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Environmental Geochemistry on a Global Scale

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Recent population growth and economic development are extending the problems associated with land degradation, pollution, urbanization, and the effects of climate change over large areas of the earth's surface, giving increasing cause for concern about the state of the environment. Many problems are most acute in tropical, equatorial, and desert regions where the surface environment is particularly fragile because of its long history of intense chemical weathering over geological timescales.

The speed and scale of the impact of human activities are now so great that, according to some authors, for example, McMichael (1993), there is the threat of global ecological disruption. Concern that human activities are unsustainable has led to the report of the World Commission on Environment and Development *Our Common Future* (Barnaby 1987) and the establishment of a United Nations Commission on Sustainable Development responsible for carrying out Agenda 21, the action plan of the 1992 Earth Summit in Rio de Janeiro, Brazil.

Considerable research into the global environment is now being undertaken, especially into issues such as climate change, biodiversity, and water quality. Relatively little work has been carried out on the sustainability of the Earth's land surface and its life support systems, however, other than on an ad-hoc basis in response to problems such as mercury poisoning related to artisanal gold mining in Amazonia or arsenic poisoning as a result of water supply problems in Bangladesh (Smedley 1999). This chapter proposes a more strategic approach to understanding the distribution and behavior of chemicals in the environment based on the preparation of a global geochemical baseline to help to sustain the Earth's land surface based on the systematic knowledge of its geochemistry.

Geochemical data contain information directly relevant to economic and environmental decisions involving mineral exploration, extraction, and processing; manufacturing industries; agriculture and forestry; many aspects of human and animal health; waste disposal; and land-use planning. A database showing the spatial variations in the abundance of chemical elements over the Earth's surface is, therefore, a key step in embracing all aspects of environmental geochemistry. Although environmental problems do not respect political boundaries, data from one part of the world may have important implications elsewhere. To achieve a common database with permanent value, it is necessary to adopt standardized procedures for every step of the acquisition process.

Essential and Potentially Harmful Chemicals

Three groups of chemicals are of particular concern in relation to the Earth's life support system: essential and potentially harmful chemical elements; radioactive substances; and persistent organic pollutants.

In the case of chemical elements, two main groups are of particular importance for health: those that are essential to animal life and those that are potentially harmful. Elements essential to animal life include K, Na, Ca, P, Cl, S, and N as well as the first row transition elements Fe, Mn, Ni, Cu, vanadium (V), Zn, Co and Cr, and Mo, tin (Sn), Se, and I. Some of the disorders associated with deficiency of these elements are given in Mertz (1986). Boron has not yet been shown to be necessary for animals, although it is essential for higher plants. By contrast, potentially harmful elements (PHEs) known to have adverse physiological significance at relatively low levels include As, silver (Ag), beryllium (Be), Cd, Pb, Hg, U and some of its daughter products, and possibly the rare earth elements Ce and gadolinium (Gd). Aluminium (Al) can also have adverse physiological effects in trace amounts in animals and plants (Sposito 1989) and has been implicated in some types of neurological diseases in humans (Harrington et al. 1994). All trace elements are toxic if ingested or inhaled at sufficiently high levels for long enough periods of time. Se, F, and Mo are examples of elements that show a relatively narrow concentration range (of the order of a few $\mu g\ g^{-1}$) between deficiency and excess (toxic) levels.

Radionuclides can also be considered in two groups: those that are naturally occurring, and those produced deliberately or accidentally by nuclear reactions as a consequence of human activities. Naturally occurring radionuclides include ^{40}K, ^{235}, ^{238}U, and ^{232}Th, and their daughter products. Man-made radionuclides potentially hazardous to health include ^{137}Cs, ^{95}Zr, and ^{131}I, which are chemically indistinguishable from non-radioactive isotopes of the same elements normally present in the environment.

In the case of synthetic organic (carbon-based) chemicals, most are manufactured by the worldwide chemical industry that produced 400 million tons of chemicals in 1995. According to the European Environment Agency, the exact number of marketed chemicals is unknown; the current estimate varies from 20,000 to 70,000 (Teknologi-Rådet 1997). Little is known about the toxicity of about 75% of these chemicals (Environmental Defence Fund 1997, Natural Research Council 1984). In addition to marketed chemicals, chemical by-products formed by processes such as energy production can also have impacts on the environment.

The organic chemicals that are of most concern are those that are persistent and travel long distances, in some cases on a global scale, especially those that bioaccumulate up the food chain. Some persistent organic pollutants (POPs) are found in the Arctic thousands of miles from major primary sources. Some health effects of chemicals in the environment are listed in Table 20.1.

The link between chemicals and health effect varies from well-known causal relationships such as that between benzene and leukemia, to suggestive associations such as that between pesticides and chemical sensitivity.

Generating a Geochemistry Database

Geochemistry can be used to identify, map, and monitor not only the total amount of substances in soil, dust, or water, but also the amount of a substance that is bioavailable and hence most significant in terms of likely human health effects. For example, Al, which is the most common metal in the Earth's surface layer, occurs in both inert and bioavailable forms, and its potential toxicity depends on its chemical form or speciation. It can occur in a large number of dissolved aqueous species, especially in conditions of low or high pH, or in association colloids with organic carbon or silica that limit its bioavailability and, therefore, toxicity. The toxicity of As and Sb also depends on their chemical form. They are most toxic in the M^{-3} gaseous state with decreasing toxicity in the sequence M^{3+} > M^{5+} > methyl As/Sb (Abernathy 1993, Chen et al. 1994).

Table 20.1: Potential effects on human health of chemicals in the environment (after EEA 1997)

Health Effect [(a)]	*Sensitive Group*	*Examples of Associated Chemicals*	
Cancer	All	Asbestiform minerals Polycyclic aromatic hydrocarbons (PAHs) Benzene Some metals Some pesticides Some solvents Natural toxins	
Cardiovascular diseases	Especially elderly	Carbon monoxide Arsenic Lead Cadmium	Cobalt Calcium Magnesium
Respiratory diseases	Children, especially asthmatics	Inhalable particles Sulphur dioxide Nitrogen dioxide Ozone	Hydrocarbons Some solvents Terpenes
Allergies and hypersensitivities	All, especially children	Particles Ozone	Nickel Chromium
Reproduction	Adults of reproductive age	Polychlorinated biphenyls (PCBs) DDT Phthalates Other endocrine disrupters	
Developmental	Fetuses, children	Lead Mercury Other endocrine disrupters	
Nervous system disorders	Fetuses, children	PCBs Methyl mercury Lead Organophosphates, including pesticides	Aluminium Organic solvents Manganese

(a) The link between chemicals and health effect varies from well-known causal relationships, such as that between benzene and leukemia, to suggestive associations such as that between pesticides and chemical sensitivity.

As concern about the environment has increased, more emphasis has been placed on studies concerned with issues such as the quality of water resources; waste and pollution related to historical mining, industrialization, and urbanization; and, in developing countries, soil degradation and desertification as a result of salination and deforestation. Such studies make an important contribution to applied environmental research, but are limited by their tendency to investigate specific media. Groundwater studies in particular tend to be carried out in isolation from those of surface water, stream sediment, or soil. There is also a tendency to study one or two chemical elements in detail — an approach that fails to provide a complete picture of interaction between chemical species in the surface environment as a whole. Methods of sampling, analysis, and data interpretation often vary greatly. Moreover, such studies are generally published in the journals of learned societies and are communicated mainly to other experts in the same field with relatively little impact on society as a whole.

In most developed countries, fully integrated digital multimedia, multi-element geochemical data are becoming available as a basis for both economic and environmental studies. When linked to process and modeling studies, such data provide a powerful means of documenting environmental or natural resource problems, as well as providing solutions and subsequently assessing their effectiveness (Plant et al. 2000). Developing countries are increasingly recognizing that geochemical mapping should be given a high priority within their national programs (Reedman et al. 1996).

Some of the applications of data obtained from geochemical mapping include:

- Delineation of areas with mineral resource potential.
- Identification of contaminated land.
- Studies of water quality.
- Studies of the environmental impact of agriculture and forestry.
- Assessment of acid drainage potential and other contamination from mines.

Table 20.2: Summary of principal recommendations for preparing a global geochemical database (after Darnley et al. 1995)

1.	Commonly available representative sample media, collected in a standardized manner.
2.	Continuity of data across different types of landscape.
3.	Adequate quantities of the designed sample media for future reference and research requirements.
4.	Analytical data for all elements of environmental or economic significance.
5.	Lowest possible detection limits for all elements.
6.	Determination of the total amount of each element present.
7.	Tight quality control at every stage of the process.

Extending modern systematic geochemical databases such as those prepared by the BGS and USGS over the Earth's land surface clearly provides one of the most effective methods of addressing environmental concerns worldwide. However, available data are incomplete and inconsistent between different countries (Darnley et al. 1995). Many older datasets that were collected mainly for prospecting purposes do not meet the basic requirement for establishing national environmental baselines. Moreover, although there are exceptions, different national and international agencies have carried out different aspects of geochemical surveys using different methodologies. Hence, geological surveys have traditionally provided chemical data on rocks and stream sediments; soil surveys data on soils; and hydrological survey organizations data on the chemistry of ground and surface water. It is difficult to interact such datasets using GIS or to use them as a basis for studying processes operating in the Earth's surface environment as a whole.

The Global Geochemical Baseline Program

The concept of internationally standardized geochemical mapping procedures originated in the 1970s under the auspices of the International Atomic Energy Agency, specifically for uranium. Successful application of the concept led, in 1984, to discussions on the need to have standardized data for all elements. In 1988, formal support was obtained from the IUGS/UNESCO International Geological Correlation Program (IGCP) for what has become the Global Geochemical Baseline Project (Darnley et al. 1995). Since then, a worldwide network of professional geochemists from over 120 countries has been established. A summary of the principal recommendations for preparing the global geochemistry database is given in Table 20.2.

Initially, a comprehensive review of sampling, analytical, and data processing methods in use was carried out and a framework was developed for standardizing methods for geochemical mapping at the global-regional scale. The recommended sampling, analytical, and data processing methods are described in Darnley et al. (1995); a more detailed sampling manual has been prepared by Salminen et al. (1998). All this information is also available through web sites (Table 20.3).

In order to begin systematic international geochemical mapping, a primary geochemical reference network (GRN) comparable to a geodetic grid has been established, a copy of which is available through the web (Table 20.3). The samples collected for the GRN also serve as standard reference materials. In the case of radionuclides, airborne gamma ray surveys provide the most effective method of mapping and standard procedures have been recommended (Darnley et al. 1995) based on those of the IAEA.

The GRN of geochemical samples has been completed for China and parts of Russia and work is on schedule to complete the work over 27 European countries (Plant et al. 1997, Salminen et al. 1998) by the end of 2002. Australia is carrying out an airborne gamma ray su.vey of the whole country as a component of the project. A considerable amount of work on developing a geochemical baseline is also being carried out in southern Africa, Colombia, Brazil, South Korea, and many other countries. Geological survey organizations preparing geochemical maps in developing countries are also increasingly using the standard methods, although much more financial assistance is required to extend the network especially over such countries. As indicated by Darnley et al. (1995), the total amount of money required for such an important study of the Earth is no greater than the launch preparation costs for one space shuttle mission.

Conclusions and Recommendations

Preparation of a systematic multimedia (surface and groundwater, soil and stream sediment) multideterminand global geochemical database would make a major contribution to understanding and hence improving environmental quality worldwide. In the longer term, the aim should be to include POPs. Such a program could involve all countries with the communication of methods, data, and information over the world wide web. This would provide the best method of technology transfer, and for documenting and communicating information on the environment of particular regions and countries in a global context as a basis for sustainability. It would also provide a sound basis for targeting scarce resources and developing strategies for remediation and amelioration. A global database would also provide a baseline against which future change could be measured.

Table 20.3: List of web sites

Organization	*Acronym*	*Internet or Web Site Address*
British Geological Survey	BGS	http://www.bgs.ac.uk/iugs
U.S. Geological Survey	USGS	http://www.usgs.gov
Geological Survey of Finland	GSF	http://www.gsf.fi/foregs
International Union of Geological Sciences	IUGS	http://www.iugs.orgiugs/science/sci_wggb.html
International Association of Geochemistry and Cosmochemistry	IAGC	http://www.cevl.msu.edu/~long/IAGC/html
International Geological Correlation Programme	IGCP	http://www.unesco.org/science/earthsciences/igcp
United Nations Educational, Scientific and Cultural Organization	UNESCO	http://www.unesco.org

References

Abernathy, C.O. 1993. Draft drinking water criteria document on arsenic. US-EPA Science Advisory Board report, contract 68-C8-0033.

Barnaby, F. 1987. Our Common Future – The Brundtland-Commission Report. Ambio, v.16, p.217–218.

Chen, S.L., Dzeng, S.R. & Yang, M.H. 1994. Arsenic species in the Blackfood disease area, Taiwan. Environmental Science & Technology, v.28, p.877–881.

Darnley, A.G., Bjõrklund, A., Bølviken, B. & 8 others 1995. A Global Geochemical Database for Environmental and Resource Management. Recommendations for International Geochemical Mapping. Earth Science Report 19, UNESCO Publishing, Paris.

EEA — European Environment Agency. 1997. Chemicals in the European Environment: LowDoses, High Stakes? The European Environment Agency and United Nations Environment Programme Annual Message 2 on the State of Europe's Environment. UNEP/ROE/97/16.

Environmental Defence Fund. 1997. Toxic Ignorance: The Continuing Absence of Basic Health Testing for Top Selling chemicals in the US, Environmental Defense Fund, Washington.

Harrington, C.R., Wischik, C.M., McArthur, F.K., Taylor, G.A., Edwardson, J.A. & Candy, J.M. 1994. Alzheimer's-disease-like changes in tau protein processing: association with aluminium accumulation in brains of renal dialysis patients. Lancet, v.343, p.993–997.

McMichael, A.J. 1993. Planetary Overload. Global environmental change and the health of the human species. Cambridge University Press.

Mertz, W. 1986. Trace elements in human and animal nutrition. US Dept of Agriculture. Academic, Orlando.

Natural Research Council. 1984. Toxicity Testing, National Academy Press, Washington.

Plant, J.A., Klaver, G., Locutura, J., Salminen, R., Vrana, K., Fordyce, F.M. 1997. The Forum of European Geological Surveys Geochemistry Task Group: Geochemical inventory. Journal of Geochemical Exploration, v.59, p.123–146.

Plant, J.A., Smith, D., Smith, B & Williams, L. 2000. Environmental geochemistry at the global scale. Journal of the Geological Society, London, v.157, p.837–849.

Reedman, A.J., Calow, R.C. & Mortimer, C. 1996. Geological Surveys in developing countries: strategie ; for assistance. British Geological Survey Technical Report WC/96/20.

Salminen, R. et al. 1998. FOREGS Geochemical Mapping, Field Manual. Geological Survey of Finland, Guide 47.

Smedley, P.L. 1999. Environmental Arsenic Exposure: Health Risk and Geochemical Solutions. BGS Technical Report for DFID.

Sposito, G. 1989. The Environmental Chemistry of Aluminium. CRC, Boca Raton, Florida.

Teknologi-Rådet 1997. The Non-assessed Chemicals in EU. Presentations from the conference 30 October 1996. Danish Board of Technology, Copenhagen.