Mineral Spectroscopy: A Tribute to Roger G. Burns

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The science of earth materials—New priorities in a changing world: A tribute to Roger Burns

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PROLOGUE

IT IS WITH great sadness that I write these notes devoted to the memory of my former student and colleague in research, Roger Burns. Roger came from New Zealand to work at Berkeley in the early 60's. His main background preparation was in chemistry (but he had to take the rigorous Berkeley field course!) It was a time when various groups of chemists around the world had realized that crystal field theory (ORGEL, 1960) could explain much of the behavior of transition metals and their compounds. I had been fortunate, in that the National Science Foundation had given me the support to acquire a then state of the art visible - uv spectrophotometer, with a sample chamber that allowed us to insert a standard petrographic microscope (with a u-stage), or an optical cell that could hold fluids up to 10 kilobars pressure. Roger and I could see a host of problems that looked interesting, and he had the fresh young mind, the energy, and the background preparation to attack the difficult experiments. A steady stream of papers was to follow (BURNS *et al.*, 1964). After Berkeley, Roger spent time at Cambridge, U.K., and there had the great fortune to meet many in their excellent chemistry department, including Mike Bancroft, and this encounter was to produce many seminal developments in mineral spectroscopy. It is interesting that many of the most productive workers in Earth System Science came with diverse backgrounds, a fact that our geology departments, which have tended to become over-specialized, should remember.

EARTH MATERIALS: EARTH HISTORY

As many have stressed, earth materials hold the record of events on this planet. The exact study of such materials is at the heart of our understanding of time, P-T stress history, and processes influencing all parts of the planet, from outer space, to atmosphere, to core.

From the earliest recorded history, humankind has been concerned with earth materials. The discovery of many of the elements came from those who worked with minerals. Those involved in improving our understanding of the nature of the chemical bond and inorganic structures, such as PAULING and BRAGG, were very familiar with naturally occurring substances. The discovery of radioactivity, the early developments in the understanding of the atomic nucleus, and the appreciation that these nuclear processes must hold the record of time, led to the technologies and the theories needed to advance the science of natural isotopes in all planetary systems and to understand the thermal histories of the planets. I often think that we forget the contributions of earth science to science in general.

At the present time, those who live in the rich (developed) worlds use something like 20 tons of rock materials per person per year to satisfy their various needs (from building materials to gold). If our world is to achieve some form of social equality and tranquility in the coming decades, given the present rate of population growth, in the next century, we may use something like 100 km^3 of earth materials per year—we will move and modify more rock than all natural processes on our planet (FYFE, 1981).

At this time, there are great and growing concerns with the state of our planet. But, if one examines many of the most fundamental aspects of our environmental and resource problems, almost all involve our knowledge of earth materials and their processes of formation and modification. At a time when the geosciences are under threat (KERR, 1995), this is also a time of great opportunity. As the papers in this volume show, we have powerful techniques available today to improve our precise quantification and understanding of the behavior of earth materials.

EARTH MATERIALS AND THE LIFE SUPPORT SYSTEM

Consider some of the most basic problems facing sustainable development, and the relationship between these problems and the study of earth materials. A list of such mega-problems must also recognize the new demographic facts of the world of the next century. First, over 80% of the future population will live in the so-called developing countries. Second, the future population will be urban; it is already 85% in the developed world.

Some fundamental problems with which all earth scientists must be involved (not in order of importance) include:

- Energy resources
- Water resources
- Soil resources
- Materials for 10 billion
- Waste management
- Understanding and predicting fundamental geo-fluctuations

ENERGY

At the present time, the bulk of world energy comes from the combustion of coal, oil and gas; all these resources are non-sustainable, natural capital. The thoughtless waste of such valuable resources is a global disaster. Of the fossil carbon sources, only coal and certain types of carbon rich sediments have reserves of interest for more than a few decades. In a general way, there has been little change in burning technologies - add air - burn - and exhaust to the atmosphere.

There is no need here to discuss the potential future impacts of the climate changes related to the fact that we have rapidly changed the chemistry of the atmosphere. Discussion is normally concerned with CO_2, CH_4, and acid compounds, but, as stressed previously (FYFE and POWELL, 1995), many coals contain significant quantities of all halogens: F, Cl, Br, I, and the steadily increasing ozone depletion catastrophe may be influenced by combustion of these fuels. Also, time after time, the detailed chemistry of coal and coal ash is not well known, and many coals have significant quantities of elements like uranium and arsenic, and an array of heavy metals immobilized in the reducing, sulfur-rich, medium of coal. It is amazing how little is known about the detailed chemistry and phase chemistry of this major world fuel.

It is certain that nations like China and India will depend on coal for decades to come. Can the technology be changed at reasonable cost to reduce the environmental impact of coal combustion? I think the answer is positive. We have been studying the fixation of CO_2 and organics in the cracked, permeable basalts in the caves of Kauai, Hawaii, deep beneath a very heavy forest cover. Every crack is covered with white materials (silica, clays, carbonates) formed by the action of organics with the basalt, a process mediated by ubiquitous bacterial biofilms. Bacteria can live to depths of over 4 km, up to 110°C, in favorable locations (PEDERSEN, 1994). Can such processes be used to fix the exhaust gases of coal combustion? Certainly, some rock types will be better than others, and volcanics with Ca-feldspars and rich in Fe-Mg phases should be ideal, as in Hawaii. Also it is interesting to note that adding H_2O-CO_2 to appropriate rocks can be a highly exothermic process and the gas disposal could lead to a geothermal energy bonus! Recently, on a field trip in China (East of Beijing), we discussed the possibility of using their rapidly exploited oil-gas fields for disposal of wastes of many types. If a basin can isolate oil-gas for millions of years, it undoubtedly has capacity to isolate wastes (DESSEAULT, 1995). And, generally, oil field structures are well known.

The growing knowledge of the deep biosphere also raises the possibility, with certain types of carbonaceous sediments, of using microorganisms for *in-situ* methane production. In place of opening deep mines, with all the related water pollution problems, could it be possible to produce bio-gas?

There is no shortage of energy sources on this planet. Ultimately, the world must move to solar energy of all types (photovoltaics, wind, tidal) and geothermal energy. Wind energy use is increasing across the world, and photovoltaic devices are becoming more efficient and cheaper (NEW SCIENTIST, 1995). Geothermal sources are normally associated with regions of high heat flow (volcanic systems) but, for some purposes (city heating, greenhouses and aquaculture systems), the normal geothermal gradient can provide background heating. There are many regions of the ocean floor with impressive potential for geothermal energy. All such potential use requires exact knowledge of deep geologic structures, porosity, permeability and geochemistry.

WATER

According to POSTAL (1992), today, forty nations have a crisis of water supply. In many places, uncontrolled extraction of ground water (mining) is being used to promote non-sustainable increases in food production. In vast areas, bad water-management has led to salinization of soils and massive pollution by agri-chemical residues. Examples of pollution abound as in Calcutta, and their major problem of groundwater arsenic pollution, which has led to serious health problems with very large numbers of people who live from ground waters. Where does the arsenic come from? This problem is not solved, but arsenic compounds have been used for a long time in rodent control.

There are many examples of the use of mineral surfaces in controlling heavy metal pollution (as with mercury adsorption on pyrite, BROWN *et al.*, 1979). In general, by using our mineralogical-geochemical knowledge, most metal pollution problems can be solved. And, increasingly, living microorganisms can be used to secrete metals and degrade organics (BEVERIDGE and FYFE, 1985). Possibilities exist of using reactions like:

$$\text{Organo-Cl} + \text{Na(silicates)} \rightarrow \text{graphite} + SiO_2 + NaCl.$$

to dispose of certain compounds subsurface. Most of these processes have very favorable thermodynamics.

In the developing world, there are few places where the total water cycle is adequately described. While sea level is slowly rising in many sensitive coastal regions, land subsidence and apparent sea level rise are often associated with subsidence, compaction, following the mining of groundwater. Again, exact geoscience is required to describe the water resource potential of any region, and to live with the natural fluctuations in precipitation.

SOIL

At this time, at least one billion humans do not have an adequate supply of food of well balanced nutritional values (SADIK, 1989). Across the world, wood is becoming an expensive and declining commodity. Despite the electronic revolution, the use of paper products is increasing (per capita, 3x in the last 40 years). In addition, the world's marine resources are declining at an alarming rate. Again the rich-poor gap is dramatically increasing the nutritional difference in the world's population.

Sustainable food-fiber production depends on climate, climate fluctuations, soil quality and water resources, and knowledge from the geosciences is involved in all these parameters. Given that we are not adequately providing nutrition for the present human population, what are the prospects for the next 5 billion?

All organisms require a large array and balance of the chemical elements (about 50) for efficient production of the organics needed for life (MERTZ, 1981). The geochemistry and the mineralogy of soils are critical in estimating the capacity of a soil for sustainable organic productivity. According to the Worldwatch Institute, topsoil loss globally is approaching 1% per year, while natural remediation can take 100's of years. The technologies exist now for erosion and salinization control, but such technologies are not adequately used, and there is great need for new soil maps which clearly show good soils, soils for forests only, and ones we should leave alone (FYFE, 1989)!

Given the chemical and physical properties of a soil, additives may greatly enhance bio-productivity. Often, such additives require the addition of simple mineral materials containing species like K, Mg, Ca, P . . . . , and appropriate trace metals like Co, Mo, etc., that may be critical in biofunctions like nitrogen fixation. The types of additives may be closely linked to soil type and climate. For many situations as with the laterite soils of the humid tropics, slow release mineral fertilizers (K in feldspars, rock phosphates . . . .) may be more effective and less wasteful than soluble chemical fertilizers.

Soil contains a complex array of ultra-fine inorganic and bio-mineral materials with vast surface areas which control key soil-bio functions. Today, with the modern techniques of surface chemistry (Auger, ESCA . . . .) and the power of modern high resolution transmission electron microscopy (TAZAKI *et al.*, 1987; TAZAKI and FYFE, 1986), we can precisely examine the inorganic-bio-gas-liquid interactions, which was not possible a decade ago. In soils, many of the mineral-forming processes involve reactions with living cells. There is a new world in the science of biomineralization which, as H. LOWENSTAM showed decades ago, is of vast importance in all aquatic environments to at least 100°C (LOWENSTAM, 1981).

MATERIALS-MINERALS-MINING

Advanced societies use about 20 ton of rock per person per year for their needs. Most is for various forms of construction, highways, buildings, etc., and giant mining operations include those for fertilizers, ores like iron, and coal. The average "student" gold ring weighs about 10g and represents the processing of about 3 ton of rock. It is amazing, but humans in general do not understand where their resources come from, and the impacts on the ecosphere, geosphere, hydrosphere made by mining operations. With modern understanding of Earth convection, our understanding of the resource base and prospecting strategies has dramatically increased. If the world needs more copper, we know where to look, and we find it.

Since mining technology has historically been careless, many large companies have increasingly moved to developing countries with less stringent environmental laws. For example, I was amazed that, when the NAFTA agreement was signed, it was clearly stated that only local environmental regulations applied. What of the future of the use of mineral resources?

First, the world must move to more efficient recycling and, for this to be successful, it requires careful quality control at all stages of the use—mining to fabrication. In mining, there must first be careful 3D mapping of structures, permeability, porosity, faulting, etc., to assess accurately the environmental impacts, and there is great need for extreme quality control in the extraction of ore materials. The total geochemistry must be known: the desired and the undesired elements. Such data must be available to plan the mining technology, and to assess the environmental impact of the operation, and waste products from mining must be studied for potential uses in construction, soil remineralization, etc. The growing knowledge of microorganisms at depths (now over 4 km) opens a host of new technological opportunities. Silica secreting organisms might be used for permeability control; metal-secreting organisms can be used for removal of heavy metals and secondary recovery, as has been well demonstrated. Also a host of new possibilities must be considered for ''*in situ*'' metal extraction via sulfide oxidizing species. The same is true for ''*in situ*'' methane production from carbonaceous sediments. To develop such technologies, there is need for cooperation between geologists, geo-microbiologists, hydrogeologists, engineers and economists. Far too little thought has been given to the end use of mines. In some cases, by careful planning, these could become waste disposal sites for urban areas, a growing world problem.

There is no doubt that, with the correct team for planning *from the start*, the environmental impact of extracting resources from the crust can be vastly reduced and I am sure that, in many cases, the long term economics of the operation will be improved. The development of new materials is producing new opportunities. According to the British journal ''The Economist'', there is a world shortage of high purity silicon for modern electronic devices, and soon there will be vastly increased use of photovoltaics. For such purposes, there is a giant difference between 99.99% SiO_2 and 99.9999% SiO_2.

I have always been intrigued by the possibilities for use of near ocean ridge sites for metal extraction and energy production (*cf* the Salton Sea Thermal fields of California). On Canada's well-described Juan de Fuca system, by drilling through the impermeable sediment cover, with thermal gradients of up to 300°C/km, one might simultaneously extract both metals and energy.

WASTE MANAGEMENT

This century will go down in history as that of careless technologies and waste production. There is no doubt that the long term costs can be staggering (as with the arsenic pollution in India, mentioned above). The complexity of modern wastes is enormous, from organics to radionuclides, urban garbage, etc. It is amazing that the nuclear industries developed before any serious attention was given to wastes—the ''we-will-do-it-when-necessary'' philosophy. In Ontario, Canada, where nuclear electricity dominates the system, the current estimates are that it will cost something like 15 billion dollars for nuclear waste disposal over the next decades and, at this time, no ''best'' site has been proposed. This problem exists in many nations, and it is strange that only recently has a combustion gas like CO_2 been considered a waste product. Combustion has changed the concentration of many critical components of the Earth's atmosphere.

The time has come to change drastically our philosophy on wastes. First, we must precisely describe the nature of waste, chemistry, compounds, etc. Then, we must search for uses for the waste, and recognize that time after time it can be a resource. (Denmark recycles 97% of its paper, Canada 17%.) The secret of domestic waste management is the five minutes a day spent in separating the components. As mentioned above, we have shown that, by using careful geochemistry, many types of coal ash (but not all) can be a valuable soil additive. In the past few years, a group from The University of Western Ontario, Bombay and Orissa State in India have been studying the use of coal ash in soil remineralization for forestry. The results have been spectacular and widely recognized (Young, 1994; Geoskop, 1994). But the success has been related to very detailed geochemistry and phase studies of the coal ash (Sahu, 1991). The same is true for most urban sewage, as long as it is not mixed with other toxic wastes from, for example, the chemical industries. Again, we need teams of the appropriate scientists, not just engineers! One case I would like to emphasize again is that of the gas products from combustion, CO_2, NO_x, SO_x and, as we have shown with halogen bearing coals that are common, possible halogen-organics. Are the latter partly responsible for the growing problems of stratospheric ozone destruction? As mentioned above, is disposal of these gases below ground possible and not simply vent to the atmosphere? I was recently in China, in the Beijing region, which has catastrophic atmospheric pollution from combustion and other industries. The cost reduction on public health of reducing all the lung problems might well cover the additional engineering costs of gas disposal. Japan is seriously considering the marine dumping of CO_2.

Every waste product requires a unique approach. Many wastes can be resources and, for most, secure disposal is possible. For geological disposal, we require a new precision in the total description of the subsurface environment.

GEO-FLUCTUATIONS

Given the future population of our planet, and the fact that most of this population will be urban, geo-fluctuations will have increasingly serious social and economic impacts, if they are not fully considered in planning all forms of development. Imagine the cost of careless site selection and waste packaging in nuclear waste disposal. But, for earth system scientists, certain problems present major challenges. Some, in which we require vastly increased knowledge include:

- prediction of the sites, magnitude and character of future volcanic events—events which can cause a serious climate perturbation. We have not had a mega-eruption this century (STOMMEL and STOMMEL, 1994).
- prediction of the sites and magnitude of major seismic events. One need only reflect on Kobe, Japan, and some recent events in southern California, to appreciate the economic impact.
- the general problems of slope stability.
- the monitoring of the arrival of significantly large objects from space.

If one considers the first three of these processes listed above, and the fundamental science behind the process, it is obvious that they involve complex aspects of mineral-fluid interactions in various depth regimes. Their understanding requires integrating knowledge and techniques from almost all Earth science areas of specialization. The new and developing International Program of Continental Scientific Drilling (ZOBACK and EMMERMAN, 1993), provides an example of the types of cooperation urgently needed to address critical global problems. Data from the ODP program has made massive contributions.

CONCLUSION

As world human population continues to grow, to move to over 10 billion next century, the need for exact geoscience must be a priority in planning the needed future development of the support systems. There is urgent need to improve the communication and effective cooperation between all the experts in modern science and technology, economists, engineers, politicians, and all educated citizens. At this time, Europe leads in demonstrating that sound economic and environmental policies are not in conflict, but must form a working partnership. We must and can reduce pollution and wastes; must recognize the limits of the Earth system; and we must develop holistic natural science. Given the future numbers of humans on Earth, the cost of errors will become intolerable, and it is teams of people with spirit and talent, like Roger Burns, who are needed.

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