Toward 2050: the past is not the key to the future – challenges for the science of geochemistry

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Abstract The human population moves to 10–12 billion next century; there is an urgent need for the exact description of the behaviour of all chemical elements in all parts of the Earth system and changes in geochemical cycles induced by human technologies. For many or most earth materials used on massive scales, such as energy systems, mining, agriculture, water treatment, waste systems, such data do not exist. There is an urgent need for geochemists to become involved in the crisis problems of sustainable development and in the development of new clean technologies for the twenty-first century. To solve these complex problems, there is need for teams integrating all the expertise, from the sciences, engineering, social science and economics.

Key words Chemistry · Physics of earth materials Resources · Human forcing of change · New technologies · Energy · Soil · Water · Wastes

Introduction

World population data clearly shows that, by the year 2050, barring catastrophe, the human population will be in the range 10–12 billion, double that of present. Most of the additional six billion will live in the ’developing‘ nations and most will live in urban environments (see World Resources Institute 1996). Perhaps the greatest questions facing all scientists and technologists and all educated citizens of the world are “can we support 10–12 billion humans well without destruction of our most basic life-support systems? Can we develop truly sustainable support technologies?” As I write this paper, I have just listened to a report from the BBC World Service on the catastrophic famine in North Korea. We know that 40,000 children under the age of five die every day, the principal cause being malnutrition. In Asia 60% of the children suffer from malnutrition and 55,000 people die daily from polluted water and waterborne diseases. As Postel (1992) has shown, over 40 nations have a water supply crisis. NASA has a famous poster “the fragile Earth”, but our planet is not fragile. It is the biosphere that is fragile, particularly the part that lives at or near the surface of Earth (Fyfe 1996a).

When one considers the most fundamental components of our life-support systems, all involve the need for exact geochemical knowledge of the materials, the processes and the interactions between all parts of the Earth system from atmosphere to core. We must understand the processes which control the chemistry of the atmosphere, the climate, the interactions of the biosphere with the hydrosphere and soils, the factors which control bioproductivity, the materials and systems which provide our energy resources and all the material resources used by humankind. In addition, today a new problem facing all Earth system scientists involves the intelligent management of our waste products. For all such problems, we require knowledge of the complete chemistry (the periodic table) and the dynamics of element mobility. It is incredible, that only now, are we beginning to produce the most basic maps of the chemical composition of the Earth’s surface environments (Darnley and others 1995). Such data are essential if we are to understand bioproductivity, the health of the species of the biosphere, and the needs and limitations required for sustainable development.

Change and anthropogenic forcing of change

At the present time, there are a host of projects like the International Geosphere Biosphere Program (IGBP) designed to study change in our environment. This project states in its mission statement: “To describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions. Priority in the IGBP will therefore fall on those areas of each of the fields in-

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volved that deal with key interactions and significant change on time scales of decades to centuries, that most effect the biosphere, that are most susceptive to human perturbations, and that will most likely lead to practical, predictive capability".

But when one examines many or most of the present mega-projects, the influence of humankind, with the evolving technologies, is largely neglected (Fyfe 1992). The recent report from the Worldwatch Institute on "imperiled waters" (Abramovitz 1996) shows the incredible changes occurring, and planned for continental freshwater systems. This report raises the question "will any river in the world flow naturally to the ocean by 2050?" For example, in 1950, there were about 5,000 large dams in the world; by 1985, the number had increased to over 36,000. Analogous problems arise with soil erosion, soil degradation, etc. The geochemical dynamics of a host of elements are changing dramatically (Nriagu 1984, 1996). Today, we use about 50,000 xenobiotic (not known in nature) chemicals. Deforestation, soil erosion and genetic manipulation of the biomass (Edwards 1996) can lead to fundamental changes in many fundamental properties (e.g. the albedo) of our planet.

By 2050, the chemistry and biology of Earth's surface domains will be very different from that of 1950. Such changes *must* be monitored and their influences *must* be understood at the most basic level. *The past is not the key to the future.*

The power of observational technologies

Given the urgent needs to describe all aspects of change occurring on our planet, it is fortunate that, for almost all major problems, we have the techniques for exact description of all materials on our planet. As described by Darnley and others (1995), today geochemistry can involve airborne systems for radionuclides of many types. Using modern techniques such as plasma, laser, mass spectrometers, neutron activation, etc., today we can analyse for almost the entire periodic table on samples of a few milligrams. The same is true for common isotopic systems. Modern high-resolution transmission electron microscopy allows us to describe microparticulates of almost all types in soils, living cells, aerosols, etc. Of great importance is the significance of all the new techniques for the analysis of a few atomic layers on the surface of materials, as these allow the study of interfaces that control the reactions of most environmental geo-bio-chemical systems. A great advance has resulted from the use of strange isotopes (^{10}Be, ^{26}Al) generated by the action of cosmic rays on surface materials, as these allow us to determine the exposure age of soils and rocks at the Earth's surface. Today, given the necessary facilities and financial support, we can describe the materials of our environment with the detail and precision for their wise use in sustainable technologies.

The great problems

For truly sustainable development, a number of our major technologies must be improved. All are connected and in what follows the order is not in any priority.

Energy

Imagine for a moment that we have no oil, gas, or coal, (no electricity), which provide about 90% of our energy systems. How many people would live on our planet or in a nation like Canada? Today, nuclear energy provides about 8% and hydropower 3% of total world energy. There is also little doubt that, for decades to come, fossil carbon will dominate world energy production, particularly in countries like China and India which have large coal reserves and great need for more energy. Our quality of life is linked to energy. The present world is divided into those who waste energy (N. America), those with active energy reduction programmes (Europe, Japan) and those who need more energy.

Over the past two decades, we have become very interested in the geochemistry of coal. It is strange that, for this major fuel, that has been used for centuries, our knowledge has been so inadequate. Classically, the engineer has asked only what is the ash, moisture, and more recently, sulphur contents. But coal is a very complicated and variable material. This is obvious when we consider its bio-origins, together with the unique reducing environment it creates in a sedimentary pile undergoing diagenesis. When one examines the chemical composition of coals, almost every coal field, or even coal stratum, is unique. Coals can be rich in halogens, uranium, arsenic, nickel and even gold, as well as a host of inherited bio-essential elements. Coals often occur in fault-bounded basins, and fluids are always associated with fault system; thus coal can be mineralized and demineralized.

Recently, I and my colleagues have been studying coal chemistry in India and Thailand (Sahu 1991; Fyfe and others 1993). In both of these nations, there has been recent massive development of coal electric systems, often promoted by foreign experts and the World Bank. In most cases, there were no preliminary studies of the detailed coal composition. For example, in India, the coals are often ash rich, but they are not very anomalous in toxic heavy metals; however, they can have significant quantities of halogens. Fyfe and Powell (1993) discuss halogenic carbon-dominated aerosols emitted in the exhaust gas systems. In Thailand, Hart (1995) found coals enriched in arsenic and his studies clearly show that in the combustion cycle, arsenic was not retained in the dust precipitation systems. In Brazil, while working with Nucleabras, the Brazilian nuclear energy company, we described coals with ore-grade uranium (at the percent level). The same coals were sulphur rich and had very high concentrations of heavy metals.

The use of coal is increasing in many parts of the developing and developed worlds (in the USA, use of coal increased 77% in the period 1971–1991, according to the

World Resources Institute 1994). This being the case, geochemists must be involved in the selection of fuels and in planning the optimum coal-burning technology. Our work in India and Canada has shown that, given careful chemical control (essentially all elements), coal-ash wastes can have useful fertilizer potential (Young 1994). Some coal ash can have useful quantities of glassy phosphates and other bio-essential elements.

Here, there is no need to discuss the global problems of our changing atmosphere related to the increasing emission of combustion gases. The related impact on public health has reached catastrophic dimensions in some regions. The problem the Earth scientist must consider is the containment of exhaust gases from stationery combustion systems.

It is interesting that, at its November meeting in Orlando, Florida, the American Chemical Society (1996) devoted a special symposium to the capture, utilization and disposal of CO_2. Several papers considered the possibilities of disposal of such gases in rocks at depths of a few kilometres below the surface. Obviously, the acid gases (SO_x, NO_x, HF, HCl,...) and particulates will be rapidly removed by reactions with common carbonate and silicate minerals. However, in rocks with Ca-feldspar and Ca-Fe-Mg silicates, the possibility exists that carbonate-mineral formation might be used to fix carbon dioxide. In preliminary studies (Fyfe and others 1996) it seems that such processes do occur and can be catalyzed by subterranean microorganisms (Fyfe 1996b). In Norway and Japan, injection of CO_2 into the oceans and ocean floor is being considered, as is injection into exhausted oil fields (Hitchon and others 1996). Interest is growing in all such possibilities, but an interesting factor involves the energetics of CO_2 fixation. Reactions such as

$$CaAl_2Si_2O_8 + CO_2 + H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4$$

are highly exothermic, and given appropriate kinetics, can yield a geothermal energy bonus in the range of 30–40% of the initial combustion energy per carbon atom.

Soil

Around the world, there is vast concern with the growing world food crisis. As stressed by Sadik of the United Nations Population Fund (1989), at least 20% of the world's population suffers from severe malnutrition, and in some major nations, 60% of the children suffer from malnutrition. At the roots of food bioproductivity are factors which include climate, biodiversity, water and soil quality. There is a world crisis in soil degradation (Fyfe 1989). Soil productivity is related to soil thickness, mineralogy (which controls structure and water retention) and detailed chemical composition. As was stressed by Mertz (1981), almost half the elements have bio-essential functions, and their presence or absence can greatly influence bioproductivity and the health of all species, plant and animal. Striking examples include iodine and the human thyroid, cobalt and the immune systems of animals (cf. vitamin B12), molybdenum and nitrogen fixation (Darnley and others 1995; Cotter-Howells 1996). The assessment of the sustainable productivity of soil must include consideration of the complete mineralogy by high-resolution electron microscopy of particulates at all scales, total chemical composition, surface chemistry of solid phases (which in part controls nutrient availability) and the biological diversity (micro and macro), of the soil. Such essential data are rarely available in most parts of the developing world.

This century, many technologies have expanded to enhance agricultural productivty, including irrigation, use of fertilizers, pesticides and herbicides, and change in the species used in food production. Across the world, these methods are beginning to break down. Careless use of mineral-based fertilizers have caused vast pollution problems, the same is true for pesticides, herbicides, and many other agri-chemicals.

Particularly in tropical areas with nutrient-poor lateritic soils, we have found that simple mineral-based additives can produce spectacular results on a sustainable basis (see Konhauser and others 1995). Given exact knowledge of the bio-functions of the elements, very simple element additives may be highly effective in enhancing bioproductivity. But with all such additives, particularly when mineral-based, quality control at the source is essential. Phosphate rocks can be rich in elements like uranium, and cadmium, and long-term or excessive use can lead to serious toxicity problems, as has been well documented in many regions of the world (see Nriagu 1984).

Water and wastes

Across the world there is a growing concern with the deterioration of the surface-water resources of our planet. In a recent report to the American Chemical Society, Lepkowski (1996) reports that 20% of rivers in China are too polluted to be used for irrigation. Vast land areas have serious problems related to salinization. Today, over one billion people do not have access to clean drinking water. All our technologies for energy, mining, agriculture, urban systems, inject wastes into the hydrosphere systems. The situation was elegantly described by the former editor of Science, Koshland (1993).

First of all, it is important to identify the main villain as overpopulation. In the good old days (viewed through the myopia of nostalgia), the water, air, flora and fauna existed in an idyllic utopia. But, in truth, there were famine, starvation, horses and buggies that contributed to pollution, fireplaces that spewed forth soot from burning soft coal, and water contaminated with microorganisms. *The humans were so few, and the land so vast, that these insults to nature could be absorbed without serious consequence. That is no longer true".*

To manage wastes of all types, all aspects of their total chemistry must be accurately described. Given such data, certain choices can be made. Some wastes may be useful (e.g. metals, coal ash). Some wastes must be isolated or destroyed (e.g., nuclear wastes, isolation or transmutation of long-lived toxic nuclides: Fyfe 1996a). But in many examples, the basic technologies to eliminate wastes must be changed. Quality control at the input of all materials must be improved.

Conclusion

As world human population continues to grow, the need for exact geoscience must be a priority in planning the future development of human support systems. Moreover, there is urgent need to improve the communication and effective cooperation between all the experts in science, technology, economics, engineering and politics and to convince all educated citizens of the urgent necessity of this course of action. At this time, Europe leads in demonstrations that sound economic and environmental policies are not in conflict, but must form a working partnership. Furthermore, we must (and can) reduce pollution and wastes. We must recognize the limits of the Earth, we must develop holistic natural science. Given the future numbers of humans on Earth, the cost of errors will soon become intolerable. Exact geochemistry is essential for all developments which use Earth materials.

References

Abramovitz JN (1996) Imperiled waters, impoverished future. Worldwatch Paper 128
American Chemical Society, Division of Fuel Chemistry (1996) Capture, utilization and disposal of CO_2. Vol. 41 No. 4,
Cotter-Howells J (1996) Environmental geochemistry and health. Mineralogical Society Bulletin No. 112, pp 3–6
Darnley AG, Björklund A, Bølviken B, Gustavsson N, Koval PV, Plant JA, Sttenfelt A, Tauchid M, Xie X (1995) A global geochemical database for environmental and resource management. UNESCO Press
Edwards R (1996) Tomorrow's bitter harvest. New Sci August 17, pp 14–15
Fyfe WS (1989) Soil and global change. Episodes 12:249–254
Fyfe WS (1992) The life support system in danger: challenge for the earth sciences. Earth Sci (Japan), 47:249–254
Fyfe WS (1996a) The biosphere is going deep. Science 273:448
Fyfe WS (1996b) Energy and wastes from plutonium to carbon dioxide. Sci Int 62:14–17
Fyfe WS, Powell MA (1993) Halogens in the atmosphere. Chem Eng News Am Chem Soc April 24, p 4
Fyfe WS, Leveille R, Zang W, Chen Y (1996) Is CO_2 disposal possible. In: American Chemical Society, pp 1433–1435
Fyfe WS, Powell MA, Hart BR, Ratanasthien B (1993) A global crisis: energy in the future. Nonrenewable Resour 2:187–196
Hart B (1995) Inorganic geochemistry of coal and fly ash from Mae Moh, Thailand. Ph.D. thesis, University of Western Ontario, London, Ont.
Hitchon B, Gunter WD, Gentzis T (1996) The serendipitous association of sedimentary basins and greenhouse gases. In: American Chemical Society, pp 1428–1432
Konhauser K, Fyfe WS, Zang W, Bird MI, Kronberg B (1995) Advances in Amazonian biogeochemistry. In: Seidl PR, Gottleib OR, Kaplan MAC (eds) Chemistry of the Amazon (Am Chem Soc Symposium Series 588), pp 208–247
Koshland DE (1993) Clean thoughts on clean air. Science 261:1371
Lepkowski W (1996) Researcher explores economics of China's ecological degradation. Chem Eng News Am Chem Soc June 10, p 27
Mertz W (1981) The essential trace elements. Science 213:1332–1338
Nriagu JO (ed) (1984) Changing metal cycles and human health. Springer, Berlin Heidelberg New York
Nriagu JO (1996) A history of global metal pollution. Science 272:223–224
Postel S (1992) Last oasis – facing water scarcity. WW Norton, New York
Sadik N (1989) The state of world population, 1989. United Nations Population Fund, UN, New York
Sahu KE (ed) (1991) Environmental impact of coal utilization. Indian Institute of Technology, Bombay
Tazaki K, Fyfe WS, Sahu KC, Powell MA (1989) Observations on the nature of fly-ash particles. Fuel 68:727–734
Young E (1994) Waste does wonder for India's forests. New Sci July 16, 1934:19
World Resources (1994–1995) World Resources Institute, Oxford University Press, Oxford
World Resources (1996–1997) World Resources Institute, Oxford University Press, Oxford