The water inventory of the Earth: fluids and tectonics

W.S. FYFE

Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada N6A 5B7

Abstract: As the human population continues to expand, to approach ten billion, there will be an increasing demand upon all Earth's resources. Of particular importance will be resources related to energy, soil and water, all of which involve geofluids. Problems associated with waste disposal also involve systems for protecting near-surface water quality. There is an urgent need to quantify the fluid inventory and fluid dynamics of the near surface, while understanding volatiles and their deep recycling is fundamental to our understanding of the major dynamic processes of the Earth.

Over the past century, the growth of human population (now almost 100 million per year), supported by diverse and complex technologies, and increasing expectations of quality of life, have placed vast new demands on Earth resources, which come mainly from the atmosphere, hydrosphere, soil and the top few kilometres of the solid crust. At this time, we are concerned with the need for careful management of our fossil carbon fuel resources from which we derive most of our energy and our usable water resources, which, in many nations, are approaching limits on the local scale. There is little doubt that oil–gas (and coal) will eventually be replaced by other energy sources, such as solar, geothermal and biomass sources. However a limiting resource for human occupation of Earth may well be water. There is an urgent need for the best possible inventories of all such resources, and a growing need to integrate the knowledge from all involved with the study of geofluids.

It was, perhaps, with the development of observations from space that we acquired a new sense of the limits and fragility of our wet planet. Studies of crust and hydrosphere history have also revealed that, unlike our nearest planetary neighbours, for about 4 billion years of recorded history, the Earth has always had a massive hydrosphere which has never boiled or totally frozen (Broecker 1985). Earth has some remarkable environmental buffer systems, which we still do not adequately understand. We also know that micro-organisms have been present for essentially all of our recorded history, and new studies (Schopf 1992) suggest that photosynthetic organisms may have been present much earlier than has been suggested by other workers. The outer surface and the top, porous–permeable layers of Earth are wet, and the recent search for micro-organisms at depth (stimulated by consideration of deep biocorrosion of nuclear waste systems), indicates that rocks may well host life at all places where temperatures do not exceed 100°C (Pederson 1993).

Studies of surface heat-flow patterns (for example, the spectacular new results from the German deep drilling, KTB) clearly show that, in the outer layers of Earth, fluids transport a substantial amount of heat out of the crust. The work of Straus & Schubert (1977) showed that the adiabatic gradient for fluid convection in a porous medium is almost always exceed in crustal situations. Studies of fluid convection through the oceanic crust, oceanic heat flow studies and the famous hot and cold discharge systems have shown that the sea floor crust is water-cooled, with something like half the thermal energy removed by fluid convection (Fyfe & Lonsdale 1981; Boulègne & Pflumio 1992).

Another growing world problem, which has focused our attention on deep and near surface fluids and their motions, is that of disposal of wastes of all types (urban, chemical, agricultural, nuclear . . .), and the scale of the problems which will be associated with a human population of 10 billion is vast. In most cases, the available technologies are not adequate.

The inventory

In general, we have only a moderate knowledge of the global inventory of water-rich fluids. Most accessible, the oceans and ground water are the most massive (Berner & Berner 1987). Of much smaller mass is water in the ice caps (which we must leave alone!) and surface waters in rivers and lakes. There is a massive quantity of water

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(similar to the ocean mass), contained in the hydrous mineral phases of the crust. While the inventory of volatiles fixed in the crust (H_2O, CO_2, N compounds, halogen compounds) are often not well-quantified, we know that change in the P–T conditions of their environment may lead to their evolution or fixation, processes which often lead to chemical transport related to formation of mineral resources. The rock mechanics of the crust would be very different on a planet without water (Fyfe *et al.* 1978). However, below the accessible crust, the inventory of volatiles in the deep Earth, mantle and core, is very uncertain. Thompson (1992) has recently reviewed the situation of water in the mantle. There are many ways in which water and other volatiles may be held in the mantle. Thus Fyfe (1970) discusses the substitution of SiO_4^{4-} by $(OH)_4^{4-}$ at high pressures and possible tetrahedral CO_4^{4-}, Pawley *et al.* (1993) discuss hydrogen in stishovite and Schrauder & Navon (1993) report solid carbon dioxide in diamond. But, while there is evidence that the core must contain some elements of low atomic number, the candidates (O, H, C, etc.), are less certain. Anderson (1993) has recently reviewed the problem of helium isotopes in deep crustal systems. He proposed that recycling from the surface from solar inputs may be more important than deep primordial sources (see also Fyfe 1987).

The global water cycle

Most discussions of the global water cycle are restricted to consideration of atmosphere–biosphere–hydrosphere interactions within the top few kilometres of the planet. Certainly, in terms of usable water for humans, these systems dominate our fluid resources. The global state of water resources has recently been reviewed by Postal (1992). But, if we broaden our interests to all geochemical fluxes related to fluid motions and hydrosphere evolution, and particularly the flux of bio-essential elements (Mn, Fe, Co, Cu, Ni, Zn, etc.) into the oceans, it is necessary to consider much deeper interactions (see Gillet 1993). If we wish to quantify the total evolution of the hydrosphere and all volatile systems, over geologic time, the deep systems must be considered. All phenomena which involve mantle convection, and the magmatic-tectonic-metamorphic expressions of such convection (plate tectonics) result in volatile transport.

Rising magma convection cells

We are increasingly aware that the nature of the surface of our planet is largely controlled by heat-mass transfer in the mantle, even down to the core–mantle boundary, and by erosional processes involving surface atmosphere–hydrosphere–biosphere interactions. The major sites of rising mantle convection cells are the great ocean ridge systems, where new basaltic crust is formed. It is also recognized that the same processes, but certainly with different spacing and higher intensity, operated in the ancient crust (see Kroner & Lager 1992; Fyfe 1974).

The water cooling processes which transfer almost half the energy from the ridge systems were first modeled by Lister (1977) and Davis & Lister (1977), whose general ideas have been well confirmed by a host of later direct observations. When magmas cool, they contract, and zones of high porosity and permeability must be common. Boulègne & Pflumio (1992) report a bulk porosity of 15–20% in ocean crust, and a mean hydrothermal flux from the ridges of about 40 $km^3\ a^{-1}$ and, for the overall ocean floor flux, 148 $km^3\ a^{-1}$. Given that the ocean mass is 1.4×10^{21} kg, this implies recycling of the entire ocean mass through the sea floor systems in about 10 million years; a massive exchange process. The discharged fluids (hot or warm) are enriched in many species (CO_2, CH_4, H_2S, H_2, SiO_2, Li, Mn, Fe, Cu, Zn, etc.), and this process makes a major contribution to the geochemistry of ocean water, sediments, and to the nutrient fluxes for the marine biomass. In addition, many of the great sulphide ore deposits with Cu, Zn (Ag, Au) are related to such processes over geological time.

A process of great significance to the global water inventory is the hydration of the seafloor crust that must accompany the cooling process. Altered seafloor basalts are highly hydrated, the limiting case being the transformation of peridotites to serpentinites (see MacDonald & Fyfe 1985). While the ridge processes are intense, slow convective cooling occurs over the entire ocean floor regions, and the early ideas of Hess (Fowler 1990) on massive serpentinization appear confirmed. The total mass of water contained in the ocean crust is similar to that in the ocean and, in addition, large quantities of CO_2, ammonium and halogen compounds must be present, but this inventory is not well known (Fyfe & Lonsdale 1981).

The hydrothermal processes associated with hot spot phenomena, and with the great continental flood basalts are less well studied. Of the present Earth's surface, almost 7% has been influenced by recent hot spot events (Fyfe 1992a). When the mass of some flood basalt events is considered, it even seems possible that cooling processes could perturb atmospheric oxygen (Fyfe 1990).

Subduction and fluids: subduction-induced mantle convection

There is very little ocean floor ophiolitic crust older than 200 million years. 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, etc.) and the gabbro–peridotite basement has been partially converted to amphibolite–serpentinite before subduction (Fyfe 1992b).

In the last few years, we have also come to recognize that pelagic sediments may be subducted on a scale of cubic kilometres per year. This concept, originally proposed by Gilluly (1971), once strongly opposed by those involved with isotope systematics, has now become respectable because of the direct observation of trenches and the structure of lithosphere near trenches. Thus, Hilde & Uyeda (1983) and Uyeda (1983) and the more recent Kaiko Project (Lallemand *et al.* 1986; Le Pichon 1986) 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 structure, tectonic erosion of the overplate occurs: Japan is being tectonically eroded and underthrusted. Such studies clearly show that initially light materials which are tectonically trapped may move towards the mantle (Lallemand & Malavieille 1992). It is of note that there is little evidence for sediment subduction in the case of the Northern Cascadia subduction zone (Davis & Hyndman 1989).

Consideration of volatiles shows that, for species like H_2O and CO_2, the recycling of the major reservoirs occurs with time constants of the order of a billion years, at the present rate of subduction. The Earth has 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 adsorb gases. Thus if a cooling Earth continues to convect, the ocean volume might be expected to diminish. Is this what has happened on Mars (Carr 1987)?

Processes involved in the return flow of volatiles are complex. At the initial stages of thrusting, pore fluids are literally squeezed out and pass up the thrust structures, reducing friction on the thrusts (Anderson 1981). Exotic fauna, originally characteristic of ridge vents, have now been found in deep trenches, but the fluids are cold, and would 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. There are 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 provide evidence for fluid flow transporting hydrocarbons, Mn–Fe–Ag, and related species. Recently, ODP Leg 110 Scientific Party (1987) reported gases including methane being produced, presumably by the reprocessing of subducted organic debris. Lewis *et al.* (1988) have described the thermal influences of slab dewatering.

Once the preliminary compression stage has passed, metamorphic processes will dominate, eventually leading to the formation of eclogites from basalts; kyanite and garnet-bearing rocks from pelagic sediments, and even kyanite–coesite–pyrope rocks (Chopin 1984). At this stage, fluids may hydrofracture their way to the surface along faults. Some fluid may be carried to very great depths in minerals like phlogopite, a natural product of the 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 and 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 forms the mountain chains of the volcanic areas of Andean type. In a general way, every gram of fluid introduced will probably lead to something like 100–1000 times the mass of volcanic rock. The injected fluids have led to a process which drains energy and mass out of the overlying mantle wedge.

Studies of heat flow and electrical conductivity across subduction zones show the scale of this energy transfer process, catalysed 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, an array of fluid-mass-energy transfer processes occur (see Rice 1985; Fyfe 1987):

(i) basaltic andesite rises, extrudes, intrudes and underplates continental crust;
(ii) the crust melts, producing granitic plutons and acid volcanics;
(iii) the basal crust undergoes progressive metamorphism;
(iv) magmas mix, and complex hybrids are produced near the Moho region;
(v) ultra-high-temperature gases are injected into the base of the crust from the andesite magmas and assimilated dense crustal components, which founder in the underplate magmas;
(vi) high-level plutons and volcanics are water-cooled by deep groundwaters in the high heat flow near-surface environments;
(vii) 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 are impressive. We are not at a stage to quantify such fluxes, but we can make some order of magnitude calculations. For example, if we consider the western Americas, where the plutonic–volcanic terrains 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 year 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 20% of that of ocean ridges. In this case, there is no question that the fluxes of fluids, just as the volcanic eruptions, will not be steady state, as plutons rise and Tamboras erupt. There will be large spatial variation of fluid flux, fluctuations which may influence the global temperature for years, or even cause mass extinctions (Officer *et al.* 1987; Grove 1988). It is the knowledge of these events, their intensity and frequency distribution which are needed for the IGBP.

Recently, we have become interested in the problem of dewatering of slabs, and the possibility of fluidized bed injection associated with such processes. Le Pichon *et al.* (oral comm. 1990) showed recent observations of the large (30 km^3) warm mud volcanoes being extruded from the Barbados accretionary complex. Barriga *et al.* (1992) have described a number of tectonic regions where such processes may occur, and A. Ribeiro has named the process 'eduction', where fluidized beds are injected from mantle depths. One of the common consequences of thrusting is the rapid burial of fluid-rich rocks, including water-saturated sediments and metamorphic rocks with variable water contents. Physico-chemical processes that range from compaction to prograde metamorphism will tend to produce less hydrated rocks plus water. Hydraulic fracturing is a common mechanism when impermeable rocks cap fluid-rich zones, and fast and concentrated fluid flow may generate vein mineral deposits (Fyfe & Kerrich 1985). Tectonically-induced fluid generation, at all lithospheric levels, can lead to rock fluidization and injection. These processes are well known by sedimentologists and neotectonics specialists, as they are responsible for intrusive sediments and seismically-induced mud and sand volcanoes. This process is suggested to explain some of the blueschist-eclogite-serpentine associations of California and even, perhaps, the coesite rocks of the Italian Alps (see Barriga *et al.* 1992; Maekawa *et al.* 1993).

Continental collisions and associated strike-slip faults

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 & 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 currently being thrust under Asia (Allegre *et al.* 1984; Barazangi & Ni 1982). In this region, a section of crust, 1500×3000 km, has been doubled in thickness. Present seismic results provide 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 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.

In Fyfe (1986) some aspects of the problem of fluid fluxes when crust on this scale is heated and compressed due to the thrusting and shortening processes is considered. Essentially, the underthrust rocks will be dehydrated, lose CO_2 and other volatiles, and eventually melt. The young plutons of Himalayas show such 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 may be similar to the mass of the present day ice caps. If thick carbonate sequences are involved, CO_2 release could perturb the atmosphere and its greenhouse effect. A particularly interesting situation can occur if large salt basins are involved in which 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 and 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 collisional 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, similar phenomena may occur on regional strike-slip faults, when these form plate boundaries. Thus, the present models of structure on the great Alpine Fault of New Zealand shows major regions of over-ride 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 forward (e.g. Tibet over India), a vast front of fluid expulsion must advance before the thrusts. Fluids would 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 (3000 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 would be steady state.

It is interesting to note that the crustal granites formed during these thickening processes may also lead to the formation of large deep aquifers. Thus, the rising plutons and dykes described by Le Fort *et al.* (1987) and Thakur (1987) may act as excellent aquifers once they cool, crystallize, and contract and thus direct fluid flow. We have described these phenomena in Saudi Arabia, where acid dykes coming off plutons are almost totally converted to epidote by flooding with descending meteoric fluids (Marzouki *et al.* 1979). Plutons will cause local fracturing as is well shown by Drummond *et al.* (1988) in their description of granodiorites being converted to tonalites by salt-water flooding.

The impact of high elevations on fluid flows

Subduction and collision processes produce extensive belts of high elevation on our planet. These are normally associated with vast fault and thrust structures, and discontinuities associated with magma activity, plutonism and dyke emplacement. Deep gravity driven flow in such systems is now becoming well documented (e.g. Nesbitt & Muehlenbachs 1989; Rye & Bradbury 1988). The scale of this giant hydrogeological process, which may float frontal thrusts, can obviously be significant (Fyfe 1986).

High elevations also drive rapid erosion and ocean sedimentation. As Milliman & Meade (1983) estimate, present continental erosion moves about 1.7×10^{16} g a^{-1}. Given the mass of continental crust of 1.6×10^{25} g, erosion could reprocess all crust in a billion years. A metre of rain per year could dissolve the Himalayas to sea level in 100 million years!

Very thick (5–10 km) accumulation of sediment are common near many of the great delta systems of the world (Burk & Drake 1974). For example, such sediment piles are common around the entire margin of Brazil, the Amazon delta regions, and the great Bengal Fan system. For example, what happens when ocean floor crust, with a thick deep serpentine layer, is loaded with over 10 km of sediment? At thermal equilibration, the base of the now 20 km section could reach 600°C. The peridotites will deserpentinize, and hot, highly reduced fluids will rise, transporting a range of metals. Faulting in such regions is ubiquitous. The chemistry of systems where reduced hot fluids interact with organic-rich cover sediments along fault systems must be highly anomalous. Hot seeps along such sediment sections are common (Grassle 1985).

There is a great need for submersible observations in these systems. There is an obvious final question: does such loading and metamorphism of the oceanic basement provide the guide for future sites of subduction?

Concluding statement

As understanding environmental change, and providing human resources, become great challenges for modern Earth science, the necessity to quantify the total global water inventory, and the inventory of other volatiles, is essential. We must better understand the surface bio-nutrient cycles, and the impact of water use on climate changes. For example, we need models of climate impact when all rivers are dammed and evaporation and evapotranspiration replaces runoff. Water, water quality, and life are inextricably connected.

An intriguing question is whether the mass of the oceans has been constant over geological time? If water is being subducted in large quantities, and if the planet is cooling, will the mantle slowly absorb this volatile? Or, as Frank (1990) has suggested (a not popular view), do we receive constant additions of water via small comets. It is time we visited Mars, and studied a planet where Gaia has failed.

I would like to dedicate this brief review to Geoffrey Brown of the Open University, who lost his life while in Columbia on a volcano watch. Geoff, a wonderful student and colleague, worked with me in Manchester, to do some of the classic work on the melting of dry metamorphic rocks.

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