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Water Gaia: 3.5 Thousand Million Years of Wetness on Planet Earth

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Without continuous flows of carbon, hydrogen, nitrogen, sulfur, phosphorus, and other essential elements, primarily as compounds in watery solution, no known life form continues to thrive. The purpose of life, much like other thermodynamic systems open to the flow of matter and energy, is to dissipate chemical and thermal gradients (differences across distances) as elegantly detailed by Schneider and Sagan (2006). The assurance of energy and matter flows in appropriate amounts, rates, and useable chemical form is a sine qua non of the living state. All living beings tend to overgrow their bounds and are invariably limited by appropriate availability of energy and matter. The many limitations to life's intrinsic capacity for growth and diversification is the process Charles Darwin (1809–1882) recognized as "natural selection."

Our Thesis: Life Retained Planetary Water

We champion the poorly developed Gaian view that life has vigorously helped maintain abundant water on the Earth's surface over the last three and a half thousand million years. We defend the idea that life's populations persist and continue to expand on Earth not because a "lucky accident" has situated our moist planet at an optimal distance from the sun; rather communities of living organisms have actively maintained wet local surroundings. The result has been the retention of moist habitability over geological time. We suggest that without life's involvement in complex geological, atmospheric, and metabolic processes, Earth would long ago have lost its water, becoming a dry and barren world much like Mars and Venus. Theoretical interpolation of a lifeless planet Earth between that of Mars and Venus shows that our planet now would be a dry, carbon dioxide-rich world with a temperature primarily determined by steady increase in solar luminosity (Lovelock 2000).

In recognition that independence from the biosphere is death and that life is a powerful geological force, V. I. Vernadsky (1863–1945) explained that all life is connected through Earth's fluid phase (Sagan 2007). This comprises the atmosphere (air, including that in soil, caves, and dissolved in water) and the hydrosphere (oceans, lakes, rivers, streams, springs, etc.). Early in the twentieth century, Harvard University scholar L. J. Henderson (1958) presented a persuasive but nearly forgotten argument that life would not exist on this planet without the water that sustains and supports it. He reviewed the salient features of life's "universal solvent system" in his chapter dedicated to the physics and chemistry of water. The thermal properties of water (its specific heat, latent heat, thermal conductivity, expansion before freezing) and its action upon other substances (as a solvent, and by virtue of its ionization and surface tension properties) are unique among solvents and are utterly required by the physiological and ecological systems of life on our planet. The eclipse of Henderson's virtually unknown work may be attributable to the tendency in evolutionary biology literature to overlook environmental chemistry in general and, in this case, the chemistry and biochemical involvements of water in particular. What is remarkable is the fact that Henderson's analysis is not at all obsolete: we find it germane to any Gaian analysis of the water anomaly on Earth relative to the other inner planets.

In the spirit of Ian McHarg's remarks we recommend that a modern detailed reappraisal of Henderson's concept of the "fitness of the environment" be undertaken (Margulis and Lovelock 2007). McHarg adds Henderson's concept of the environmental importance of water to Darwin's work on evolution in his search for understanding the creative survival of the living. For McHarg, there is a criterion by which living (and other) processes can be evaluated for their creativity (and destruction). He calls it "creative fitting in health," contrasting it with "reductive misfit revealed in pathology" (McHarg 2006). He points out that whereas Darwin emphasized that the organism "is fit for the environment," Henderson (whom McHarg admired as much as Darwin) maintained that "the actual environment, the actual world constitutes the fittest possible abode for life." McHarg unites Darwin's and Henderson's viewpoints when he concludes that "there is a requirement for any system—whether subcellular, cell, tissue, organism, individual, family, institution—to find the most fit of all environments and to adapt both the environment and the system itself" (2006). Survivors, on McHarg's analysis, adapt by actively and continuously changing their environment to accomplish fitting in a thermodynamically creative way. The sum of active and incessant local environmental alteration, in this case by the movement of water and matter with which life interacts, we recognize as "Water Gaia."

We expand the insights of our predecessors by elucidating the tight correlations between life and water. Life, aptly called *animated water* by Vernadsky and colleagues, is mandated by the presence and properties of water. Life ensures its own continuity by retaining and interacting with liquid water on our planet's surface.

Water on Venus, Earth, and Mars

Scientists concur that all three inner planets Venus, Earth, and Mars, prior to the Archean eon over 3,500 million years ago, began with meteoric and probably subsurface water in abundance. Geomorphological observations of erosion by water, steady bombardment by water-rich comets, asteroids, and meteorites, along with other evidence attest to copious quantities of early water on Earth (Robert 2001). Further evidence for the presence of surface liquid water on the Hadean Earth comes from analyses of Hadean zircons (Wilde et al. 2001). Water must have out-gassed from ancient tectonic activity, as all these planets and their moons were bombarded by the water-rich bolides of the early solar system. The surface of Venus, closer to the Sun, and that of Mars, beyond Earth's orbit, reveal riverine, lacustrine, or marine features that suggest vast quantities of open water flowed on pristine active lithospheres of our early "sister planets." Recent analysis of phyllosilicates from Mars suggest that water-rich environments conducive to life were widespread during its earliest geological history (Mustard et al. 2008). Whereas much, perhaps even an ocean's-worth or more of water, was lost from both our neighbors, the early Earth retained its primordially wet conditions.

Our hypothesis that water retention is a Gaian phenomenon is testable. Venus probably lost its water because its proximity to the Sun meant that even early in the history of the solar system it would have received 40 percent more solar radiation than today's Earth. This high radiative flux would have evaporated huge amounts of water vapor into the atmosphere of Venus that set in train catastrophic positive feedback on heating due to the powerful greenhouse effect of water vapor; this is known as the runaway greenhouse. Abundant water vapor in the stratosphere would have been photo-dissociated by ultraviolet radiation leading to massive quantities of hydrogen loss to space (Kump et al. 2004).

Although Mars receives some 43 percent less solar radiation than the Earth, it likely once had sufficient greenhouse gasses in its atmosphere to generate temperatures high enough to liquefy water on its surface. Carbon stripped out into carbonate rocks would not have been returned to the atmosphere because of the absence or early demise of plate tectonics on the planet (Kump et al. 2004). Some of this water would then have evaporated into the thin Martian atmosphere, followed by photo-dissociation of water vapor and hydrogen loss to space. The extent to which water ice exists in the Martian north pole, the south pole, or trapped under large areas of the Martian surface is the subject of vigorous current research.

By comparison to the 10 centimeters, or fewer, precipitable water measured today on dry and barren Mars and Venus, the Earth is shockingly wet. More than 10^4 times the quantity of water expected on an Earth without life is still here. From reconstruction of its past history scientists conclude that throughout the geological eons our planet has been watery. Today water is found mostly in its liquid phase within the global oceans which cover some 70 percent of our planet's surface. Quantitatively small but climatically crucial amounts of water also exist in the gas phase as clouds and water vapor. In the solid phase as sea and glacial ice, frost, hailstones, and snow, water augments the Earth's albedo (i.e., greater reflectivity of solar energy to space).

The movements of water between these and other reservoirs constitutes the hydrological cycle—"the largest movement of any substance on Earth" (Cahine 1992). The hydrological cycle has massive effects on climate because of the ways water determines the exchange of heat and moisture between the atmosphere and the planet's surface. Contemporary organisms actively configure the Earth's climate into a state suitable for water (and thus for the perpetuation of life) by influencing the hydrological cycle through the process of evapotranspiration in trees and plants. Evapotranspiration involves massive movements of water, against gravity, from the entire root zone (rhizosphere) up a few to over 30 meters into the air. The flow of water up through tree trunks and plant stems is powered by solar energy. Water is released as vapor through the stomata—the active pores that open and close on the undersides of leaves. Organisms also influence the hydrological cycle in important ways by retaining water in soils and by emitting a variety of cloud-seeding chemicals over land and ocean (Hayden 1998; Bonan 2002). Furthermore bacteria such as *Pseudomonas syringae* that are commonly swept up into clouds in large numbers exert a massive influence on the hydrological cycle. Proteins on the outer surfaces of these bacteria facilitate the formation of ice crystals that eventually return significant quantities of water to the Earth's surface as rain and snow (Christner et al. 2008).

Water and Gaia's Thirst

Earth's abundant water in comparison to Mars and Venus lead us to a Gaian analysis of this "water anomaly." Scientists often assume that environments are physicochemical givens to which organisms must adapt in order to survive. But unlike the prevalent assumption that life passively adapts to its environment, Gaia researchers propose that life may contribute to active regulation of biologically relevant aspects of Earth's surface within habitable limits (Lovelock 1972, 2000, 2005; Lovelock and Margulis 1974). This regulation is posited to emerge from tightly coordinated feedback subsystems that intrinsically and continuously embed the biota in its abiotic surroundings (Lovelock 2005; Lenton 1998). In a masterful analysis of the Earth's physicochemical history, NASA geoscientist Paul Lowman and astronaut Neil Armstrong show that during the Archean the major influences were the same as those prevailing on Mars and Venus. But from the Proterozoic eon (2,500 million years ago) until the present day, Gaia's unique signature is writ large: Earth became the Gaian planet. Paucity of water, failure to detect granite, vastly slower geochemical cycles of elements such as oxygen, carbon, and phosphorus, and much other evidence testifies to the fact that neither Venus nor Mars are Gaian (Lowman and Armstrong 2002). Lowman and Currier (2009) provide a short accessible summary explanation that connects Gaia theory with the uniqueness of water-dependent lateral plate tectonic movement on Earth.

Life's sensitivity to water quantity and saltiness seems to be the most elemental of all senses. Thirst and the knowledge of desiccation level is apparently universal. The universality of water detection and the response of living cells to this ubiquitous solvent, that some equate with life itself, lies apparently in the properties of the lipid-protein membrane, the bilayer semipermeable external boundary of all cells. When breached and membrane integrity is lost, the autopoietic entity known as the cell, whether a small bacterial cell or a large egg, dies. The ability for material and energy flow is irretrievably lost, as water leaks into the environment. This is what we call death. Self-maintenance and identity are replaced by an inert puddle of carbon-hydrogen-nitrogen compounds that immediately lose all signs of animation and become food for those who retain their membranes and, with them, the profound ability to sense water.

Life does indeed *adapt* itself and its environment as Henderson and McHarg insisted. Yet, when used in a way that implies a passivity of life and that ignores emergent synergies between our planet's physics, chemistry, and biology, the term adaptation can hinder our understanding of the Earth as a complex system.[1] We prefer statements of passive adaptation of organisms to their surroundings to be replaced by a conception of life's "active fitting." Gaia emerges directly from this active fitting, writ large, since all organisms impact each other and their surroundings through the exchange of heat, light, liquids, and gases, as well as a huge array of metals, salts, sugars, and myriad other chemical compounds (usually dissolved in water).

With regard to the hydrosphere, Gaia theory proposes a prospective research program: that organisms have actively retained water by thwarting its tendency to be lost. Without the involvement of life's complex and often metabolic innovations,[2] Earth would long ago also have lost its water to space by atmospheric photolysis and hydrogen escape. We propose that life does not regulate the amount of water on the planet through a specific feedback process, but rather that it greatly reduces the rate of water loss by metabolic hydrogen capture and by regulation of relevant variables such as planetary temperature.

Here we explore the major abiotic processes that drive the loss of water from our planet, including the photodissociation of water and methane by solar UV radiation at the top of the troposphere and the chemical reactions in seafloor basaltic rocks that strip out oxygen atoms from water molecules. We then go on to outline the various ways in which life prevents such processes from drying out the planet. We include a discussion of how, by contributing to the regulation of the planetary carbon cycle over geological time, organisms have kept the planetary temperature suitable for the existence liquid water despite an ever-brightening sun and ongoing outgassing of carbon dioxide from volcanic activity.

Modes of Water Retention by Life

Any chemical or physical process that liberates hydrogen from water molecules may, in principle, lead to water loss from a planet. Hydrogen (H_2) gas has a mass so light that it reaches escape velocity from the Earth's gravitational field.

We summarize some chemical and biological processes that both liberate and capture free hydrogen over geological time in table 4.1. They exemplify our habitation of an Earth with abundant water and serve as a guide to further detailed investigation. Geochemical processes that result in the liberation of molecular hydrogen began at least in the Archean and have continued until the present. They occur in basalt, the major rock type of the world ocean bottom. Basalt contains ferrous oxide (FeO), which, in the presence of carbon dioxide, strips out oxygen atoms from seawater. The net effect is to remove oxygen and place it in solid form in carbonate rock, a process that liberates hydrogen gas (reaction 1, Lovelock 2005). Hydrogen liberation via loss to space may entirely desiccate an inner planet within two billion years (Lovelock 2005). Bacterial metabolic pathways also liberate hydrogen (e.g., anoxygenic photosynthesis, anoxic decomposition of dead organic matter [fermentation, reaction 2], anaerobic glycolysis, and many others release hydrogen on geologically instant time scales).

The Earth has evaded desiccation by many means that inspire further investigation. Since Archean times bacterial communities have released oxygen into the sediments, water, and air by oxygenic photosynthetic processes that split water (reaction 3), a reaction that to this day is limited to only three immensely talented inclusive taxa. In a purely abiological process, hydrogen gas (e.g., that released from reaction 1) combines with oxygen from photosynthesis, thereby regenerating water (reaction 4). Oxygenic photosynthesis (reaction 3) also captures and retains hydrogen extracted from water for carbon dioxide reduction, thereby renewing organic matter in the making of food, body parts, and energy storage molecules such as sugar and starch. New avenues of oxygen liberation were opened up during the Proterozoic eon (some 1,200 million years ago) by photosynthetic algal protoctists, as well as in the lower Phanerozoic eon (about 450 million years ago) by the first land plants. All these oxygenic photosynthetic processes continue today unabated. Even anti-Gaia scientists admit that chlorophyll *a* photosynthesis produced the oxygen-rich atmosphere that permanently altered

Table 4.1
Selection of key biological and abiological processes that influence the retention of water on planet Earth

Reaction and domain in which it takes place	Reactants	Effect on Earth's water
(1) $2FeO + 3CO_2 + H_2O \rightarrow Fe_2(CO_3)_3 + H_2$ Abiological: geochemical	Ferrous oxide in sea floor basalt reacts with carbon dioxide and water	Desiccates the Earth by liberating free hydrogen
(2) $3CH_2O + H_2O \rightarrow CH_3COO^- + CO_2 + 2H_2 + H^+$ Biological: fermenting bacteria in anoxic environments	Organic matter and water	Desiccates the Earth by liberating free hydrogen
(3) $CO_2 + H_2O \rightarrow CH_2O + O_2$ Biological: oxygenic photosynthesis by bacteria, protoctists, and plants	Carbon dioxide and water reacted by photosynthesizers; organic matter and oxygen produced	Oxygen available for reaction with hydrogen, potentially reconstituting water
(4) $2H_2 + O_2 \rightarrow 2H_2O$ Abiological: atmospheric chemistry	Hydrogen and oxygen, producing water	Free oxygen from (3) reacts with free hydrogen, reconstituting water
(5) $S + H_2 \rightarrow H_2S$ Biological: bacterial reduction of elemental sulphur	Elemental sulphur and hydrogen	Sequesters hydrogen into hydrogen sulphide gas
(6) $2H_2S + O_2 \rightarrow 2S + 2H_2O$ Biological: aerobic chemautorophic bacteria	Hydrogen sulphide from reaction (5) with oxygen from reaction (3)	Reconstitutes water
(7) $CO_2 + 2H_2 \rightarrow CH_2O + H_2O$ Biological: anaerobic chemautorophic bacteria	Carbon dioxide and hydrogen	Organic matter produced, reconstituting water
(8) $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ Biological: anaerobic methanogenic bacteria	Carbon dioxide and hydrogen	Methane produced, reconstituting water

Source: Data from Smil (2003) and Lovelock (2005).

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Earth and its evolutionary course. Without these bacterial metabolic innovations, no animal would exist.

Another bacterial contribution to hydrogen capture comes from the activities of bacteria such as *Desulfovibrio* that live in ocean sediments in sulfur-rich habitats. *Desulfovibrio* and its many relatives liberate hydrogen sulfide gas (reaction 5) as they reduce elemental sulfur, thiosulfate, or the sulfate ion itself by "breathing." Water is reconstituted when hydrogen sulfide is oxidized by aerobic chemoautotrophic bacteria such as *Sulfolobus* or *Beggiatoa* that abide at oxygen-rich seawater/sediment, caves, sulfur springs, and other interfaces (reaction 6).

An important metabolic pathway in certain bacteria hardly seems possible, in principle. These bacteria reconstitute water by reacting molecular hydrogen with carbon dioxide under conditions where oxygen gas is absent (reaction 7). Known as anaerobic chemoautotrophy, in this process hydrogen is used to reduce carbon dioxide to organic matter, and water is thereby reconstituted. Also in regions without any oxygen gas, methanogenic bacteria remove carbon dioxide and react it with free hydrogen to produce methane and water (reaction 8). Reactions 7 and 8 both require anoxic habitats, such as marine, lacustrine, and riparian sediments, or the intestines of insects and mammals.

Water Loss via the Photodissociation of Methane

A physical process that is thought to have led to hydrogen escape during Earth's geological history is the photodissociation of water by ultraviolet radiation in the lower stratosphere. Yet relatively little hydrogen must have escaped via this route because of the "cold trap" in the tropopause (Catling et al. 2001). Since Archean times, water vapor molecules have frozen out in this region of very cold air and fallen back into the lower atmosphere before they could be photodissociated by stratospheric ultraviolet radiation. David Catling and his colleagues suggest that the photodissociation of methane provided the main exit route for hydrogen during the Archean eon, and hypothesize that abundant methane was the major greenhouse gas that counteracted the early lower solar luminosity. Methane's lower freezing point relative to water allowed it to transit into the stratosphere through the cold trap in gaseous form unaffected. There (much like the few water molecules that managed to reach the lower stratosphere above the cold trap) the methane was split by ultraviolet radiation, yielding molecular hydrogen that could escape to space and leaving carbon dioxide and oxygen in the atmosphere.

These reactions are simplified and summarized as (Catling et al. 2001)

$$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2 \rightarrow CO_2 + O_2 + 4H\ (\uparrow \text{space}),$$

which is reaction 9. In this scenario the methane came from the bacterial decomposition of organic material in which hydrogen from water was originally fixed by oxygenic photosynthesis (reaction 3). One could thus argue that methanogenic bacteria could have been responsible for life-threatening water loss during the Archean (David Schwartzman, personal communication). However, life as a whole may have prevented this eventuality in at least two ways. First of all, during the Archean, carbon dioxide released mostly by decomposing bacteria would have permitted hydrogen to accumulate in the lower atmosphere via a newly proposed hydrodynamic mechanism that slows down the rate of hydrogen loss except when carbon dioxide levels are very low (Stevenson et al. 2008). Then, in the Proterozoic, biogenic oxygen would have captured the hydrogen. Thus it seems that there might have been a rather dangerous period during the Archean when biogenic methane production could have accelerated water loss, but that this danger was avoided early on thanks to biotic carbon dioxide release, and later on when biogenic oxygen became sufficiently abundant to reconstitute water via reactions 4 and 10. Clearly, a synergy between robust photochemistry and sound biology is required to further explore this issue.

Reaction 9 may have led to the so-called Great Oxidation Event that took place between 2,400 and 1,800 million years ago during the Proterozoic. This event involved a relatively rapid transition to an oxidizing atmosphere, and may have ultimately produced the high levels of oxygen gas (ca. 20 percent) in today's atmosphere. The rise of atmospheric oxygen gas during the Proterozoic has been amply documented in the geological record, especially by worldwide deposits of banded iron formations, or BIFs (Cloud 1989). Apparently a relatively small increase in the burial rate of organic carbon may have triggered a nonlinear switch to a high oxygen atmosphere at that time (Goldblatt et al. 2006). The stratospheric ozone layer that resulted has significantly influenced the effectiveness of the cold trap to this day (Nisbet 1991).

Whatever led to the surplus of free oxygen gas in the Proterozoic, it is agreed that hydrogen loss via the photo-dissociation of methane would have declined significantly when oxygen became sufficiently abundant to oxidize methane to carbon dioxide and water via the reaction

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O,$$

which is reaction 10. As the Archean atmosphere probably contained a thousand times more methane than today's value of 6 to 7 parts per million, the rate of hydrogen loss must have been approximately three hundred times greater than at present (Catling et al. 2001). The modern biosphere's effectiveness at preventing hydrogen loss, and hence planetary desiccation, is illustrated by the very low rate of hydrogen loss to space. The Earth currently loses a mere 50 tonnes of hydrogen per day from an atmosphere with a total mass of around 50×10^{14} tonnes (Morton 2007: 182).

The Great Oxidation Event marked a shift from methane to carbon dioxide as the Earth's dominant greenhouse gas (Lovelock 2000). Other consequences for life and its effects on the planetary surface include the appearance of early eukaryotic cells and their obligate relation to oxygen respiration in symbiotic bacteria that became mitochondria (Margulis et al. 2006) and a Gaian redistribution of many chemical elements such as manganese, copper, phosphorus, lead, tin, and vanadium.

The metabolic versatility of bacteria permits oxidation of methane even in the absence of oxygen gas. Sulfate reducers, such as *Desulfovibrio* and some relatives, use oxygen in sulfate ions that are abundant in seawater to reconstitute water from methane:

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O,$$

which is reaction 11. Could these reactions (10 and 11) have produced water in sufficient quantity to increase the depth of the global ocean (S. Marashin, personal communication)?

Water and Earth's Temperature

Why has Earth retained both life and abundant liquid water since the Archean despite at least two strong external factors that have conspired to enhance the similarities between Mars, Venus, and Earth? One external factor is the increase of luminosity of the Sun (with an energy output 25 percent greater than it was 3,500 million years ago), and the second is the continual eruption of carbon dioxide from volcanoes over the same period. These and other observations lead us to conclude that global temperatures have been actively regulated within the range suitable for liquid water by the Earth as a whole system. That the behavior, metabolism, and physiology of organisms are essential to this regulation is a central tenet of Gaia theory (Lovelock 2000; Margulis and Lovelock 2007).

Much remains to be learned, but we can now state with some confidence that organisms help to regulate the Earth's temperature by manipulating the ratios of greenhouse gases in the atmosphere and by altering the planetary albedo (reflectivity), primarily by emitting cloud-seeding chemicals. Other effects on temperature and hence water retention by organisms involve the albedo of living beings themselves, such as the extensive cover of dark coniferous trees in the far northern latitudes that help to warm the modern Earth (Bonan 2002). Organisms can also change the amount of surface water directly exposed to evaporation: elephant bodies carve out ponds and thus expose subsurface water to the surface; exudates of microbial mat organisms directly retard evaporation; caves made by water flowing through limestone, or the conversion of limestone to gypsum, protect water flow beneath the rocks.

We suggest that liquid water would have left the Earth's surface long ago if organisms had not regulated global temperatures by these and other means. Continued volcanic activity that puts methane, water vapor, carbon dioxide, and other greenhouse gases in the atmosphere in the face of an ever-brightening sun would long ago have led the Earth into a Venus-like runaway feedback on global heating. On the other hand, too little carbon dioxide would have caused the oceans to freeze over, with the consequent albedo increase plunging the planet into a permanent frozen state via positive feedback (Ward and Brownlee 2000). A major way in which life contributes to the regulation of global temperature is through its involvement in the long-term carbon cycle in which calcium carbonate from the weathering of basaltic and granitic (silicate) rocks is deposited in the oceans (table 4.2, reactions 12 and 13).

On the land, reaction 12 is enhanced by organisms: roots and hydrophilic microbial chemical exudates physically fracture the rock and thereby increase its reactive surface area; microbial and plant root respiration increase carbon dioxide levels in the soil, and bioturbation of the soil increases the flow of water onto particles of rock, taking water into places it would not otherwise be able to access. This process, first proposed by Lovelock and Whitfield (1982) and now referred to as "biologically assisted silicate rock weathering," amplifies the purely chemical weathering rate between 10 to 1,000 times depending on

Table 4.2
Reactions in the long-term

Reaction
(12) $CaSiO_3 + 2CO_2 + 3H_2$ $Ca^{2+} + 2HCO_3^- + H_4SiO_4$
(13) $Ca^{2+} + 2HCO_3^- \rightarrow$ $CaCO_3 + H_2O + CO_2$
(14) $CaCO_3 + SiO_2 \rightarrow$ $CaSiO_3 + CO_2$

Source: Adapted from K

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Table 4.2
Reactions in the long-term carbon cycle

Reaction	Effect on Earth's temperature
(12) $CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4$	$CaSiO_3$ is wollastonite, a simple mineral representing the general chemical composition of all silicate rocks. Note that two carbon atoms are removed from the atmosphere for each calcium ion weathered out of the rock.
(13) $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + H_2O + CO_2$	Denotes the intracellular precipitation of calcium carbonate. Note that one carbon atom is released to the atmosphere for each calcium ion precipitated. The net effect of reactions 12 and 13 is thus to cool the Earth.
(14) $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$	Granite is regenerated, and carbon dioxide is liberated to the atmosphere via volcanoes, thereby warming the Earth.

Source: Adapted from Kump et al. (2004).

location (Schwartzman and Volk 1989); it is greatest where high temperatures combine with abundant rainfall.

Thus carbon that once resided in the atmosphere finds itself in calcium bicarbonate flushed by rivers and groundwater into the oceans where it is precipitated intracellularly as calcium carbonate by coccolithophorids (haptophyte algae) and foraminifera in their scales and exoskeletons (reaction 13). When these organisms die the calcium carbonate accumulates in ocean sediments. Their fate is lithification into chalk and other limestones. Huge quantities of carbon have been sequestered in this way over geological time—the stock of carbon in the contemporary calcium carbonate reservoir is 4×10^7 GtC, almost four orders of magnitude greater than the carbon in present-day fossil fuel reserves (Kump et al. 2004). Chalk and limestone also contain significant quantities of silica (from the silicic acid in reaction 12) that may be deposited as radiolarite (chert rock that come from remains of radiolarian skeletons), or diatom tests (shells) and glass sponge spicules (Lovelock 2005).

Such dynamics imply negative feedback with respect to the carbon cycle (Lenton 1998) and hence surface temperatures suitable for liquid water: if surface temperature increases (because of volcanic inputs of carbon dioxide to the atmosphere, together with an ever-brightening sun) so does rainfall. In a wetter and warmer world biologically assisted silicate rock weathering transfers more carbon from the atmosphere to calcium carbonate in the ocean, which cools the Earth, potentially down to a stable but lifeless frozen state. However, in a cooler and hence drier world this fate is avoided because the terrestrial biosphere rapidly becomes less effective at weathering silicate rocks, and so carbon dioxide accumulates in the atmosphere from volcanoes, thereby raising the global temperature (Lovelock 2005). An emergent property of this feedback has been the regulation of planetary temperature within limits suitable for life (and hence liquid water) over geological time.

The carbon dioxide that returns to the atmosphere via volcanoes is regenerated when silica-rich carbonate sediments are subducted into the mantle as the raised portions of descending slabs (plates) of the seafloor (reaction 14, table 4.2). Here, at high temperature and under immense pressure, the sediments metamorphose and produce carbon dioxide and fresh granitic material that floats on top of the denser mantle to become new continental land mass available to be weathered (Kump et al. 2004). Without such recycling of Earth's crustal materials, no terrestrial biota would exist to enhance silicate weathering.

Water and Plate Tectonics

The long-term carbon cycle thus cannot operate without volcanic activity, itself an integral component of the colossal processes of plate tectonics, with its mountain chains, subduction zones, and large granitic continents afloat on giant rafts of spreading seafloor basalt. These tectonic processes, which are essential for the maintenance of all organic life, cannot take place without huge quantities of liquid water.

Water infiltrates the laterally moving seafloor basalt, changing its chemical nature so that it is pliable enough to sink into the Earth's mantle when it collides with the edge of a continent at a subduction zone. Seafloor basalt becomes extensively hydrated at the mid-oceanic ridges. Here, magma chambers act as heat sources that drive local-scale convective systems that force hot seawater through fractures in the basalt. For it to be effective at hydration of seafloor basalt, the process requires an overlay of large amounts of water (Campbell and Taylor 1983). At subduction zones, water-rich slabs of seafloor basalt are carried deep into the mantle where the material melts to produce vast amounts of granitic magma that rises up to form the continents. This process adds to the granite generated by the metamorphism of silica-rich calcium carbonate sediments beneath subduction zones mentioned earlier. The volatility of limestone produces watery carbon dioxide–rich lubricant, which enhances the rates of plate tectonic activity. A vast amount of water has been required to generate the Earth's continents, 60 percent of which were almost certainly present since the beginning of the Proterozoic some 2.5 billion years ago (Taylor and McLennan 1995).

Without subduction, plate tectonics would stop because there would be no closure of the convective cycle that reaches down to the planet's outer core, in part driven by the decay of radioactive materials in the Earth's depths (Kump et al. 2004). Without plate tectonics, the return of carbon to the atmosphere would be severely curtailed or perhaps completely shut off. In tens of millions of years all the Earth's land masses would be removed by weathering, with no new granite to replace this loss. The long-term carbon cycle would cease, and the Earth would perhaps be plunged into a permanently frozen state (Ward and Brownlee 2000). We therefore propose an interesting and appropriately circular Gaian dynamic here: no life, no water→no water, no plate tectonics→ no plate tectonics, no life.

Water and Culture

Western culture is expert at the abuse of our planet's watery heritage. Two examples will suffice to illustrate the scale of our misappropriation of water. First: *concrete*. Scientists focus, rightly, on the massive emissions of carbon dioxide liberated during the process of making this material, but we should also be aware that prodigious amounts of water are extracted from the water cycle when concrete is mixed, poured, and set. Each decade, we lock up about 3,400 km^3 of water in concrete—a volume approximately equivalent to that of Lake Huron.[3] How long it will take for these Huron-loads of water to return to the natural cycle is anyone's guess—clearly it depends on how timing of the weathering processes liberate the water from its prison of artificial rock. Second: *oil*. Natural hydrocarbon reservoirs (oil and gas wells) contain large amounts of water, which is often brought to the surface during extraction as "produced water." Much of this is pumped back down to extract more hydrocarbons, but some remains at the surface where it becomes a hazard to agriculture and other aspects of human and plant life due to its saltiness, its oil and grease content, its burden of chemical additives from extraction process, and sometimes its radioactivity from radio nuclide contamination. A recent estimate by Sergio Maraschin (personal communication) suggests that up to 74.4 m^3 of this oil water remains on Earth's surface annually. Sadly, every year, approximately 49 km^3 of clean surface water is captured and used to force oil out of the ground. In some places, notably the Middle East, so much surface water is pumped into oil wells that rivers such as the Euphrates in Syria are in danger of drying up. On the plus side, or so it would seem, our economic activities also liberate water. As much as 62.7 km^3 per year is released when hydrocarbons are burned in our engines and generators. Thus, in total, the hydrocarbon industry injects some 88.1 km^3 per year of water into the natural water cycle (S. Maraschin, personal communication). This sounds good, until one realizes that much of this tailpipe water carries a contaminant burden that affects human well-being in the global ecosystem.

Fortunately our culture is also capable of engaging in more benign relationships with water. From the facts of a watery Gaian Earth can be inferred knowledge and wisdom that extends beyond science (Harding 2006). Recognition of the complex relationship of water, life, and Earth history has recently become available in two oversized, gorgeous books: *Water* (also published identically as *Agua* in 2006) and *Water Voices from Around the World* (Marks 2007). The frontispiece of the first states: "We need to create a new culture that acknowledges and respects the value of water. The survival of future generations of humans and all other species on this planet depends on such a new culture." The second is dedicated to our ancestor, Water, and bears testimony of citizens from fifty countries around the world. Nobel laureates figure in both books and the color photographs from satellite to microscopic levels are remarkable. In *Water Voices* we learn about Lake Sarez in Tajikistan formed by the 1911 earthquake's landslide, and kept in place by the largest natural dam in the world. Tajikistan's reverence for fresh water is palpable. The song of this Central Asian country is joined by many human and nonhuman voices: a cayman from Cuba most of whose close relatives have been extinguished, a Red Eye tree frog from a Central American rain forest, wild salmon from Kamchatka, clown fish and corals, and the tail of a humpback. The spectacular photographs in *Voices* and those of Antonio Vizcaino in *Agua* (*Water*) need no admonishment to induce us to protect our home planet. We commend both these magnum opuses; they speak louder than our words in search of Water Gaia. They represent a step, along with others expressed in this volume, toward actions that respect the

Earth. We end with a suggestion: that we properly rename our third from the Sun inner planet after the humble, crucial chemical compound that sustains us: Water!

Notes

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1. In fact common claims of adaptation, with its passive connotations, may impede investigation of the evolution of the Earth's environment through geological time. We recommend a re-examination of this ambiguous term. Usually biologists study specific correlations of behavior, morphology, or chemistry of a given organism to its immediate environment. But the assertion that any organism is well adapted to its habitat has little meaning, since the adaptation is not measurable nor even estimable in a communicable way. All organisms alive today are adapted by virtue of the implied continuation of their ancestors from the past to the present.

2. Examples are lipid monolayer biosynthesis, calcium ion extrusion that induces changes in carbonate, bicarbonate, and CO_2 equilibria, oxygenic photosynthesis, and reversible protein absorption and release of water.

3. Unpublished experiments with three different kinds of concrete and calculations showed these to be repeatable results. B. Wartski, North Carolina, 2008 (personal communication).

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