Deep Earth Chemical Fluxes and the Biosphere

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As the International Geosphere Biosphere Project moves to centre stage of cooperation in International Science, the earth scientist faces new and demanding tasks in describing the geochemical fluxes which influence the environment for life. In our world of next century, with a human population of near 10 billion, in part stability will be related to our understanding of such fluxes and perhaps even more in understanding the fluctuations in events which influence the Biosphere.

We now know that geochemical fluxes from the deep earth are important in the overall balance. Our knowledge of the fluxes to the biosphere environment associated with the major systems of plate tectonics (ocean ridges, conveyer belt, subduction-collision zones, hot spots), ranges from moderate to almost zero.

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Introduction

Those involved in the Earth Sciences today are perhaps facing their greatest challenge. In the past there have been certain traditional problems, a shortage of copper or molybdenum, prediction of oil reserves and the like. But now we face a new and much more difficult challenge, that of defining the limitations of the ultimate biological planetary resources of air-water-soil.

A series of developments have forced us into this new situation. The phenomenal growth of population (at present 5 billion with 87 million per year added), together with the material needs of modern man and modern agriculture, have forced us to recognize the fact that WE are now the dominant agent of geomorphic and often geochemical change (Fyfe, 1981). We are changing the chemistry of our atmosphere (CO_2, CH_4, O_3, CO . . .) at rates close to or even above the percent per year level. Global temperature is rising, sea level is rising at a time when solar inputs are actually falling (Willson et al., 1986). Arctic temperatures are possibly rising much faster than predicted by almost all climate models (Lachenbruch and Marshall, 1986). Brown and Wolf (1984) estimate that we are losing topsoil at a rate of 0.7 % per year, a rate almost certainly accelerating as man invades areas which often are quite unsuitable for agriculture. Such a list of the influences of human impact on the lift support system could be extended. Aldous Huxley has suggested that they could lead to human catastrophe on scales we have never seen before.

Here I would stress the analysis of natural events based on "fractals", the topic of Huang & Turcotte's paper in this volume. Imagine a world with ten billion inhabitants next century. Imagine a major crop failure (a new pest, a very dry season, a little ice age. . .). We are used to millions or more facing starvation. How will we deal with billions facing such a situation!

Our recognition of the significant, observable, and accelerating influence of human impact on this planet coupled to our remarkable ability to observe and monitor on all scales, from satellites, through molecules, to atomic nucleii, has led to the development of new scientific endeavour, the International Geosphere Biosphere Programme – A Study of Global Change. This project was formally launched by the International Council of Scientific Unions (see ICSU, 1986) in September of 1986. Quotations from ICSU (1986) perhaps summarize the objectives and focus of the programme, the IGBP: "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 involved that deal with key interactions and significant change on time scales of decades to centuries, that most affect the biosphere, that are most susceptible to human perturbation, and that will most likely lead to practical, predictive capability". Perhaps this great new initiative begins to approach in a realistic way the concerns recently stressed by the recent Brundtland report (1987) of the World Commission on Environment and Development.

Many in the Earth Sciences have read these statements and concluded that the program will exclude most geologists except a few groups involved in quaternary geology, hydrogeology, present geochemical cycles and the like. But I would stress that this can hardly be true. The time has not yet come to exclude many large areas of geological science. Perhaps the greatest problems of the Earth Sciences involve the origin of life and the time variations of life, of genetic diversity, of genetic stability. Understanding of these ultimate problems involves almost all of our science (e.g. the history of the magnetic field, the history of volcanism, ice ages, etc.).

In this essay I wish to consider the following question. How do fluxes from deep sources (as opposed to the surface zones of runoff and soils) influence the biosphere? It is now becoming clear that fluxes from some of the deeper sources are significant, but for most, our knowledge is not quantitative. But of even greater significancce is that we know almost nothing of the time variation and fluctuations of these deep fluxes. In the analysis of geochemical cycles we tend to use steady state "box models". But our planet is not really in a steady state and hardly can be for a convecting system (volcanism, earthquakes, etc. have fractal distributions – not steady state distributions). It is the fluctuations in the "normal" state that will cause the giant catastrophes of the future!

I would also like to stress a point made long ago by Lyell (1872). "In reference to the extinction of species it is important to bear in mind, that when any region is stocked with as a great a variety of animals and plants as its productive powers will enable it to support, the addition of any new species to the permanent numerical increase of one previously established, must always be attended either by the local extermination or the numerical decrease of some other species". Perhaps no better example could be given than that of what is now happening in the Amazon Basin as it is invaded by man. And this case may serve to show that a "local" event may have global consequences.

Let us briefly examine the geochemical fluxes which result from the processes involved in the modern plate tectonic cycle. In particular, are there parts of these cycles when there are fluctuations which may influence the biosphere or environmental systems on short time scales of 10^1-10^3 years?

Ocean Ridges – Rising Mantle Convection Cells

Most of the present dynamic processes on planet earth start at the great ocean ridges where almost half the internal energy production is focussed in rising convective flow from the mantle. This process drives plate tectonics and forms the new oceanic crust. At the surface the rising cells produce basaltic magmas and gabbroic intrusives with a basement of ultramafic accumulates and mantle peridotites. As is now well known, perhaps as much as 50 % of the energy carried to the surface is transported away by deep circulation of sea water in the hot and permeable crust. We are now beginning to understand the chemistry of these fluids at the spectacular discharge sites observed near the ridges. We also know that such discharge sites are short-lived and fluctuate but our quantitative knowledge of processes along the vast ridge lineaments is really quite trivial. Only recently have the first giant plumes of ascending waters been observed (Anderson, 1987). The excess heat in a single plume equalled 10 billion kilowatt hours of energy!

But even with the few real-time observations it has become clear that the ridge fluxes (5×10^{17}g a^{-1} at 100°C) *are* significant in terms of the nutrient cycles of bio-essential elements (Wolery and Sleep, 1976). While ridge discharge volumes are only 0.1 % of continental runoff fluxes, for many elements and compounds (SiO_2, Cu, Zn, Co, Ni, Li. . .) where solubilities in salt water are much larger at 300°C, the total flux may be highly significant (e.g. SiO_2 in river water 15 ppm; SiO_2 in hydrothermal discharge 1 000 ppm; for copper and zinc 10–100 ppm). Recently, the first observations from seismic studies at ridges are showing the size and shape of magma bodies at ridges (Detrick et al., 1987). Given more of these data, we will begin to understand the fluctuations in ridge fluxes. One of the most intriguing recent observations has been that of the enrichment of ^{3}He in discharge ridge fluids. The ^{3}He plumes observed over ridges could provide a highly sensitive monitoring system for studies of the fluxes and their fluctuations (see Rona et al., 1983).

Another set of observations which may have great use involve the systematics of the $^{87}Sr/^{86}Sr$ isotopes in marine sediments. At this time the ocean water Sr ratio is about 0.709. The river input average is 0.711 while hydrothermal discharge will have near-basalt i.e. values of 0.702. These data show us that part of the present day Sr is from continents and part from sea floor systems. But one would expect to see local short time fluctuations of these over periods of anomalously high or low ridge activity.

The mixing time of the oceans is about one thousand years so that fluctuations will show quite differently on different scales. Quantifying such fluctuations must be one task for the submarine volcanologist in an IGBP.

With regard to the above, some will argue that because ocean mixing is rather slow, the hydrothermal fluctuations will tend to even out in terms of their impact on the biosphere. I tend to doubt the validity of such an argument. While the modern oceans are indeed a great buffer and perhaps present ocean-volcanic styles were necessary to produce the environmental stability on a cooling planet necessary for the post Cambrian explosion of genetic diversity, it must be remembered that any significant fluctuation which allows a special local advantage for a species (cf. Lyell, 1872) may lead to a much longer-term perturbation. The record of fluctuations must be available in the geochemistry and-paleontological record of sediments successively deposited on the new ocean floor basalts involved in the spreading process.

In summary, we now know that processes associated with mantle convection at ridges produces a significant flux of bio-essential elements. Our quantitative data on these fluxes is inadequate and our knowledge of fluctuations is almost zero. I will leave it to the student to contemplate the state of the marine biomass if these fluxes were to cease.

The Conveyer Belt

The greatest relatively unknown terrains of our planet are the off ridge, sediment covered, ophiolites which start near ridges and stop at active or passive continental margins where continental crust borders the fossil rift margins or active subduction zones. These quiet areas are heavily faulted beneath the sediments but most studies of such regions have involved the sediment cover and not the basement to the sediments.

Lister (1977) predicted that the open, free venting (black smoker) convection of the near-ridge environment would change to closed convection involving cells in the relatively permeable lava-dyke complexes beneath the impermeable blanket of marine muds. Davis and Lister (1977) found heat flow patterns in accord with this idea in muds off the Juan de Fuca ridge. Anderson et al. (1979) showed heat flow evidence for such convection in even older ocean crust.

As shown in Emiliani (1981) ocean floor topography and heat flow approximate the $(\text{time})^{1/2}$ law expected for a conductively cooling lithosphere. Anomalies occur near ridges and are attributed to hydrothermal cooling. But it should be noted that at large distances from the ridges heat flow and elevation tend to be too large. The negative anomalies of the near ridge environment tend to become positive. There is too much elevation and heat flow.

Such anomalies are not explained. Fyfe and Lonsdale (1981) suggested that if deep slow convection occurs, a second large heat source can be tapped. This heat source is related to the highly exothermic hydration of periodotite to form low density serpentine. For the reaction:

$$Mg_2SiO_4 + MgSiO_3 + H_2O \rightarrow Mg_3Si_2O_5(OH)_4$$

$$\Delta H^0 = -16 \text{ Kcal}$$
$$\Delta V^0 = +33 \text{ cm}^3/\text{mol } (40\ \%)$$

and there is no lack of evidence for the presence of serpentine in sea floor environments and at times for spectacular development of diapiric structures (Fryer et al., 1985). Lister (1977) considered that the swelling process would tend to eliminate permeability by crack sealing. On the other hand hydration will produce high volume strain and stress rates related to the rate of hydration. Most massive serpentinites or partially serpentinized peridotites show evidence on every scale for the development of brittle fractures.

MacDonald and Fyfe (1985) showed the difficulty of stopping serpentinization even with the low, clay-like, permeability of the product serpentine. In deep water, the difference between P_{fluid} and $P_{equilibrium}$ (serpentine $\rightleftarrows$ peridotite) is so large that the dehydrating agent peridotite acts as multi-Kbar suction pumps which can drive flow even in a low permeability medium. Macdonald and Fyfe also showed that serpentine acts as a rather good semi-permeable membrane and thus a process can occur:

Seawater + Peridotite → Serpentine + Salt

Recently Vibetti et al. (1985) have shown that such fluids do in fact exist in alteration zones of the deep levels in Cyprus where Na-K-Ca-Mg brines exist in fluid inclusions.

The exotic fauna typical of black smokers have been reported from seeps in old ocean floor crust (Grassle, 1985). Such observations along with serpentine diapirism shows that the conveyer belt region is by no means geochemically dead. Exchange processes between ocean-sediment cover and basaltic basement may well occur all the way to subduction. The exothermic formation of serpentine may well drive such flow and is in accord with the possible low velocity seismic layer reported by Lewis and Snydsman (1977). The fact that residual warm fluids may be extremely saline will promote the transport of all metals which form chloride complexes. In fact this could be their major environment of transport. Finally, I would note thet ophiolites tend to show rather horizontally uniform metamorphic patterns, not what would be expected if hydration reactions were restricted to convection cells in the near ridge environment.

In summary, off ridge transport processes are not quantified in nature or intensity. They are possibly large and related to the amount of serpentine generated in sea floor environments and the presence of highly saline fluids. Better data on the structure of old ocean floor is needed to unravel such processes and more detailed observations of geochemical anomalies in old ocean floor.

Subduction and Fluids: Subduction induced mantle convection

There is very little old ocean floor ophiolitic crust. Ocean crust is subducted at a rate almost equal to its rate of formation. But the materials subducted are very different from those which form the ridges. The original basaltic crust and gabbro-peridotite basement has been changed to a spilitic crust (with H_2O, CO_2, S, U, . . .) and the gabbro-peridotite basement has been partially converted to amphibolite-serpentinite before subduction.

In the last few years we have also come to recognize that pelagic sediments may be subducted on a scale of km^3 per year. This concept originally proposed by Gilluly (1971), once strongly opposed by the isotope experts, has now become respectable because of the direct observation of trenches and the structure of lithosphere going into trenches. Thus Hilde and Uyeda (1983) and Uyeda (1983) and the more recent Kaiko Project (1985) have clearly shown that when the lithosphere bends, it cracks in the upper part and forms horst and graben structures which fill with sediments. If there is not enough sediment to fill the structures, tectonic erosion of the overplate occurs: Japan is being tectonically eroded and underthrust. Such studies show clearly that initially light materials, tectonically trapped, may move towards the mantle.

Consideration of volatiles shows that for species like H_2O, CO_2, the recycling of the major reservoirs occurs with time constant of the order of a billion years at present rate. We have a hydrosphere, so that return flow must be moderately efficient. But the present processes, and their scales, should warn us that any purely steady-state model of ocean volumes and other volatile reservoirs, may be inadequate. Thermodynamics tells us that heating bodies degass while cooling bodies absorb gases. Is this what has happened on Mars (Carr, 1987)?

We now know that the processes involved in the return flow of volatiles are complex. At the initial stages of thrusting, some are literally squeezed out and pass up the thrust structures reducing friction on the thrusts (Anderson, 1981). Exotic fauna originally characteristic of ridge vents has now been found in deep trenches. But the fluids are cold and will not transport large quantities of silica or metals.

Recently, the Canadian Lithoprobe Project (Yorath et al., 1985) has been studying the structure of the subduction of the Juan de Fuca plate beneath Vancouver Island. We have been impressed by the complex fault structures above the subducting slab. Seismic studies have revealed the complexity of the structures beneath the continental edge. The very young and active faults show evidence for fluid flow transporting hydrocarbons, Mn-Fe-Ag and the like. Recently, ODP Scientific Party (1987) report gases like methane being involved presumably formed by the reprocessing of subducted organic debris.

But once the preliminary compression stage has passed, metamorphic processes will dominate eventually leading to formation of eclogites from basalts; kyanite, garnet rocks from pelagic sediments and even kyanite-coesite-pyrope rocks (Chopin, 1984). At this stage fluids may hydrofrac their way to the surface along faults. But some fluid maybe carried to very great depths in minerals like phlogopite, a natural product of metamorphism of K-bearing spilite or pelagic sediments in an ultramafic mantle environment.

When deep degassing occurs, with hotter mantle above, a new chain of events must occur. Water injected into this hotter mantle (water which will essentially be a soup of SiO_2-alkalis-trace metals) will soften the mantle and lead to convection and plume formation. As plumes of contaminated mantle rise they will melt to produce the contaminated basalts we call andesites.

Thus mantle convective motions are induced by the rising fluids. The small amount of fluids are amplified into a much larger heat flow process which eventually build up the mountain chains of the volcanic areas, Andean type. In a general way, every gram of fluid introduced will probably lead to something like 100−1 000 times the mass of volcanic rock. The injected fluids have led to a process which drains energy out of the overlying mantle wedge.

Studies of heat flow and electrical conductivity across subduction zones show the scale of this energy transfer process catalyzed by subduction.

Almost one third of the continental crust of the Americas has been influenced by recent subduction events. But we should not forget that it is the volatile loading in the sea floor environment that has led to this process. It would not occur on a dry planet.

Once mantle plume processes start above a subduction zone, a magnificent array of fluid-mass-energy transfer processes occur (see Rice, 1985; Fyfe, 1987).

(1) basaltic andesite rises, extrudes, intrudes, underplates, continental crust
(2) the crust melts producing granitic plutons and acid volcanics
(3) the basal crust undergoes progressive metamorphism
(4) magmas mix and complex hybrids are produced near the Moho region
(5) ultra-high-T gases are injected into the base of the crust from the andesite magmas and assimilated dense crustal components which founder in the underplate magmas
(6) high level plutons and volcanics are water cooled by deep ground waters in the high heat flow near surface environments
(7) high topography is created and deep ground water circulation through fractured intrusives and porous volcanics must follow.

The total fluid fluxes which must result from the entire array is impressive. We are not yet at a stage to quantify such fluxes but we can make some order of magnitude guesses. For example if we consider the Western Americas where the plutonic-volcanic terraines extend for about 20,000 km with a width of 500 km, and assume that a 5 km thickness of crust has been "granitized" or melted, the total acid igneous mass is about 5×10^7 km^3. Given a 10^8 a cycle, pluton production is 0.5 km^3 a^{-1}. Andesite production is about 2 km^3 a^{-1} (Thorpe, 1982). Thus about 2.5 km^3 of magma can be water cooled per year. The fluid fluxes will thus be about 25 % of that of ocean ridges. In this case there is no question, the fluxes of fluids just as the volcanic eruptions, will be non steady state as plutons rise and Tambora's erupt. There may be massive fluctuations at local sites or as in the case of massive acid eruptions, fluctuations which may influence the global atmosphere for years or even cause mass extinctions (Officer et al., 1987). It is the knowledge of these events, their intensity and frequency distribution, which are needed for the IGBP.

Continental Collision

At the present time most subduction processes involve the underthrusting of oceanic crust in situations near continental margins. But periodically, a continent is moved into the zone of subduction. Molnar and Gray (1979) considered the problem of the possible subduction of such a continental edge and concluded that it was indeed possible in terms of density relations. Over the past 50 Ma major collision events have occurred and are still proceeding at a rate of 5 cm a^{-1} in the Himalayas. While slightly different models of detail occur, there is no question that India is presently being thrust under Asia (Allegre et al., 1984; Barazangi and Ni, 1982). In this region a section of crust, 1 500 × 3 000 km, has been doubled in thickness. Present seismic evidence provides evidence for a jagged Moho at 60–80 km depth with 10 km steps. The region appears to be highly electrically conductive (Pham et al., 1986) with active zones of conductive fluids or melts.

The scale of the phenomenon is impressive. The area of thickened crust is similar in area to about 60 % of continental Australia and a section of crust of Australian size has been reworked in the process.

Fyfe (1986) has discussed some aspects of the problem of fluid fluxes when crust on this scale is heated and compressed due to the thrusting and shortening processes. Essentially the underthrust rocks will be dehydrated, lose CO_2 and other volatiles and eventually melt. The young plutons of the Himalayas show geochemical features (e.g. extreme initial $^{87}Sr/^{86}Sr$ etc.) as would be expected. The quantities of metamorphic water which may be expelled up fracture zones and thrust planes are similar to the mass of the present day ice caps. If thick carbonate sequences are involved, CO_2 release could perturb the atmosphere. A particularly interesting situation can occur if large salt basins are involved, even ocean salinity could be influenced (we tend to forget the frequency and scale of large continental salt deposits). In a collision event of this scale a vast perturbation in the volatile element flux, from H_2O to salt, hydrocarbons and even elements such as Hg, As etc., is likely. It is also likely that the present rise of the $^{87}Sr/^{86}Sr$ ratio of the oceans is related to enhanced weathering of evolved continental crust at high elevations (Burke et al., 1982).

It is clear that a collision event of this magnitude will change the global environment by altering global wind and ocean current patterns. But there may be even more subtle and fluctuating influences on global ocean chemistry. Such processes are not quantitatively understood but the record of change must exist in ocean sediments.

On a smaller scale the same phenomena may occur on large scale strike slip faults when these form plate boundaries. Thus the present models of structure on the great Alpine Fault of New Zealand show major regions of override with thick crust (Allis, 1981). The strike slip process requires fluids for lubrication and the override processes will produce the necessary fluids.

As Oliver (1986) has suggested, when major thrusts occur, there must be a huge "squeegie" effect ahead of all overthickening tectonics. As the load moves foreward (e.g. Tibet over India), a vast front of fluid expulsion must advance before the thrusts. Fluids will be typical pore fluids, zeolite facies fluids and salt and hydrocarbons if appropriate rocks are present. Thus there could be fluid pulses of highly different geochemistry as a thrust develops. For a thrust front of Himalayan scale (3 000 km) moving at 10 cm a^{-1}, the fluid expulsion rate could attain 0.5 km^3 a^{-1}. If this fluid is rich in hydrocarbons or salt, local influences could be dramatic. It is also unlikely that the thrust motions will be steady state.

Hot Spots

In a sense, hot spots reflect random thermal noise to the large convectional structures of plate tectonics (Turcotte and Oxburgh, 1978). Inspection of any global map, particularly that for the ocean basins, indicates that the areas of crust influenced by hot spots is non trivial, well over one hundred occur across the globe. As shown in Turcotte and Oxburgh, a deep mantle plume leading to a hot spot may influence the thermal structure of the lithosphere over areas of the order of 100,000 km^2. If this is multiplied by the number (say 100), the global area influenced approaches 10 million km^2, 7 % of the surface. The impact of hot spots in fluid circulation is quite unexplained and unquantified.

But one thing is certain, the volcanism is highly non-steady state. For example for the well documented Hawaiian volcano of Kilauea in the period 1959–60, and over a few days, more than 0.1 km^3 of lava was erupted (Press and Siever, 1986). In 1950, Mauna Loa produced 0.5 km^3 of lava (Macdonald et al., 1983). While the total hot spot magma volumes are much smaller than for the ridge systems, they may drive very significant local variation. Water cooling processes associated with hot spots are little understood.

Weathering

The process which is generally considered to dominate the mineral nutrient supply to the biosphere is that of particle and solute transport by continental runoff. Clearly on a long term basis this process is not steady state. The average elevation of the continents, which must play a role in climate patterns, and the amount of material transported, and the type of material transported, are not constant. Changes in average elevation over time and the total runoff is one factor related to changing $^{87}Sr/^{86}Sr$ patterns in ocean sediments or changes in the ratio of runoff/hydrothermal fluxes. The general nature of weathering processes of fluxes is well summarized in the recent work of Berner and Berner (1987).

Understanding change in weathering transport phenomena clearly calls on an understanding of global climate and global geomorphology and surface geochemistry. One of the great tasks of the IGBP will be to look for the recent record of fluctuations in these processes (dust in ice cores, etc., growth patterns in tree rings and the like). The recent El Nino event (Oceanus, *27,* 1984 and *29,* 1986) where for parts of the Pacific Ocean temperatures rose 4°C with far-reaching global consequences, reminds us of the sensitivity of our climate systems.

The Ancient Earth

Above I have discussed our knowledge or lack of knowledge of major chemical fluxes which influence the biosphere. When we move to the ancient earth our knowledge clearly is less precise but certain features stand out:

(a) Tectonics were very Rambergian! Vertical hot spot systems appear to dominate.
(b) Given greater heat production all the fluxes associated with volcanism must have been more extreme.
(c) As the Archean world was largely submarine, the world would have been hydrothermally dominated. Is it this "igneous-hydrothermal" world, with major fluctuations, lack of great ocean basins, that led to the great time delay in the development of complex species which demanded environmental tranquility?

Epilogue

As our environment moves to centre stage as our ultimate limiting resource, the next generation of

Table 1 Knowledge of Geochemical Fluxes Associated with Modern Tectonic Processes

	Steady State	Fluctuations
Ocean Ridge Phenomenon	moderate	almost zero
Ocean Floor Conveyer Belt	almost zero	" "
Subduction Zones – magmatism and metamorphism	poor	" "
Collision Zones – Faults	almost zero	" "
Sedimentary Basins	poor	" "
Hot Spots, Intra-plate processes	almost zero	poor
Surface Run-off	good	moderate

(No excellent grades have been given!)

earth scientists will face demanding challenges. We will be expected to quantify some of the processes I have discussed and because natural systems are complex, quantification is difficult. Being a university person, in Table 1, I have attempted to grade our state of knowledge and there is no case for which I can give an A+. But, for the first time, we have the tools to do the job. We can see, can monitor, on all appropriate scales using satellites, mass spectrometers, ion probes, etc.

During my brief visit to Uppsala and discussions with young earth scientists, I noticed their concerns with jobs and their futures. I am confident that they will be needed as never before – but the work done will be even more exciting as human domination of this planet moves to potentially catastrophic scales.

And finally, it was a great pleasure to contribute to this symposium in honour of Hans Ramberg. I can say with great truth and sincerity, that if I was to list ten teachers and scientists who have had great influence on my thinking, Hans would be there!

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