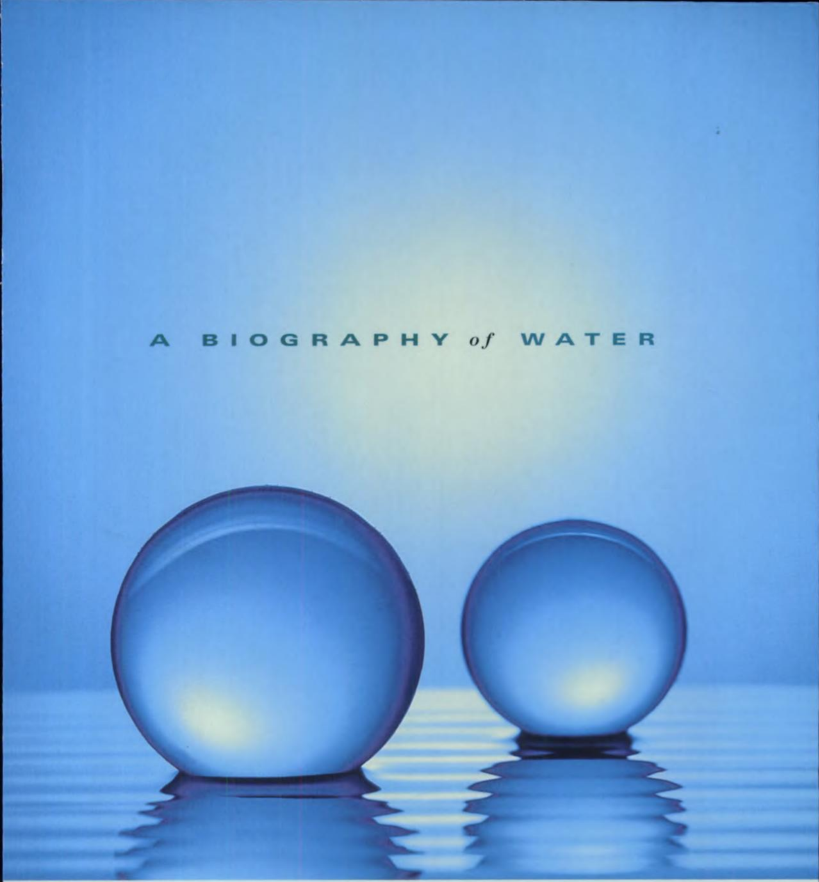
A BIOGRAPHY *of* WATER



Life's Matrix

PHILIP BALL

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THE FIRST FLOOD

WATER'S ORIGINS

> Surely this is a great part of our dignity . . . that we can know, and that through us matter can know itself; that beginning with protons and electrons, out of the womb of time and the vastness of space, we can begin to understand; that organized as in us, the hydrogen, the carbon, the nitrogen, the oxygen, those 16 to 21 elements, the water, the sunlight—all, having become us, can begin to understand what they are, and how they came to be.
>
> *George Wald, Nobel laureate in medicine*

> Those stars are the fleshed forebears
> Of these dark hills, bowed like labourers,
> And of my blood.
>
> *Ted Hughes, "Fire Eater"*

In the beginning there was water. While the earth was formless and empty, the Hebrew God was "hovering over the waters." There was no sky, no dry land, until God separated "the water under the expanse from the water above it" and commanded that "the water under the sky be gathered to one place."[1] Then the world emerged—from an infinite primeval ocean.

This is echoed in similar myths throughout the world. In central and northern Asia, North America, India, and Russia, a recurring motif is that of the Earth Diver: an animal or a god who plunges to the bottom of a primordial ocean to bring up a seed of earth. The Polynesian cosmogeny reproduces that of the Old Testament in extraordinary detail: the supreme being, Io, says, "Let the waters be separated, let the heavens be formed, let the earth be!" For the Omaha Native Americans, all creatures once floated disconsolately on a wholly submerged Earth until a great boulder rose from the deep. In Hindu mythology, the sound that embodied Brahma became first water and wind, from which was woven the web of the world. "Darkness was there, all wrapped around by darkness, and all was Water indiscriminate" says the beautiful creation hymn of the Rig Veda (3700 B.C.).[2] For the Maya of Central America also, the deity Hurakan called forth the land from a universe of darkness and water.

Why does this idea of a watery beginning resonate throughout disparate cultures, without heed to the local particulars of geography or religious tradition? Ultimately its origin may be psychological: the land was knowable for ancient peoples, but the sea was a symbol of the unconscious—something mysterious, pristine, unfathomable. I know of no creation myths where the land came first and the seas followed in a subsequent deluge.

Yet land and sea are contemporaneous and complementary in some traditions. The Judeo-Christian distinction between flesh and blood is a distinction between the earthy and watery aspects of the corpus of the world. In Norse mythology, the land is the flesh and bones of Ymir, the first giant, slain by Odin. His salty blood, gushing from the spear wound in his heart, became the oceans. So too in Chinese myth are land and sea coeval aspects of a primal being, Pan-Ku the sculptor, whose medium was his own body.

But is there any truth of a more material nature in these myths—was the world once covered with water? And where has the water come from?

IN THE BEGINNING

In myth, the origin of the Universe is seldom differentiated from the origin of the Earth. To look beyond the beginning of our world is to ponder the eternal: the Chaos of the Greeks, the abyss of fire and ice called Ginnungagap by the Norse, or the supreme deity Akshara-Brahma in

Hindu tradition. Today, Earth's beginning is merely a local question, a moment of parochial interest in an already mature universe. The real moment of creation goes back at least six billion years beyond that, and it is as fantastic as any myth.

Origins are seldom uncontentious. Current fashion sometimes has it that the idea of a cosmic Big Bang is best regarded as our latest cultural myth, as much a social construct as the slaying of Ymir. On the one hand, it can only be arrogant to suggest otherwise; on the other, it's this particular kind of confidence that makes science possible. From a scientific perspective, the Big Bang is beyond question still the best model we have for the birth of the Universe, and rests on some formidable pillars. To address the question of why water is what it is, modern cosmology provides a consistent and explanatory framework in a way that Odin's murder of Ymir does not.

Imagine watching a movie of an explosion moments after it has happened. You see many fragments, rushing away from one another within a "bubble" of expanding size. When, in 1929, the astronomer Edwin Hubble saw the galaxies of the Universe behaving in the same way, he was forced to the same conclusion as the one we would reach from the movie: this is the aftermath of an explosion. But Hubble was seeing it from the inside—we are riding on one of those fragments, the Milky Way galaxy. The Universe is getting bigger as all the galaxies rush away from one another. The natural inference is that all the matter in the Universe was once focused into a much smaller volume, which went Bang! Albert Einstein had deduced as much in 1917: when he applied his theory of general relativity to the Universe as a whole, he found the equations predicting that it had to be either expanding or contracting. That seemed to him then to be a crazy notion, and so he added a "fudge factor" to remove the expansion. But Hubble's discovery persuaded him in 1931 that no fudging was needed after all.[3]

After just one-millionth of a billionth of a second, when according to some theories the Universe might have been just a few feet across, the temperature would have been in the region of a billion billion degrees. In such extremes, there can be no atoms and molecules, no matter as we currently know it.

But as it expanded, the temperature of the Universe dropped rapidly. At the end of the first day of creation, it would have been about twenty million degrees—about as hot as the center of a star. The Universe today, with all its stars and supernovae and quasars, is but a dim, cool remnant of this cosmic fireball. In 1965 Arno Penzias and Robert Wilson at Bell Telephone Laboratories detected the faint afterglow that pervades the sky: a uniform background radiation of microwaves coming from all directions, indicating an average temperature of about five degrees Fahrenheit above absolute zero. This cosmic microwave background is all that is left of the Big Bang's fury.

THE FABRIC OF WATER

George Wald's view, quoted at the beginning of this chapter, is mine: understanding what we are composed of, and where that stuff came from, is part of our dignity. It demands, too, a greater humility to read the lives of stars, rather than divine providence, in our bones and blood. But bones and blood must come later; for now, I want to follow only the gestation of those protons and electrons, and from them the hydrogen, the oxygen—and the water.

For this is what we're after, these two elements: the H and the O, which unite so readily to create our subject. Water is H_2O, the only chemical formula that everyone learns: two atoms of hydrogen welded to one of oxygen. Their union is a molecule—a cluster of atoms. Chop up a block of ice, and keep chopping—and your finest blade, finer than the keenest surgical scalpel, will eventually reduce the fragments to these individual three-atom clusters. If you chop beyond that, you no longer have water. The H_2O molecule is the smallest piece of water you can obtain, the basic unit of water.

So here is a central aspect of water's character: it is a *compound*, an association of atoms, divisible into atoms of different natures. Yet water is so fundamental to the world that for millennia it was mistaken, naturally enough, for an *element*, something indivisible. Hydrogen and oxygen are elements, because they each contain only one kind of atom. But there is no "water atom"—only a water molecule, made up of two different types of atom.

Before making bread, one must make flour; and before water could come into the Universe, there had to be hydrogen and oxygen atoms. But before flour comes wheat—and atoms too have more fundamental constituents, Wald's protons and electrons.

As far as atoms are concerned, protons and electrons are like knives and forks at the dinner table: no matter how big the table, there are equal numbers of each. The difference between atoms of different elements—between an atom of oxygen and one of carbon, say—is simply that they contain different numbers of protons. In this regard, the underlying pattern of atoms is numerical, as Jacob Bronowski says in *The Ascent of Man*. An atom with one proton (and one electron) is hydrogen; an atom with eight of each is oxygen. At one level, chemistry is as simple as counting.

At another level, it is clearly not. For mere proton bookkeeping offers no clue as to why hydrogen atoms join with oxygen atoms in the ratio of 2:1, or why sodium (eleven protons) is a soft reactive metal, chlorine (seventeen protons) a corrosive gas, silicon (fourteen protons) an inert gray solid. To understand any of this, we need to consider how the electrons are deployed: for there are deeper patterns in the arrangement of the electrons that determine the element's chemical properties.

Protons and electrons are not, as British physicist J. J. Thomson believed at the turn of the century, lumped together inside the atom as a heterogeneous blob. Rather, they bear to one another something like the relationship of the planets to the Sun, with the electrons orbiting a central, dense nucleus where the protons are. In this "solar system" model of the atom, proposed by Thomson's protégé, New Zealander Ernest Rutherford, if the nucleus of an atom were scaled up to the size of the Sun, then the electrons would be more distant than Neptune's orbit by a factor of about ten. Yet we shouldn't take the model too seriously: electrons can't be pinpointed like planets, and do not follow well-defined elliptical paths, but instead occupy regions of space called orbitals. These regions, which have the shapes of spheres, lobes, and rings centered on the nucleus, are best regarded as hazy "electron clouds," rather like swarms of bees around a hive. From the manner in which an atom's electrons are distributed among the various available orbitals flows the whole of chemistry.

Moreover, atomic nuclei grasp their electrons not by the force of gravity but by electrical attraction: an electron is negatively charged, and a proton has a positive charge of equal magnitude. An atom, with equal numbers of both particles, is electrically neutral. Electrons, however, can be stripped away from atoms, rather as a passing star could pull a planet from a nearby solar system. The depleted atom then has an excess of protons over electrons, and so is positively charged. Atoms can also gain an excess of electrons over protons, and so become negatively charged. These charged atoms are called *ions*. This is why, even though protons and electrons are equally represented in a neutral atom, it is the number of protons that is the fundamental characteristic of an element. To pull a proton out of an atom, you have to dig it from the dense mass of the nucleus. That takes a huge amount of energy, and it converts the atom into a different element entirely.

Although hydrogen atoms have one proton and oxygen atoms have eight, oxygen is about sixteen times heavier than hydrogen. There is a third ingredient to the atom—a particle called the neutron, which has virtually the same mass as a proton but is electrically neutral. All atoms bar hydrogen have neutrons as well as protons in their nuclei, and generally speaking the nuclei contain equal numbers of each. The vagueness in this statement is, I fear, unavoidable, for two reasons. First, the number of neutrons tends increasingly to exceed the number of protons for heavier atoms: the proportions are pretty much fifty-fifty for light atoms like carbon, oxygen, and nitrogen, whereas lead atoms have around 40 percent more neutrons than protons. Second, even atoms of the same element can possess different numbers of neutrons. Oxygen atoms can contain seven, eight, nine, or ten neutrons to accompany their eight protons, while hydrogen atoms can contain no, one, or two neutrons. These different forms of atoms of the same element are called *isotopes*. Most hydrogen atoms have no neutrons; but 0.000015 percent of all of those in nature have one neutron. This heavier isotope is called heavy hydrogen, hydrogen-2, or deuterium.

This is, I appreciate, the stuff of dry chemistry textbooks, and I regret forcing it on you so soon. I hope it is of some consolation to learn that this is all you will need to know about atoms for the rest of the book. But they are the alphabet of chemistry, so we need to be at least on familiar terms with them. Besides, if we are to consider how the Universe cooked up water, we need to know which ingredients must go into the pot.

THE SOUP GOES COLD

Water is but a simple dish: the recipe tells us to mix hydrogen and oxygen. The first ingredient is the easy one: it dropped right out of the Big Bang, once things got cool enough. That's to say, protons—the nuclei of hydrogen atoms—condensed out of the fireball about a millionth of a second after time and space were born.

But at this point the temperature would have been around a trillion degrees, which is too hot for protons to hold on to electrons. The Universe was then a soup of protons and electrons, seasoned with neutrons and other subatomic particles such as neutrinos, all swimming in a seething broth of X-rays. And for a good few minutes, that's how things stayed; the Universe was too hot to be interesting.

Although protons could not yet combine with electrons, they could at least team up with each other and with neutrons—for the force that binds protons and neutrons together in the nucleus, called the nuclear strong force, is many, many times stronger than the electrical force of attraction between protons and electrons. Just one hundred seconds into the Big Bang, with temperatures close to six billion degrees, protons and neutrons began to combine to form the nuclei of heavier elements—a process called nucleosynthesis. Fusion of these particles led to the formation of the nuclei of several light elements: helium-4 (an amalgam of two protons and two neutrons),[4] lithium (three protons and three or four neutrons), and boron-11 (five protons, six neutrons). About a quarter of the mass in the Universe is helium-4, formed by nucleosynthesis in the early days of the Big Bang.

The proportion of the Universe's total mass that comes from all other elements is tiny, however: about 1 to 2 percent in all. In other words, around three-quarters of the Universe's mass is hydrogen, and the rest is mostly helium. Once the temperature had dropped to around 7200° F, nuclei became able to grasp and retain electrons. Protons teamed up with electrons, and hydrogen atoms were born.

ATOMCRAFT

If chemistry had relied solely on the Big Bang, the periodic table would be but a short, formless list of half a dozen elements—easier to grasp, perhaps, except that you wouldn't exist to appreciate it. By the time it had fashioned boron, the Big Bang had exhausted its atom-making vigor.

Fortunately for us, gravity came to the rescue. Within the diffuse clouds of matter synthesized in the Big Bang, gravity began the slow but inexorable task of galaxy-building. Where the gas was ever so slightly denser, the inward tug of gravity was that bit stronger. And so, almost imperceptible variations in density gradually became accentuated, condensing into ever more compact blobs, like a sheet of rainwater on a windshield breaking up into a network of droplets. These amorphous clumps became the precursors of vast galaxy clusters, within which smaller clumps condensed into separate galaxies—a hierarchical fragmentation right down to the scale of the nebulae that would ultimately become stars.

As the pull of gravity made matter collapse in on itself, the stuff heated up. Stars ignited and began blazing. One by one, the lights came on again throughout the Universe. The stars are more than mere fireballs—they are engines of creation, and out of their fiery hearts come the elements needed to make worlds.

TRANSMUTATION MADE REAL

Astronomy is an indispensable art; it should be rightly held in high esteem, and studied earnestly and thoroughly.[5]

So said the itinerant physician and alchemist Paracelsus in the sixteenth century, unsuspecting all along that the stars possessed the art he himself sought: the ability to convert one element to another. Stars are the alchemists of the Universe.

In the interiors of stars, hydrogen nuclei are fused together to generate heavier elements; this is the process of nuclear fusion, and it is how stars conduct nucleosynthesis. Young stars are made mostly of hydrogen, which fuses in three steps to generate helium-4 and a great deal of energy. Over its lifetime, a typical star burns about 12 percent of its hydrogen to helium in this way.

One often hears that this transmutation of elements is a thoroughly modern idea, unrelated in more than a coincidental sense with the alchemists' belief that elements can be interconverted. But on the contrary, it is possible to follow a continuous thread of logic and supposition from Paracelsian metaphysics to Enrico Fermi's first atomic pile in Chicago in the 1940s.

In 1815 the British chemist William Prout proposed that atoms of the heavier elements were formed by the clustering together of hydrogen atoms, making hydrogen the "first matter," or *prote hyle*, from which Aristotle had suggested all matter is composed.[6] Tempting though it is to suggest that in this way Prout anticipated the twentieth-century discoveries of nuclear fusion and the structure of the atom, the reason Prout's idea wasn't laughed out of court (although it was by no means uncontroversial) was in fact because the legacy of alchemy was still in the air. Indeed, no less a figure than the eminent British chemist and physicist Michael Faraday remained convinced of the doctrine of elemental transmutation throughout his life.

Prout's theory was elaborated on by the French chemist Jean Baptiste Dumas in the 1840s. Dumas noted that the atomic weights of some elements, which by then were known with impressive accuracy, were certainly *not* whole multiples of the atomic weight of hydrogen, and therefore these elements could not be made of clusters of hydrogen atoms. Dumas proposed that the fundamental unit of matter might instead be some subdivision of the hydrogen atom, perhaps a quarter or a half. Unknown to Dumas, the discrepancies are actually a consequence of the fact that elements exist in nature as a mixture of isotopes, so that their average mass does not correspond to a whole number of protons. The link between these ideas and the chemistry of the extraterrestial Universe was made by Norman Lockyer in the 1870s. During this and the preceding decade, astronomers detected the fingerprints of many earthly elements in the light emitted by the Sun and other stars. Lockyer, in parallel with the Frenchman Pierre Janssen, discovered a new element in 1868 purely from its distinctive imprint on the spectrum of sunlight—a series of dark bands where the element absorbs light of certain colors. Lockyer called the element helium (after *helios*, Greek for the Sun), and it was not found on Earth until twenty-seven years later.

Lockyer developed a theory of the "evolution of stars and chemical elements" which drew explicitly on Dumas's elaboration of Prout's hypothesis. He proposed that heavy elements were made from lighter ones inside stars as the stars cooled from a blue-white brightness to a red dimness—a progression inferred from the observed colors of different stars. The British chemist William Crookes developed a similar hypothesis in the 1880s, based on the observation that gases subjected to high voltages could be decomposed into a plasma, a mixture of ions and electrons. Crookes considered plasmas to be a "fourth state of matter" consisting of subatomic particles akin to those postulated by Prout and Dumas. He constructed an exotic scheme for the evolution and transmutation of elements from this plasma, which he assumed to be the stuff of stars.

ENTER OXYGEN

In 1919 the British physicist Francis Aston, working at the Cavendish Laboratory of Cambridge University, developed a device that enabled him to measure the relative masses of atomic nuclei with great precision: the "mass spectrograph," which we would now call a mass spectrometer. He found that even the nuclear masses of individual isotopes are generally not exactly whole multiples of hydrogen's; they are somewhat lighter, although typically by a margin of only a fraction of 1 percent. The tiny difference in mass reflects the fact that a huge amount of energy is released when protons and neutrons combine to form heavier nuclei: the energy accounts for the "missing mass" and is calculated according to Einstein's famous formulation $E=mc^2$. For the first time, Aston realized the vast energy lurking within the nuclei of atoms. When Ernest Rutherford, the director of the Cavendish, demonstrated in 1919 that a nuclear transmutation process could be induced by artificial means, scientists realized that it might be possible to extract this energy technologically—for better or worse. French physicist Jean Perrin proposed in the same year that the Sun and other stars might derive their energy from the fusion of hydrogen to heavier elements. In other words, nuclear fusion might not be just a *consequence* of the furious solar environment, as Lockyer had supposed, but the *cause* of it. Arthur Eddington added his approval in 1920: "What is possible in the Cavendish Laboratory may not be too difficult in the Sun."

In the mid-1930s the Russian physicist George Gamow put Perrin's idea on firmer footing, suggesting that hydrogen was transformed to heavier elements by capturing a succession of protons or neutrons. The German physicist Hans Bethe showed in 1939 that a tiny dose of carbon is needed to stimulate this process. A newly formed star condensing from a gaseous nebula typically contains about 1 percent carbon, primarily in the form of the isotope carbon-12. This can provide the seed for the six-step sequence of nuclear reactions that converts hydrogen-1 to helium-4. The carbon-12 is recycled: consumed at the beginning of the sequence, but regurgitated at the end. By definition, it acts as a catalyst. This means that a tiny amount of carbon can facilitate the fusion of a lot of hydrogen.

At first glance, this cycle doesn't seem to get us very much further, since its net result is to transform hydrogen to helium—and we've seen that this can happen anyway, without the help of carbon. But in the intermediate steps of the cycle, other elements are formed: three different isotopes of nitrogen, and one of oxygen (the rare isotope oxygen-15). In Bethe's so-called C-N-O cycle, oxygen makes its entrance onto the cosmic stage.

The C-N-O cycle provides a significant fraction of a star's energy output. In fact, for stars several times more massive than the Sun it becomes a more important power source than the direct hydrogen-to-helium reactions. Because a star is constantly reiterating this cycle, it maintains a steady amount of carbon, nitrogen, and oxygen in its atmosphere. Clearly, however, this can't be the whole story either. The C-N-O cycle generates only oxygen-15, while the isotopes we see in nature are mainly oxygen-16, -17, and -18. And what about all the even heavier elements?

Bethe supplied part of the answer. He showed that at particularly high temperatures, a new set of nuclear reactions becomes possible, in which oxygen-16, oxygen-17, and fluorine-17 also take part. But this side branch of the C-N-O cycle requires a pinch of oxygen-16. Newly formed stars in the present-day Universe acquire this oxygen isotope from the interstellar material from which they condense. But where did it come from in the first place?

The answer was provided in 1957 by Margaret and Geoffrey Burbidge, William Fowler, and Fred Hoyle, in a paper that still defines today most of what we know about the nucleosynthesis of heavy elements in stars. The reason a star doesn't just keep collapsing once gravity has pulled it together from gas and dust is that the intense radiation produced by nuclear fusion gives the gas buoyancy, rather as a burner supplies buoyancy to the air in a hot-air balloon. But in the autumn years of a star's life, when it has burned up most of its hydrogen and its fusion engine grows cooler, this buoyancy is lost and the star begins to contract. Gravitational collapse generates heat in the star's dense core, which is now mostly helium-4. At the same time, the star's outer atmosphere of gas expands and cools to a red glow, and it becomes a red giant. In the hot, dense core, the star starts to burn helium. The nuclei fuse to make new elements whose masses grow in leaps of four: boron-8, carbon-12, oxygen-16, neon-20, magnesium-24, silicon-28 and beyond. Oxygen-18, meanwhile, is formed from fusion of helium-4 with nitrogen-14.

Eventually the helium in the star's core is used up too, and so the star has to resort to burning whatever it has left, which is mostly carbon and oxygen. This requires still-higher temperatures and pressures, which are conveniently supplied when the diminishing fuel reserves permit further contraction, raising the core temperature to around a billion degrees. At this point, carbon-12 and oxygen-16 undergo fusion to generate a series of elements of about twice their mass: sodium-23, silicon-28, phosphorus-31, and sulfur-32. Thereafter, silicon-28 fuses with the helium nuclei produced in other reactions to make elements up to and heavier than iron. In their final evolutionary stage, such stars have a concentric-shell structure with a core of the heaviest elements and successive shells rich in silicon, in carbon/oxygen/nitrogen, helium, and finally hydrogen.

And there is more. Stars larger than around four times the mass of the Sun may end their lives in spectacular fashion: as supernovae, which explode with a brightness that momentarily outshines the entire galaxy in which they reside. When such a star has finally exhausted its supply of nuclear fuel, there is nothing more to prevent the catastrophic collapse of the dense core under its own gravity. The inrush of matter in the core generates a shock wave, and the star becomes unstable. In an awesome rebound, the outer envelope of the star is cast off and out into space while the star's core implodes to unspeakable densities whose inner region is a liquid of neutrons. Here atomic nuclei are unable to retain their separate identities but instead become crushed to a featureless miasma, and most of the protons combine with the electrons to produce a preponderance of neutrons. So the supernova becomes a dark, compact neutron star surrounded by an expanding shell of matter rich in a variety of elements. Such is the energy of the supernova's outburst that new nucleosynthesis reactions are triggered, enriching the debris with very heavy elements such as thorium and uranium.

These elements—the whole periodic table of them—are scattered through space. As a result of supernovae, the void between the stars is sprinkled with the raw material from which worlds are made. Walt Whitman anticipated this process in 1855 in an inspired poetic leap of imagination: "A leaf of grass is no less than the journey-work of the stars."[7] And Ted Hughes, in "Fire Eater," reads the origins of earth and water in the firmament.

WET SPACE

Oxygen is the third most abundant element in the Universe—albeit a very poor third to hydrogen and helium, whose primordial generation in the Big Bang ensures that they constitute almost all of the fabric of creation. But helium is unreactive, a cosmic loner. And so should we after all be surprised that water, the combination of the Universe's most popular reactive elements, is so pervasive? This molecule, the matrix of life, is the product of the Universe's two most generous acts of creation: the Big Bang, which started it all and gave us a cosmos made mostly of hydrogen; and stellar evolution, which reformulates this element, whose very name means "water former," into oxygen and all the other elements that make up the world. Within the imponderable expanses of interstellar space, these two elements unite—and there in the making is the river Nile, the Arabian Sea, the clouds and snowflakes, the juice of cells, the ice plains of Neptune, and who knows what other rivers, oceans, and raindrops on worlds we may never see.

Every supernova sends a potent brew of atoms and molecules spewing out into the cosmos. But the cosmos is a big place, and even the creative might of an exploding star is a drop in the ocean. The space between the stars of our galaxy is emptier than the best human-made vacuum; and yet there is enough finely dispersed matter out there to make around ten billion more stars, one-twentieth of the number in the luminous drapery of the Milky Way. This tenuous stuff is mostly hydrogen, but it has been delicately seasoned over the aeons with other elements and molecules, a dizzy menu of them. You'll find plenty of hydrogen molecules (H_2, two atoms hand in hand) out there, but also carbon monoxide, hydrogen cyanide, methanol and ethanol, ammonia, formaldehyde, and yes, water. There's solid matter too: tiny grains of silicate minerals, specks of soot and diamond—often with a coating of ice. All you need, in fact, to make a planet.

In some parts of the galaxy the gas and dust between the stars is clumpy, forming vast "molecular clouds" which can block out the starlight beyond to give us fantastic sights like the Horsehead nebula in Orion. In these clouds, stars may form as the matter condenses under its own gravity. That water is abundant in these regions was discovered in 1969 by astronomer Charles Townes and his co-workers. The watery signature was barely legible: just a single bright peak in a microwave spectrum of cold interstellar gas. Molecules in interstellar space are usually detected from the lines that they strip out of the spectra of light from more distant objects—each type of molecule absorbs light at characteristic colors. But the water that Townes saw was not absorbing the microwave radiation—it was emitting it. The water was glowing! Improbable as it might seem in the deep-freeze of space, molecules in interstellar clouds can be pumped full of energy. The molecules get "hot" by undergoing collisions in dense regions of the clouds, and they cool again by emitting radiation. The molecules can synchronize their emission: the radiation emitted by one excited molecule can "tickle" a second into emitting too, and before long a whole slew of hot molecules are casting off their excess energy. Much the same processes are responsible for light emission in some lasers. Because the "light" from these collisionally pumped molecular clouds is in the microwave region of the spectrum, they are not cosmic lasers but *m*asers (from *M*icrowave-*a*mplified *S*timulated *E*mission of *R*adiation). What Townes and his colleagues saw was the first known astrophysical water maser. These extensive astrophysical objects are now known to be regions where the gas is collapsing to form new stars. Water sends out a signal of star formation to the Universe at large.

Star formation: it's what every world needs. To make a planet, you first have to make a sun.

THE GREAT FLOOD

The ancient Greeks guessed well about our planet's origin, for they believed that Mother Earth—Gaia—arose from a primordial Chaos. *Chaos* is the etymological origin for the word *gas*, and it was from gas and dust that the Earth was formed, along with the Sun and our sister planets. In an inspired guess, Immanuel Kant proposed as much in 1755.[8]

As a clump of gas collapses within a molecular cloud, it rotates and flattens out into a disk. While most of the matter gathers into the central core and is incorporated into the nascent star, some is left farther out in the disk, where it provides the material for the formation of a planetary solar system. Several disklike embryonic stars have been seen elsewhere in the galaxy. Some of the disks are punctuated by ring-shaped voids, thought to be the tracks engraved through the dust by newly formed circulating planets. This happened in our own stellar disk—the solar nebula—about 4.6 billion years ago, when the Earth was one of those orbiting blobs.

But planets do not arise fully formed from globules of condensed solar nebula. We know this because there is far less of certain gases—neon, argon, krypton—in today's atmosphere than is thought to have been distributed through the solar nebula. Because these gases are chemically unreactive, we would expect them to remain as abundant as ever they were if our planet and its atmosphere was just a clump of pristine solar nebula with its elements rearranged.

No, planet formation is less stately and more traumatic than this. The accretions of gas and dust in the solar nebula formed smaller rocky bodies called planetesimals that range in size from boulders to moon-sized asteroids. These swarming planetesimals engaged in fearsome collisons that smashed each other to rubble—but the rubble from each collision then cohered into a single, larger object through the tug of its own gravity. Rather like companies, larger planetesimals grew at the expense of smaller ones until the disk was swept free of debris and only the planets remained, the multinational conglomerates of the solar system. The inner planets—Mercury, Venus, Earth, and Mars—are relatively small, dense, rocky orbs. But out beyond the asteroid belt, where some of the smaller debris escaped capture, the planets were able to retain vast envelopes of gases and liquids: here we find the gas giants Jupiter and Saturn, and the frozen worlds of Uranus, Neptune, and Pluto.

Earth was not a good vacation destination in those early days. The heat generated during its formation from colliding planetesimals created a global inferno. And around 4.5 billion years ago the Earth seems to have collided with a planetesimal about the size of Mars. Were this to happen today, you might as well cancel the papers. Global nuclear war would be a picnic in comparison—an impact this size would almost shatter the planet, and would certainly extinguish all life. As it was, it sheared off enough material to form the Moon, boiled away any atmosphere that the Earth then possessed, and left the planet a ball of molten rock (magma) for millions of years, its surface awash with a fiery ocean from pole to pole.

Yet collisions were not wholly destructive. On the contrary, they ultimately gave the planet an atmosphere, water—and the possibility of harboring life. In the part of the solar nebula where the Earth condensed, volatile substances like water and carbon dioxide were rare commodities—only farther out, where the temperature was low enough for them to condense and freeze, could they become a major component of planetesimals. These colder bodies could sequester a coating of ice from the gas and dust, just as snowflakes high in our atmosphere sweep up water vapor from the air. Blundering in and out of the nascent inner solar system, such objects most probably added water to the rocky mixture that was becoming the Earth.

To test whether this idea holds water, so to speak, planetary scientists today study the composition of meteorites. These cosmic boulders—well, they are more like pebbles on the whole, and some are no bigger than grains of sand—are mostly the leftovers of planet formation, the bits that never quite got incorporated into planets. It's likely, then, that the mixture of elements and compounds of which they are comprised reflects the composition of early planetesimals. They are still raining down on us from the skies, albeit in far smaller numbers than when the world was young. Many meteorites do indeed carry a bountiful crust of ice—not just water ice, but also frozen carbon dioxide, ammonia, and other volatile compounds. Meteorites called carbonaceous chondrites, which are rich in carbon compounds, can contain up to 20 percent water, either as ice or locked up in the crystal structures of minerals. The most abundant type of meteorites, ordinary chondrites, carry much less water—around 0.1 percent of their mass. Yet even this would have been more than enough to fill the oceans if the Earth was formed primarily from planetesimals with this composition.

But meteorites are not the only objects still wandering among the planets. There are itinerants the size of mountains out there, and they could deliver huge quantities of water to the Earth and its neighbors in a flash. I'm talking about comets, the unruly rabble of the outer solar system. Comets mostly originate in a roughly spherical cloud of objects stretching way beyond the orbit of the most distant planet, Pluto, perhaps more than halfway to the nearest neighboring star system. This halo, called the Oort cloud, contains around a million million comets, whose immense, looping orbits bring them occasionally sweeping through the inner solar system—as we saw in spectacular fashion with comet Hale-Bopp in 1997. They consist mostly of volatile gases condensed into ices, of which by far the most abundant is water. Mixed in with the ice is a scattering of mineral dust, making comets immense dirty snowballs. Generally they are several hundred feet to several miles across, and so contain an awesome amount of water. Halley's comet, for instance, is a potato-shaped lump about five by ten miles in size, with a mass of about one hundred billion tons—most of which is ice. A typical comet is still larger, containing around one trillion tons of water. A million comets like this would be enough to supply all of Earth's oceans.[9]

I'm glad to say that comets do not collide with Earth with anything like the frequency of small meteorites: the last major collision may have been sixty-five million years ago, possibly hastening the dinosaurs' demise. But comets swarmed through the solar system in far greater numbers when the Earth was forming, and would have crossed paths with the planet far more regularly, bringing oceans on their backs.[10] It seems that the gravitational tug of the outer planets Uranus and Neptune, as well as nearby stars, helped to rearrange the orbits of cometlike planetesimals in the Oort cloud so that they would pass more often through the inner solar system. Meanwhile these and the other giant planets, particularly Jupiter, eventually swept up most of the debris from the solar system and so quieted down the game of cosmic billiards by about a billion years after the planets had formed. Had this not happened, huge impacts might have delayed the appearance of life on Earth for billions of years. So we may have our neighbors to thank not only for our oceans but also for the life that spawned in them.

But I'm jumping the gun, for the oceans did not appear until many millions of years after the planet was formed. Four and a half billion years ago the Earth was still a molten magma ball, seething from the collision that ejected the Moon. As the planet cooled, its constituents separated like curdled milk. Within about fifty million years, the iron of which much of the Earth was comprised had sunk to the core, and the lighter elements—silicon, aluminium, calcium, magnesium, sodium, potassium, and oxygen, along with some remaining iron—formed a rocky crust at the surface, just as slag floats on top of molten iron in a smelter.

Among all this rocky stuff were the volatile compounds delivered by collisions as the planet accreted—hydrogen, nitrogen, hydrogen sulfide, carbon oxides, water. While the Earth was molten, these volatile compounds dissolved in the magma, but as the molten rock cooled and solidified, the vapors were released in a process called degassing. The atmosphere that resulted from degassing was very different from today's, consisting mostly of carbon dioxide, nitrogen, and water vapor.

Hydrogen is too light to be retained by the Earth's gravitational field, and was gradually lost from the early atmosphere into space. For this reason, the Earth is steadily losing its water too, albeit very slowly. The Sun's ultraviolet rays split water in the upper atmosphere into its constituent hydrogen and oxygen atoms, a process called photolysis. The hydrogen then escapes into space. This water-splitting costs the planet the equivalent of a small lake's worth of water each year. That sounds like a lot—and it certainly would be if it all came from a single lake! But averaged over the amount of water on the planet, the loss is probably quite small: photolysis may have reduced the Earth's water reserves by just 0.2 percent since the planet was formed.

THE DAY THE RAINS CAME

Those formative years were steamy times on Earth, for all the water was in the sky. And then one day, somewhere between 4.4 and 4.0 billion years ago, the temperature had fallen far enough for water to condense. Clouds massed in the sky, and the oceans rained down. Sadly, I have to confess that this would not truly have happened so suddenly, one fine day in the Hadean era—but I like the image. Yet however you look at it, there's no avoiding the conclusion that a deluge must eventually have ensued that leaves the biblical version looking like an April shower. This was the original Flood, and had anyone been there to witness it, I don't think an ark would have done them much good.

Far from eradicating life, this deluge set the stage for life's entry. It turned the face of the world blue and created a planet that exists, in atmospheric scientist James Lovelock's words, as "a strange and beautiful anomaly in our solar system."[11]

2

BLOOD OF THE EARTH

SEAS AND RIVERS OF THE WORLD

> Whence flow the Seas? Whence have free Springs their head? Whence do the far extended Rivers rise?
>
> *Titus Lucretius Carus,* De Rerum Natura *(56 B.C.)*

> As man has within him a pool of blood wherein the lungs as he breathes expand and contract, so the body of the earth has its ocean, which also rises and falls every six hours with the breathing of the world . . .
>
> *Leonardo da Vinci,* Notebooks

We live on a blue planet, and seem more or less determined to disguise the fact. Our maps—North America and Asia stretching out to one another like Michelangelo's divine fingers in an attempt to bridge eastern and western landmasses—give no clue that, seen from some angles, the globe is nearly all sea. Standard cartographic projections appear designed to maximize land area at the expense of the waters, to hide away the awesome glaze of the Pacific Ocean. Over two-thirds of the planet's surface is covered by liquid water, and over one-twentieth by ice. We call our home Earth—but Water would be more apt.

This is only human nature. Living in London, New York, Tokyo, or even Peoria, one forgets that other places are not the same. Wherever we are, we all too easily assume that our environment is representative. If extraterrestrial beings were to drop by on Earth to collect a random sample of its wildlife, we would tend to imagine them hovering over the plains of Texas, plucking up cowboys and housewives. But it is more likely that they would collect a tank of algae from the Pacific.

Long adapted for land life, we have never truly come to terms with the dominance of the seas. These huge watery plains are hardly less scary today than they were to our ancestors, who populated their nether reaches with fabulous beasts and feared the chasms that lay just out of sight over the horizon. Even the deserts hold fewer terrors. We have colonized the dense, steamy valleys of Amazonia, the frozen Arctic wastes, and the starkness of the Siberian steppe—and yet we remain a little nervous even about what lies in the depths of the Scottish lochs, let alone the unplumbed abysses of the great oceans. In some ways we know more about the Moon, Venus, and Mars, reassuringly free of liquid water, than about the ocean floor.

So we have a curious relationship to water on Earth. It nurtured and sustained civilization—yet the fresh waterways that fed the cultures of ancient China and Egypt, Mesopotamia and the Indian continent, make up barely a tenth of a thousandth of all the liquid water on the planet. Just about all of the rest is salty, and lethal to the thirsty adventurer. Water giveth and water taketh away, in floods that resound through the legends of many cultures, in hurricanes and other wild faces of nature. Water has carried explorers far afield, yet it swallows up our puny vessels without a trace. The water gods, exemplified by Poseidon in Greek mythology, are ambiguous creatures with aspects both benign and terrible. Throughout the Book of Job, the contingencies of nature's waters are a continual metaphor for the trials of humankind.

The naïve psychological perspective associates water with life, and I will later say much that reinforces this intuition. But at a mythological level, the natural waters of the Earth offer humankind a journey into death. The Styx is the conduit to Hades, the Ganges even today a repository of the deceased. The Nile and the Tigris were not only holy in Near

Eastern belief but dwelling places of the dead, ruled by demigods with the power of resurrection. From the association of streams and rivers with death and rebirth comes the Christian practice of baptism.

But it is also via the broad oceans that water is associated with our passage beyond the borders of life. For the earliest seafarers, this link was all too real. Death at sea has a special, mythical status: the drowned pass on to an altogether more fathomless fate than those whose corporeal being is returned to the shallow earth. In ancient cultures, children who died in birth were often carried to the river or the sea for fear that their disease would harm the fertile ground. The Ship of the Dead is a potent and recurring symbol: the *Flying Dutchman,* the *Marie Celeste.* Our enduring fascination with the doomed *Titanic* taps into this rich seam, while disasters far worse have faded to obscurity. Today there are new specters abroad in the planet's liquid, as the final chapter will show.

Water is the agent of geological, environmental, and global change. It confers fecundity in parched regions, while its passing turns grassland to desert. It spells the difference between blue skies and gray. The ebb and flow of oceanic heat bring peculiarities and extremes in climate—the benevolent warmth of the Gulf Stream, the jumpy pulse of El Niño—events which threaten drought or downpour depending on where you are, even the transition to ice-age conditions. Ice itself may be not just the harbinger but part of the very cause of these glacial spells, during which the Earth is refrigerated for thousands of years.

For all its fluidity, water is also one of the main shaping agents of nature. It makes rugged corrugations in highlands, carving out the intaglio of river valleys. It eats away at coastlines to generate underhangs and caves and eventually to collapse them, and to shift entire beaches down the coast. On its course from mountain to sea it may leave exquisite rock sculptures in its path. Cycles of freezing and thawing split apart the firmest of rocks, reducing slopes to rubble or heaving up stones from beneath the ground in fantastic geological "fairy rings." And in tongues of ice, water scours the Earth into broad valleys and shifts huge boulders over great distances. Water is what makes our planet unique.

THE WATER WHEEL

But my brothers are as undependable as intermittent
streams,
as the streams that overflow
when darkened by thawing ice
and swollen with melting snow, but that cease to flow in the
dry season,
and in the heat
vanish from their channels.

Job 6:15–17

Every day, every passing second, water is on the move. The rivers flow, the oceans perform their slow and elegant gyrations, the clouds congeal and weep. Each 3100 years, a volume of water equivalent to all the oceans passes through the atmosphere, carried there by evaporation and removed by precipitation. Yet only a thousandth of 1 percent of the planet's total water resides in the atmosphere at any moment, enough to deposit just one inch of rain if it all fell uniformly throughout the world. This constant overturn of water between the reservoirs on land, in sea, and in sky is called the hydrological cycle (Figure 2.1), and it is as crucial for life on Earth as is the presence of liquid water in the first place.

Leonardo da Vinci recognized that the Earth recycles its fluids. He appreciated that evaporation creates the clouds: "The heat of the sun . . . calls up their moisture from the expanses of the sea." But he believed that rainfall alone was not quite sufficient to account for the mighty torrents that pour from the mountains to the lowlands, and instead supposed that rivers were fed largely by water drawn up from the sea through "the body of the mountain" by the "natural heat" of the Earth. His cycle from sea to mountaintop had therefore no pressing need to include evaporation:

> *. . . So therefore, one may conclude that the water passes from the rivers to the sea, and from the sea to the rivers, ever making the self-same round, and that all the sea and the rivers have passed through the mouth of the Nile an infinite number of times.*[1]

Not infinite, in fact—but certainly a huge number. And the Earth's natural heat, its internal volcanism, plays no role in the affair; rather, it is the Sun alone that powers this churning of the global water cycle.[2] The French lawyer and amateur geologist Pierre Perrault put Leonardo right in 1674, showing that evaporation and precipitation, rather than an "internal distillation in the earth," is "sufficient to make springs and rivers run throughout the entire year."[3] He estimated that the amount of rain that falls in the upper Seine valley is five times greater than the amount that the river bears away—one of the first uses ever of quantitative methods in the earth sciences.

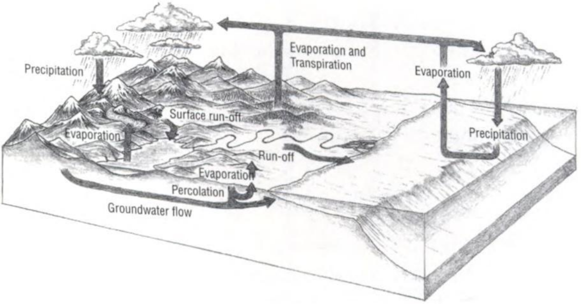

Figure 2.1 *The hydrological cycle carries water on an unending journey through streams, rivers, and oceans; the atmosphere; the ice sheets; living systems; and the deep Earth.*

Most of the water that falls as rain has found its way into the sky from the sea surface: the Sun's heat removes from the oceans the equivalent of three feet in depth each year—208 cubic miles in total every day. A further 38 cubic miles evaporates each day from the land surface. Of course, this rate of evaporation varies widely with the seasons and with geographical location: because the tropics are warmer, the rate of evaporation there is at least four times greater than at the poles.

Evaporation from the ground and from plants (a process called transpiration—see page 241) removes water to the atmosphere, while precipitation, generally as rain and snow, supplies it to the land. The difference between precipitation and evaporation defines the amount of fresh water available for lakes, streams, and other reserves on land. This "runoff," which is mostly returned to the oceans through rivers, adds up to about 24 cubic miles globally per day. In deserts, evaporation is about equal to precipitation and there is essentially no runoff. In the Amazon basin, about half of the rainfall ends up as runoff, and most of this finds its way into the great Amazon River, which delivers an awesome one-fifth of the total freshwater input to the global oceans.

The various cogs of the hydrological cycle turn at a wide range of speeds. Rainfall in a river's upland source region can take weeks to reach the sea, while water vapor evaporated from the sea surface typically takes about ten days to fall again as rain. For water locked up as ice (in the so-called cryosphere), the cogs may grind slowly indeed. The water at the base of the polar ice sheets has typically been frozen for hundreds of thousands of years. Most mountain glaciers melt and recede by several miles every decade under present-day conditions, while the sea ice in the polar seas expands and retreats seasonally.

The very existence of a hydrological cycle is a consequence of water's unique ability to exist in more than one physical state—solid, liquid, or gas—under the conditions that prevail at the surface of the planet. Volcanic areas excepted, the Earth's surface never gets hot enough to boil water; but it evaporates readily nonetheless, since the amount of water vapor in the air is generally well below the "saturated vapor pressure," the maximum humidity of air before water droplets start to condense. That's why the oceans are, to a greater or lesser degree, always "steaming." When moist air cools, the water vapor may condense back to the liquid state, producing the pearly billows of clouds or the dank blankets of mountain mist. This cycle of evaporation and condensation has come to seem so perfectly natural that we never think to remark on why no other substances display such transformations. Almost all of the non-aqueous fabric of our planet remains in the same physical state.[4] The oxygen and nitrogen of the air do not condense; the rocks, sands, and soils do not melt (except in the furnace of the deep Earth) or evaporate. If these substances are transformed at all, it is often through the agency of water, which will dissolve many gases and minerals alike.

The freezing of water, meanwhile, can send it on a millennia-long detour from the cycle of evaporation and precipitation. Yet the ability of water to enter the solid state is also a crucial aspect of the overall cycle. When water is frozen during the ice ages, the world's seas recede, the climate becomes drier, deserts expand, and ecosystems may be utterly transformed.

We will later see that this kinship of our planet's surface conditions with the temperatures of which water freezes, melts, boils, and condenses is an anomaly, a peculiar outcome of water's unique molecular character. It is only because water is different that rain washes the streets, that brooks gurgle and rivers roar down from the mountains, that the surf crashes on the rocks.

The hydrological cycle emphasizes the dynamic nature of the Earth's environment: it is constantly repeating and renewing itself. Substances other than water are cycled by geological and biological processes too. Carbon from atmospheric carbon dioxide gets woven into the fabric of plants, may be thence consumed by animals, settles as dead organic debris to the ocean floor, is carried into the deep Earth at the convergence of tectonic plates, and is recycled into the atmosphere by volcanic emission of gases. Nitrogen from the air is converted by bacteria into nitrogen-containing nutrients in the soil, and is thereby taken up into living cells before being converted back to the nitrogen molecules of air by other microbes feeding off dead organic matter. These cyclic sequences of chemical and biological transformation of the elements are called biogeochemical cycles.

Water is the lubricant for biogeochemical cycling. Because it is such a superb solvent, and because it is itself in constant flux, it helps to convey other substances hither and thither, between different ecosystems and different climates. Carbon dioxide in the atmosphere dissolves in the surface waters of the sea to provide a carbon source for marine photosynthesis, and in turn this biological growth in the ocean's upper layer drives the rest of the ocean's carbon cycle. Essential nutrients pervade the seas in soluble form: nitrate, phosphate, sulfate, and metals such as iron. The swift churning of the hydrological cycle helps to drive the cycling of these other substances: rain and rivers flush inorganic nutrients out of the minerals of the rocky Earth and carry them to the sea. There is little exaggeration in saying that it is water, in the end, that makes the world go round.

Only such a dynamic environment, constantly changing yet constantly repeating itself, can support life. At the same time, life itself can come to exert an important and often dominant influence on these natural cycles, something that is particularly evident in the carbon and nitrogen cycles. Biogeochemical cycles create feedbacks that can enhance or damp out disturbances to the environment, such as changes in the intensity of the Sun's radiation or episodes of unusually vigorous volcanic activity. This gives the planet the potential to regulate itself, to maintain stable cycles and a relatively constant environment in the face of changing circumstances. The extent to which this really does happen, and in particular the degree to which living organisms play a part in it, is the central issue in the debate over James Lovelock's Gaia hypothesis, the idea of a self-regulating Earth.

DEEP BLUE

> Have you journeyed to the springs of the sea
> or walked in the recesses of the deep?
>
> *Job 38:16*

What lies over the ocean's rim? Since humans first took to the sea, this question has been irresistible. The Phoenicians and Vikings crossed the Atlantic long before Columbus and Magellan in the heyday of European seafaring, and Chinese mariners reached the east coast of Africa in the fifteenth century, well before Portuguese colonists. By 1700, maps of the Atlantic Ocean were almost as accurate as today's. But although dragons may have been banished from beyond the world's end, it was largely the promise of distant lands (and resources), not the allure of the blue waters, that stimulated these explorations. There was little systematic effort to look at the seas for their own sake until the celebrated voyage of the British research vessel HMS *Challenger*, which circled the globe from 1872 to 1876 and took depth soundings and ocean-water samples in an attempt to look at the oceans as a part of the planet's geography, rather than as a highway to foreign exploitation.

What we have learned since then is sobering. Around half of the Earth's solid surface is between 1.8 and 3.6 miles below sea level: the places where we live are like the tips of icebergs. The deepest parts of the ocean—the trenches—can plummet about seven miles, well over a mile deeper than Mount Everest is high. The floors of the great oceans are scarred down their middle by rugged submerged ridges several miles high. These mid-ocean ridges mark the borders of tectonic plates: here magma wells up from the mantle, cooling at the sea bed to solidify into fresh ocean floor, while the plates move apart on either side.

THE GLOBAL CONVEYOR

All the oceans of the world are interconnected. Yet the lumbering continents and the high points of the ocean floor modulate the degree of connection, enabling us to define distinct water masses, "basins" separated by shallow shelves. Once mariners considered that there were seven seas to sail: the Atlantic, Pacific, Indian, and Arctic oceans, the Mediterranean and Caribbean seas, and the Gulf of Mexico. Today we recognize only three different ocean basins—the Atlantic, Pacific, and Indian—although the southernmost portions of these three, encircling Antarctica itself, are loosely designated as a fourth ocean, the Southern or Antarctic. The world's seas, including the Mediterranean, the North Sea, the Red Sea, the Arabian Sea, and the East and South China Seas, are large bodies of water that lie on the margins of the oceans and are typically separated by narrow gaps or straits, such as the Strait of Gibraltar, or by high ridges on the seabed.

The waters in these oceans do not simply sit there bobbing up and down; they are constantly passing in concerted masses from one place to another, both vertically and horizontally, like shoppers riding the escalators in a crowded multistory department store. It is a stately procession, a sluggish reflection of the jets, streams, fronts, and vortices of the ever-active atmosphere. But unlike the movement of air masses, the circulation of water between the oceans is constrained by the essentially arbitrary distribution of the continents. These have found their way to their current positions through continental drift, the movement of the tectonic plates driven by the even more sluggish convective motion in the Earth's mantle. There is thus a poetic recurrence of movement here throughout the classical elements of air, water, and earth, at a successively slower pace. We might with only a little poetic license find the sequence completed with the overturning of "fire"—molten iron—in the Earth's core.

Because the tectonic plates go right on drifting and colliding in their ponderous manner, there is nothing fundamental or fixed about the pattern of the oceans. In the Jurassic period, about 170 million years ago, there were only two major oceans. The Panthalassa Ocean occupied virtually the whole planet between longitudes 30° W (now the mid-Atlantic) and what is now the international date line (mid-Pacific), and the Tethys Ocean stretched between latitudes 30° N (level with North Africa today) and 30° S (which now passes through southern Australia) in the eastern part of the globe. The Panthalassa Ocean became the Pacific, while the Tethys was gradually squeezed out of existence as the Indian continent collided with Asia to throw up the Himalayas.

Today there is a strong asymmetry in the distribution of land and sea between the two hemispheres. Almost two-thirds of the global ocean is in the Southern Hemisphere, and a remarkable 95 percent of all land points have antipodes—equivalent points in the other hemisphere—in the sea. Only in the Southern Ocean can one sail around a complete line of latitude without encountering land.

The ocean's surface currents, which shift the top three hundred feet or so of water, are driven mainly by winds. They propel the sea surface just as blown air will create flow in a cup of coffee. So these ocean-surface currents, which are crucial to the distribution of fish and other marine organisms and to the transport of heat around the globe, are at the mercy of the atmosphere. A confusing convention has developed whereby ocean currents are defined in terms of the direction they are going, while air currents—winds—are designated by the direction from which they come. So a westerly wind drives an eastward ocean-surface current, both moving in the same direction. Westerly winds prevail between latitudes 30° and 60° in both hemispheres; closer to the equator, down to latitudes of 15°, the easterly trade winds drive westward currents. Around the equator itself the winds are weak—the Doldrums—and predominantly easterly.

This zonal (east–west) and almost hemispherically symmetrical driving of ocean-surface currents is modified by two factors: the continents get in the way, and the Earth is spinning. Except in the Southern Ocean, the currents are hemmed in by landmasses to the east and west, and so are deflected northward and southward close to the coasts to trace out huge closed loops called "gyres" (Figure 2.2). This gyration is accentuated and modified by the effect of the Earth's rotation, through an influence called the Coriolis force. Named after the nineteenth-century French engineer Gaspard Coriolis, this force acts on an object that moves within a rotating system.[5] You can feel this force if you try to walk in a straight line out toward the edge of a rotating platform: the Coriolis force impels you to veer away from the line. On Earth, this force causes a current to diverge away from its initial course toward the right in the Northern Hemisphere and the left in the Southern Hemisphere.

To see what effect this has on ocean currents, consider the North Pacific gyre (see Figure 2.2). The easterly trade winds drive a westward current in the southern part of the gyre (around 15° N), while the westerlies at around 30° N generate an eastward current at this latitude. But as the flow is deflected to the right by the Coriolis force, it becomes squashed up against the Asian coast to the west but stretched out and broadened as it proceeds toward the North American coast. What this means is that the western part of the gyre becomes a very intense northward flow, which is called the Kuroshio, while the southward limb of the gyre off California is much more dispersed. In the Kuroshio Current, the speed of the flow can reach up to three feet per second, which is three to ten times faster than that typically observed elsewhere in the oceans.

This same phenomenon occurs in the North Atlantic, where the intense northeasterly flow from the Gulf of Mexico and the Florida Straits along the eastern North American seaboard corresponds to the Gulf

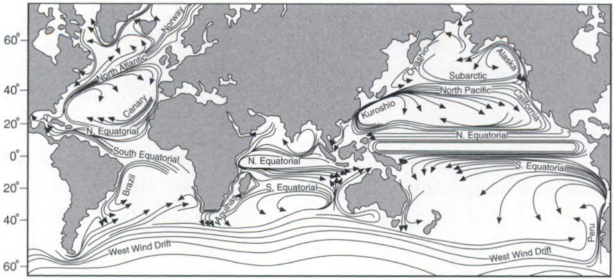

Figure 2.2 *Big wheels keep on turning. Global ocean-surface currents are driven by winds. The obstruction by the continents and the force generated by the Earth's rotation mold the currents into circulating "gyres." The circulation in the Indian Ocean reverses direction between winter and summer, owing to seasonal changes in the Asian monsoon winds.*

Stream. This narrow flow eventually becomes a more diffuse northeasterly current, the North Atlantic Current, which travels toward the British Isles and Norway, bringing warm water and a milder climate to western Europe than is experienced at comparable latitudes on the North American continent. A similar focusing of the subtropical gyres occurs in the Southern Hemisphere, leading to the intense Brazil Current in the South Pacific and the Agulhas off southeastern Africa in the South Indian Ocean (Figure 2.2).

All of this is generalization, and thus simplification, that considers only the annually averaged flows. Only the easterly trade winds are steady throughout the year. Moreover, inconstant flows at smaller scales embellish the gyre systems with vortexlike eddies. The inconstancy of the oceans is illustrated most strikingly in the Indian Ocean, where the surface currents rotate in different directions at different times of the year in response to changes in the Asian monsoon winds. From around June to September, the southwest monsoon over India drives a clockwise circulation centered somewhere near the equator; from November to March, the northeast monsoon over southeast Asia reverses this flow.

SALT POWER

Winds can't drive ocean circulation at depths of much below three hundred feet. Deep circulation has another origin: it is driven largely by differences in water temperature. This churning, at depths of between one half and three miles, carries warm water into colder seas, and so redistributes heat around the planet. Deep-water circulation forms a conveyor-belt flow which links all three of the world's oceans via the Southern Ocean (Figure 2.3). To see how this flow is sustained, let's pick up a ride at the sea surface in the equatorial Atlantic Ocean. The upper part of the conveyor belt here is traveling northward, and consists of water that has been warmed in the tropics. As it travels poleward, this water mass cools and becomes more dense. At the same time, evaporation from the sea surface leaves the surface water more salty, since the escaping water vapor does not take the salt with it. This enhanced saltiness (salinity) also increases the density of the sea water. So as the current progresses poleward it becomes heavier than the water below, and it sinks in the vicinity of the Labrador Sea, south of Greenland.

This cool, salty, dense water mass becomes North Atlantic Deep Water, which plunges to depths of more than half a mile and is then carried

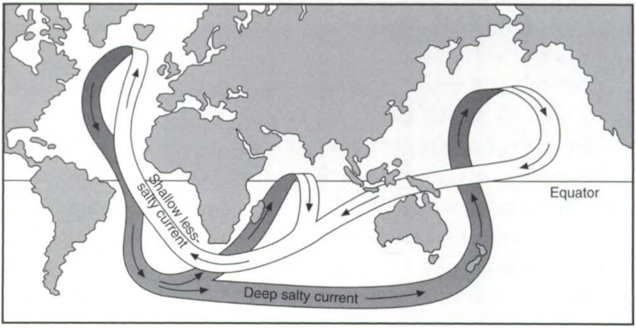

Figure 2.3 *The global conveyor. Circulation in the deep oceans bears warm, less-salty water along its upper belt and cold, salty water on the lower belt.*

in a return flow along the lower part of the conveyor belt back toward the equator. It passes from north to south across the entire Atlantic Ocean before reaching the Southern Ocean, where it rises toward the margins of the Antarctic continent. During the Antarctic winter, a portion of this water mass freezes as sea ice in the Weddell Sea, leaving behind even colder and saltier water (since freezing, like evaporation, removes relatively pure water: the ice excludes the salt). This dense water sinks right to the ocean floor as Antarctic Bottom Water, the densest water in the oceans. But most of the deep current coming into the Southern Ocean from the Atlantic is borne eastward as a salty flow called Antarctic Circumpolar Water before turning northward into the Pacific Ocean off Australia. Here it warms up as it flows into the tropical Pacific Ocean, and the warmer, less dense water rises in the central North Pacific Ocean on the ascending branch of the conveyor belt, there to be carried back westward toward the Atlantic Ocean.

These differences in temperature and salinity mean that the deep oceans are not simply one homogeneous mass of water—they can be divided up into distinct reservoirs, which follow different pathways and mix rather little. The global conveyor belt of deep circulation is called the thermohaline circulation, since it is driven by changes in heat (Greek *thermos*) and salinity (*halos*). The North Atlantic limb of the conveyor belt carries huge amounts of heat poleward in the warmer surface flow, which is released at high latitudes as the water cools and sinks. The heat delivered to the high-latitude North Atlantic Ocean in this way is about a quarter to a third of that delivered by direct sunshine. So the thermohaline circulation has a strong influence on climate. During the ice ages, it is believed that the circulation was far weaker, because the temperature difference between the tropics and high latitudes was less pronounced than it is today.

As the last ice age was coming to an end and the global climate was warming, around twelve thousand to ten thousand years ago, there was a sudden reversion to glacial conditions around 10,500 years before the present. This shift in climate, called the Younger Dryas event, seems to have been mind-bogglingly rapid: some estimates indicate that the global climate reverted from something like present-day conditions to those of the ice age in around fifty years. Some oceanographers believe that the shift may have been caused by a partial shutting down of the thermohaline circulation as the extensive northern ice sheets melted and flushed fresh water into the ocean. This dilution of the salty surface waters in the North Atlantic Ocean would have made them less dense and less susceptible to sinking, and so the conveyor belt might have ground almost to a halt. The message is sobering, and is reinforced by similar rapid climate shifts that have shown up in climate records from the still more distant past: the deep circulation of the oceans may be a sensitive switch that could plunge the world into a deep freeze if disturbed.

RHYTHMS OF THE MOON

Superimposed on the large-scale average flows in the oceans are currents due to the daily ebb and flow of the tides, which can raise sea level by as much as forty-six feet on some coasts. Because the rise and fall of the tides has always been so important to many aspects of community life in coastal regions—from river transport to fishing to land access and availability—tide cycles have been monitored with intense interest since antiquity, and their association with the phases of the Moon has been long known. The Japanese poet Shosammi Sueyoshi implies this connection with characteristic delicacy in the *Shinkokinshu* anthology (1205):

The cries of the night
Sanderlings draw closer
To Narumi Beach;
As the moon sinks in the sky
The tide rises to the full.[6]

But it was not until 1687 that Isaac Newton provided a mechanical explanation for the "Moon's floods." Newton realized that the gravitational pull of the Moon would distort the Earth's shape and modify the profile of the oceans.

The gravitational pull of the Moon draws out a bulge in the ocean on the moonward side which is highest at the closest point on Earth to the Moon (the zenith).[7] But there is more to the tides than this, because of the Moon's rotation around the Earth. To be more precise, the Earth and the Moon are rotating around their common center of mass—the point where a fulcrum would balance them on a set of cosmic scales. Because the Earth is much more massive than the Moon, the center of gravity of the two is inside the Earth, 2932 miles from the planet's center on the moonward side.

The rotation about this point creates a centrifugal force on the surface of the Earth. At the place on Earth that is farthest from the Moon (the nadir) the centrifugal force, dominating over the tug of the Moon's gravity, produces a second tidal bulge. The Moon rotates around the Earth in just over a terrestrial day—twenty-four hours and fifty minutes—dragging with it the tidal high points of the zenith and nadir and so creating a twice-daily (semidiurnal) high tide. Because of the fifty-minute difference between a terrestrial day and the lunar rotation period, high tides come twenty-five minutes later on each successive half day.

Although the dominant influence on the tides, the Moon is not their sole instigator. The Sun exerts tidal forces too, which operate in just the same way but are a little under half as strong. The main (semidiurnal) solar tide repeats every twelve hours. And both individually and acting together, the Sun and Moon establish still more subtle rhythms in the rise and fall of the seas, like the overtones of a bowed violin string. When the Earth, Moon, and Sun line up at full and new moon, the solar and lunar tides reinforce each other and the waters rise to their highest extent. These are the spring tides. The low neap tides, on the other hand, happen when the line between the Earth and Moon is perpendicular to that between the Earth and Sun—when the Moon waxes through its first quarter or wanes through its third.

If the Earth were all water, it would be possible to predict the coming and going of the oceans' tidal bulges with mathematical precision. But the continents and the topography of the sea floor hinder their progress, and the Coriolis force deflects tidal currents in opposite directions in the two hemispheres. As a result, the arrival times of high tides at any point in an ocean basin cannot be predicted on the basis of astronomical calculations alone. It is a complex and largely empirical matter to map out the phases and amplitudes of the tides in any ocean basin—and even then these are subject to seasonal and longer-term variability. While Newton no doubt envisaged the tides as clockwork-like cycles, the truth is, as usual, more complicated, and fishermen are still better served by books of tidal tables than by pocket calculators.

THE GREAT ARTERIES

When the river rages,
he is not alarmed

Job 40:23

The great rivers of the world have a profound resonance even for those who have never set eyes on them. The names alone are enough to conjure up dark tales of exploration and adventure, romance and intrigue: the Congo, the Amazon, the Nile, the Volga and Seine and Danube. Perhaps it is too facile a connection, but I cannot help but wonder whether the stirrings that these names evoke are an echo of the ancient significance of the world's waterways, which offered travel in an age before airlines and abundance in an age before supermarkets and global agroindustry. Historian Simon Schama sees still deeper roots:

> *To see a river was to be swept up in a great current of myths and memories that was strong enough to carry us back to the first watery element of our existence in the womb. And along that stream were borne some of the most intense of our social and animal passions: the mysterious transmutations of blood and water; the vitality and mortality of heroes, empires, nations, and gods.*[8]

The water that bathed and nurtured the roots of human civilization was fresh, not salt. All of the four oldest great civilizations sprang up by rivers and their fertile floodplains: Mesopotamia bracketed by the Tigris and the Euphrates (in modern Iraq); the Harrapan culture on the Indus (in what is now Pakistan); China on the mighty Yangtse and Yellow rivers from the brow of the Tibetan plateau; Egypt on the Nile. The fundamental nature of this dependence on water is reflected linguistically in Persian, in which the first word of the dictionary is *ab*, meaning "water." Herein lies the root of the word *abode*, from the Persian *abad*; and derived therefrom is *abadan*, "civilized." Quite literally, water constitutes the beginning of civilization.

Today rivers remain a source of plenty: of water for domestic supplies; for cooling, cleaning, and other industrial purposes; for agricultural irrigation; for energy generation via hydroelectric power. For many people of the world rivers supply the staple protein intake in the form of fish, and their significance as routes of trade and transportation remains hard to overstate. They supply profound inspiration to artists and poets, and to scientists also. The metaphor of a river recurs throughout myth and literature. The primal significance of rivers is made explicit by the French poet Paul Claudel in a hypnotic recitation of names:

> *Knowing my own quantity,*
> *It is I, I tug, I call upon all of my roots, the Ganges, the Mississippi,*
> *The thick spread of the Orinoco, the long thread of the Rhine, the Nile*
> *with its double bladder . . .*[9]

Tales of epic exploration on the world's great rivers abound. The Nile, steeped in Egyptian myths of death, resurrection, and fertility, its waters attributed a healing potency even as late as the seventeenth century, is the archetype of all rivers. The source of the Nile became an almost legendary Holy Grail. Caesar offered to abandon his wars in return for a glimpse of the springs from which it flowed, while for nineteenth-century explorers, obsessed with the Western idea of rivers as lines of power, the urge was to "penetrate directly to the source."[10] But the problem was that, as Claudel hints, this mighty river has no unique point of origin. The Blue Nile flows from the Ethiopian highlands, a fact known to the ancient Greeks. At Khartoum in Sudan it converges with the White Nile, whose source lies deep in the central African continent. John Speke identified this source as Lake Victoria in 1858, and in 1860 he established the Kagera River in Burundi as the Nile's southernmost point. David Livingstone found the source of the Congo on an expedition launched in 1866, but his quest for the still-disputed source of the Nile was curtailed by his death from malaria in 1873. The Amazon, which rises in the Peruvian Andes just 100 miles from the Pacific Ocean, owes the name by which it is now known to the Eurocentrism of the Spanish explorer Francisco de Orellana, who was purportedly assailed by a tribe of female warriors during his trek down the river in the 1540s. Thus did the river acquire the incongruous name of the tribe's counterparts in Greek myth.

Other rivers have long been major arteries of commerce. The Rhine, which makes a journey of 818 miles from the Austrian Alps to the North Sea at Rotterdam, is navigable as far as Basel in Switzerland, and is linked by canal to the Ruhr industrial region of Germany and recently via the Rhine–Main–Danube waterway to the Danube—Central Europe's longest river—and thence to the Black Sea. But it is perhaps in the twin threads of the Tigris and the Euphrates, which empty into the Persian Gulf, that we can see the most profound role of rivers in human history. For in the land "between two rivers," which is how the Greek name of Mesopotamia translates, nomads settled on the fertile flood plain in 8000 B.C. to become possibly the first farmers and herders in human history. There followed a succession of great civilizations: Babylonia in the lower valley from around 5000 B.C., settled by tribes from near the coast of the Gulf; Sumeria in southern Mesopotamia from around 3100 B.C.; and Assyria in the northeast from 2000 B.C. The need for coordinated irrigation to support the Babylonian settlements spurred the development of one of the earliest governmental structures, and also of industry—for coordinated engineering was required—and foreign trade in raw materials. The Sumerians made canals along the Tigris at least as far back as 2400 B.C. In this fecund land we can discern how water brought culture and learning, social order and technological advancement, to the ancient world.

A FORCE OF NATURE

> As water wears away stones
> and torrents wash away the soil,
> so you destroy man's hope.
>
> *Job 14:19*

The geological role of rivers and streams[11] has many faces. They typically carry off around 30 percent of the rain or snowmelt that falls on the areas that they drain. These areas, called drainage basins (also watersheds in the United States or catchments in the United Kingdom), are defined by the topography of the land, being typically bordered by ridges beyond which the next tiny stream feeds ultimately into another river. The shape of a drainage basin is determined by the river network itself as it incises channels into the landscape. The channel heads slowly cut back into the bedrock by washing away material through erosion. The result is typically a highly branched network, like the tree-root profile of the Amazon.

But the shapes of rivers can differ markedly. The Nile is the world's longest river—4123 miles from the source of the White Nile in Burundi to the Nile's outflow in the Mediterranean Sea—but is rather thin and straight, with a catchment never exceeding 1240 miles in width. The Amazon is just 120 miles shorter, but it sprawls more widely to encompass a catchment of over twice the area of the Nile's: 2.7 million square miles, an astonishing 5 percent of the world's total land surface area. In part these differences can be ascribed to the differing climates of the two regions: much of the Nile runs through dry, parched lands for most of the year, whereas the Amazon's moist rain forest experiences extensive precipitation, giving it a wider source area and a greater annual flow than the Nile.

Of the different shapes that rivers and streams can adopt, two of the most common are called meandering and braided. Rivers flowing down low slopes over predominantly silty or clay terrain—conditions fulfilled on many floodplains—tend to wander in broad, symmetrical curves with a roughly constant wavelength. The word *meander* derives from the river Maiandros (as the ancient Greeks called it) or Menderes (as it is now known) in Turkey, a famously twisty example. Meandering rivers change their course over time like a writhing snake, sometimes fast enough to complicate surrounding agriculture: the Mississippi can shift its tracks by up to twenty yards a year. Shifting meanders may leave behind them oxbow lakes where bends have approached close enough to fuse. These fusion events take place because the outside edges of each loop are always pushing farther out, since erosion is greatest at these points. The current is slowest, meanwhile, at the inside edges of meanders, which can consequently become clogged with deposits of silt. Braided rivers, on the other hand, follow a complex, interwoven network of paths separated by islands and spits. They seem to be the result of high sediment transport in the river water, a factor underlined by their similarity in appearance to small streams of water flowing over flat sandy beaches to the sea.

The migration of rivers and streams over a valley floor creates a flat floodplain, across which the waters rush if the river bursts its banks. Floodplains receive fresh doses of sediment during each flood; it is to such rich deposits, seasonally renewed and moistened, that the Nile Valley owes the fertility that nurtured early Egypt. But floodplain settlements live in risk too. Preferential deposition of sediment at the channel edges during floods can create natural levees around a river that help to confine it but may also allow it to rise above the level of the floodplain. If the river bursts these levees in flood, the result can be catastrophic.

Streams and rivers are a major shaping force of geology. They redistribute sediments to the tune of around sixteen billion tons each year—a figure that has risen dramatically since prehistoric times owing to human activities such as agriculture and dam building. These sediments, as they are dumped at vast river deltas, may gradually extend the borders of the continents. Rivers carve highlands into rugged landscapes, wearing away solid rock by a variety of processes. Sand and small stones carried by the flow grind away at the riverbed, slowly carving out delicate flow-forms by abrasion. Larger rocks and boulders carried by more violent flows may crack and splinter the channel's boundaries. And ever the universal solvent, water erodes by chemical action too, dissolving minerals and releasing their elements into biogeochemical cycles.

GOING UNDERGROUND

Can reeds thrive without water?

Job 8:11

Even the most arid of terrains is not always as dry as you'd think. Deserts have their oases, and regions miles from the nearest stream or river can be supplied with water from a deep well. How does this water appear from out of the parched earth?

A very small, but for human purposes highly significant, fraction of the world's water resides in hidden places. Around two-thirds of the rainwater that falls is returned directly to the atmosphere by evaporation and transpiration, and most of the rest is runoff, feeding streams and rivers. But a small amount permeates into the ground, draining through the spaces between soil grains until it reaches an impermeable layer of bedrock or dense clay. Here the water flows down the slope of the impermeable layer, winding its way through the soil's pores or through cracks and fissures in overlying rock. This is *groundwater*, and the permeable material through which it flows is called an *aquifer*—a "water-bearer." The channels of the aquifer are saturated with water, and the upper limit of this saturated region corresponds to the water table.

Strictly speaking, only the water in the saturated region is groundwater; above this, water that penetrates but does not saturate the soil is called vadose water, and this is the stuff that sustains most land plants and biological activity in the soil. If the water table rises close to the surface, the soil becomes waterlogged, and the only plants that can grow there are those tolerant to having their roots permanently doused in water, such as reeds and sedges. These saturated ecosystems are the Earth's wetlands: bogs, fens, marshes, and swamps, all of them rich habitats and crucial to the biogeochemistry of the landmasses.

The water table is not as clearly defined as the surface of a stream, since the water level peters out gradually. Moreover, its depth depends on the nature of the pore space in which the water sits, for in very narrow vertical pores the water level rises higher than gravity alone would permit. The water is sucked up the pores by "capillary action," a consequence of the molecular forces of interaction between the pore walls and the liquid. It's this same effect that pulls up a curved meniscus when water meets the side of a glass beaker. The height of the "capillary rise" is greater for narrower pores. In clay soils, where the grains are very small and the pore spaces between them are narrow, capillary action can raise the water level by over ten feet.

A well can be created by drilling below the water table to reach an aquifer. If the water finds its own way out, for example through fissures in an aquifer's impermeable base that allow the water to emerge from a hillside or valley slope below the aquifer, the result is a spring. Some aquifers are confined between two layers of impermeable rock, and so there is no water table: the water cannot find its own level, but is forced to stay below the capping layer. Then it can become pressurized, particularly at depressions where the water flow is channeled into a basin. A hole drilled through such an aquifer releases this water under pressure, so that it surges spontaneously to the surface in a so-called artesian well.

Groundwater dissolves a rich concoction of minerals from the rocks through which it flows. It contains dissolved carbon dioxide from the atmosphere and from decomposition of plant matter, which turns it weakly acidic. If this water comes into contact with chalk and limestone—both comprised primarily of calcium carbonate, in combination with some magnesium carbonate—the acid reacts with the insoluble carbonates to generate relatively soluble bicarbonates and the groundwater becomes a weakly alkaline bicarbonate solution. This is "hard water," which causes scaling of water pipes and furring of kettles: the "scale" is made up of calcium and magnesium carbonates, which precipitate when the water is boiled and left to cool. "Soft water," on the other hand, comes from aquifers that pass through rocks such as slate and granite, which contain little or no calcium and magnesium.

Dissolved minerals give springwater its health-sustaining properties. The "healing waters" of spa towns such as Bath in southwest England have been celebrated at least since Roman times. The minerals impart a certain saltiness to the spring water, and this brew is all the more potent when the water is warmed during its passage through the earth, increasing its dissolving power. At warm springs such as those at Bath, the water penetrates deep enough through rock fissures to be heated by the ground's natural thermal gradient—the Earth gets warmer with depth at a rate of around 60–120° F per mile.

The temperature of thermal springs may be no greater than a comfortable 80° F or so, although at Bath it reaches almost 120° F. The hottest of hot springs, however, such as those that attract bathers in Iceland and Japan, are warmed by different means. These countries sit over or close to

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