted with those in the eastern United States. Most of the trace elements do not show distinct nationwide patterns.

The occurrence of Se in crops (primarily forage crops) in the United States as a whole was mapped by Kubota *et al.* (1967). Many of the data had been accumulated by studies of forage compositions in separate areas in relation to animal diseases caused by deficiencies and excesses of Se in the forage crops. This map, perhaps more than any other geochemical map, has attracted the attention of epidemiologists and medical people as a base for measuring health conditions against a geochemical parameter.

Shacklette & Connor (1973) obtained 123 samples of Spanish moss, an epiphytic moss-like plant, growing in trees in the coastal plains bordering the southern and southeastern coasts of the United States. The concentrations of elements that are not essential to the plant are related to the concentrations in the air, in precipitation and in other airborne materials, and to other factors such as the length of time that the plant was exposed to an atmosphere of a particular composition. The spatial distribution of element concentrations reflected such environmental features as nearness to the sea and relation to urban and rural areas. Only 6 of the 123 samples were found to contain Sn in amounts greater than 20 parts/10^6 (the lower limit of determination) and four of these came from the Houston–Galveston area, Texas, in which the only tin smelter in the United States is located.

Another type of two-dimensional environmental survey uses stratified random sampling on conceptual units. Erdman *et al.* (1976*a*) surveyed the composition of soil and associated native plants in Missouri within vegetation-type areas, each of which was homogeneous with respect to plant communities but different from the others. The means for Mg in the soils of the six vegetation-type areas could be placed in five significantly different classes and Mg thus showed the greatest variation in soils between vegetation-type areas.

Geohydrological units are rock masses homogeneous in a broad sense with respect to both lithological and hydrological character, such as limestones of Mississippian age in Missouri (Feder & Miesch 1972). Seven major hydrological units were defined for Missouri and each was sampled according to a stratified-random design.

The maps based on such conceptual units allow objective comparison between newly gathered data on soils from a given vegetation-type area, for instance, with a scientifically justifiable estimate of an expected typical value and the range within which values might fall with a stated probability. In addition, the spatial pattern of mean concentrations allows at least first-order comparison with epidemiological patterns. Conceptual unit mapping also is efficient in that the geochemical variation within a unit can be estimated from data on relatively few samples and the reliability can be estimated to judge that it is adequate for the purpose in hand.

Sampling designs that are stratified and random in character but that are also similar to systematic sampling are useful for mapping the geochemical effects of cities. The author (unpublished data, 1978) mapped the distribution of elements within the 8000 km^2 Front Range Urban Corridor, Colorado, centred on the city of Denver. Sampling localities consisted of 178 squares, 4 km on a side, separated from adjacent squares by 4 km. For each square, the geometric mean value for each element was based on four randomly selected samples of surficial material. The clustering of the highest mean values for the expected pollution elements clearly identified metropolitan Denver as the pollutant source. Other scattered highest mean values are related to geological and other features. This kind of approach simultaneously identifies the problem, puts some limits on its magnitude, and indicates its origin.

Klein (1972) mapped the distribution of metals in about 800 km^2 around Grand Rapids, Michigan including industrial, residential, and agricultural areas. Concentrations in single samples from a systematic design, mostly at 1.5 km intervals, clearly identified the industrial core of the city.

With the use of counties in Missouri as an artificial sampling stratum and analyses of more than 1100 samples, computer-produced grey-level maps were prepared by Tidball (1972*a*, *b*, 1973) for both major and minor soil elements. Patterns of concentrations for major soil constituents conformed fairly closely to broad categories of underlying parent materials and were interpretable in relation to the composition of the parent materials. Patterns tended to be sharp for those elements for which laboratory error was only a small part of the total variation but tended to become less clear for elements for which the proportion of laboratory error was large.

Regional geochemical surveys based on a different kind of artificial sampling stratum are those made in the Northern Great Plains coal region to provide background data in advance of extensive energy development. Ebens & McNeal (1976, 1977) used squares 200 km on a side laid out to cover an area of 240000 km^2. Element concentrations were shown as figures in the squares for those elements for which statistical analysis showed that the map patterns were of sufficient reproducibility.

Tidball & Seversen (1975, 1976), in the same region, used as their basic sampling unit 100 km squares arranged in two sets so that data were obtained separately on soils developed on glacial drift in the northern part of the region and soils developed on bedrock of Tertiary age in the southern part of the region. They used contours to show the regional variation of concentrations for elements for which the map patterns were stable, but pointed out that the contours were simply a graphic presentation of the data, without the implication that the concentrations of elements in the soils were continuously variable in any predictable way.

In both of these surveys, it was shown that the regional variation of concentrations was sufficiently small that for most elements reliable regional background data could be obtained by the analysis of relatively few samples. Most of the variation was very local, lying within 1 km cells. Maps reliably showing the distribution of this local variation would require a very large number of samples and be very expensive to prepare. So far, justification for this kind of detailed geochemical mapping has not been evident. Some of these problems are discussed by Tidball (1975).

Ringrose *et al.* (1976) used supertownships 19 km on a side from the cadastral land survey of the oil-shale region of northwestern Colorado as artificial sampling strata. The map patterns for only a few elements were stable enough to justify presenting the data graphically on contour maps. From one to more than 20 additional random samples in each supertownship were estimated to be necessary to prepare acceptably reproducible maps of concentrations of the majority of elements.

Dean *et al.* (1977) used Q-mode factor analysis of the same data to produce maps showing the relative contributions at each sample site of each of four end-member compositions, or factors, found to account for about 35% of the variance for some elements and more than 90% of the variance for others. Factor 1 was interpreted to be rich in clay and contained more trace elements than the other factors. Factors 2 and 3 represented carbonate-rich and silica-rich compositions respectively. Factor 4 represented samples enriched in Na from near-surface discharge of ground-

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water. The maps showing the contributions of the individual factors to the sample compositions have patterns corresponding to the geology and hydrology, and are useful in evaluating the geochemical variability of surface soils.

Combined environmental and health surveys

Two-dimensional geochemical surveys seem generally to have been made by researchers and organizations involved in the Earth sciences and thus provide chiefly background data on the spatial distribution of geochemical parameters. The stimulation for many such surveys is their potential application to investigations of the spatial distribution of health conditions, but such maps seem to have been used sparingly in this way. In part, this is because geochemical maps and epidemiological maps are constructed from different data bases that in most respects are not strictly comparable. Much uncertainty also still exists as to the aetiological connections between most geochemical parameters and health conditions.

The aetiological connection between humans and the atmosphere is obvious, however, and air compositions have been mapped as a basis for epidemiological studies. Mahoney (1971), for instance, mapped in a very simple way the air flow in the Los Angeles, California, region, and found that mortality rates increased in successive downwind zones in a way consistent with a presumed aetiological effect of air pollution.

Winkelstein and colleagues (Winkelstein 1962; Winkelstein & de Groot 1962) undertook an elaborate study of the spatial distribution of total particulates, dustfall and total sulphates in air in Buffalo, New York. Choropleth maps showed the distribution of various levels of air pollution, and the air pollution units on this map provided the sampling strata for statistical comparison with other variables. Simultaneously, a probability sample of Buffalo households was selected and health data were obtained by interviews. Data on mortality rates for specific diseases and on cancer morbidity were obtained from standard sources. Economic indices for the census tracts were also developed. Some positive associations were found (Winkelstein *et al.* 1967, 1968; Winkelstein & Kantor 1969*a*, *b*, *c*; Winkelstein & Gay 1971). Lack of correlation for some parameters and very low levels of positive associations for others perhaps resulted from lack of precision in the determination of some of the interview variables (Winkelstein & Kantor 1969*c*).

The Nashville study of air pollution and health (Zeidberg *et al.* 1961) was based on 119 air sampling stations and interview data on health, on mortality rates, and on some autopsy material. Unfortunately, maps of air composition and quality that could have resulted from the elaborate programme design either were never prepared or were not used as such in the subsequent health studies. The various health aspects (Zeidberg *et al.* 1961, 1964; Zeidberg *et al.* 1967*a*, *b*; Zeidberg & Prindle 1963; Hagstrom & Sprague 1967; Sprague & Hagstrom 1969) were investigated in essentially a one-dimensional way. Although moderate correlations were found between some of the health parameters and air quality, results were less conclusive than had been hoped for. Limitations of the epidemiological data, such as the unreliability of interview information (Zeidberg *et al.* 1964) and the possible operation of complicating uncontrolled factors (Zeidberg *et al.* 1967*b*) were suggested as the chief reasons for relatively inconclusive results.

The mapping approaches of these two geochemical surveys of the atmosphere were relatively simple although elaborate. In Houston, Texas, Severs & Chambers (1972) used trend-surface analysis based on only 17 sample localities to map the distribution of metals in air. The computer-produced choropleth maps reflected the general distribution of pollution in the city and revealed

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differences between the distributions of specific metals that correlated with different kinds of technological activities within the city.

Geochemical and epidemiological data congruently based on all the counties in Missouri generally explained less than half the variation of swine birth defects in relation to soil compositions (Selby & Tidball 1976). Map patterns of human mortality rates (Tidball & Sauer 1975) showed little similarity to rather distinct patterns for several elements in soils (Tidball 1974). Multivariate analysis showed relations between both swine birth defect rates and human mortality rates and some of the trace elements in soils, but no aetiological connection between the elements identified and the health conditions could be determined. Tidball & Sauer (1975) discussed aspects of both geochemical and epidemiological data that probably led to the limited relationships between geochemical parameters and health that were established.

The map showing broadly delimited areas of the United States according to the Se content of forage crops (Kubota *et al.* 1967) has been used for several health investigations. Cowgill (1974), for instance, explored the distribution of birth rates and Shamberger and colleagues similarly considered rates for cancer (Shamberger *et al.* 1973) and for heart disease (Shamberger *et al.* 1975). Birth rates and mortality rates were based on States and the Se status of the States was interpreted qualitatively from the Se map. Kubota pointed out, in oral discussion of the cancer paper by Shamberger *et al.* (1973), that the Se map was not designed for such use and was not suitable for it. It seems paradoxical that statistically significant differences were found, birth rates being higher in States arbitrarily defined as being 'high-selenium' and mortality rates for heart disease and cancer being lower.

Three-dimensional geochemical surveys

Most mutual environmental and epidemiological concerns have developed within the past 20 years and this period is probably too short for the third dimension, time, to have been added to two-dimensional surveys so that changes in geochemical parameters can be estimated. Many such surveys will no doubt be made in the future to estimate rates of accumulation of contaminants in soils, for example, or conversely to estimate the rate of amelioration of a geochemical condition as a result of environmental management. The eventual need for such three-dimensional surveys has, in fact, contributed to the justification for undertaking many two-dimensional surveys.

A three-dimensional survey of SO_2 in the atmosphere has been made by Huey (1972) in the Helena Valley, Montana, around the same smelter for which both one-dimensional (Miesch 1972) and two-dimensional (Huey 1972) geochemical surveys have already been mentioned. Maps showed the average distribution of the sulphur-rich air mass for each month from June to November 1969. These maps clearly portrayed the changing outline at ground level of the contaminated air mass with time in response to features of smelter operation and seasonal changes in meteorological conditions. The decrease in extent and maximum SO_2 concentration of the air mass in June 1969, when the smelter was partly shut down, is particularly prominent.

Conclusions

Geochemical surveys have been the basis for many considerations of the relations between environmental composition and health. The interdisciplinary collaboration between geochemists and other earth scientists, epidemiologists, medical doctors, biochemists and other health scientists has been impressive, and has led to a very large body of knowledge concerning the interactions between living things and their environment. This impressive collaboration seems most often in the United States to take the form of geochemists and health specialists bringing together their separately obtained data and interpreting them jointly. In the future, it seems likely that geochemical surveys in relation to health will be planned and undertaken jointly so that maximum congruency of the geochemical and health data can be obtained. This seems the most probable way in which more comprehensive hypotheses can be formulated for testing. Such investigations could result in relations between various geochemical and health parameters being more strongly validated than many are at present, and could also lead to the aetiological connections between geochemical and health parameters becoming more clearly visible. Much remains to be learned.

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