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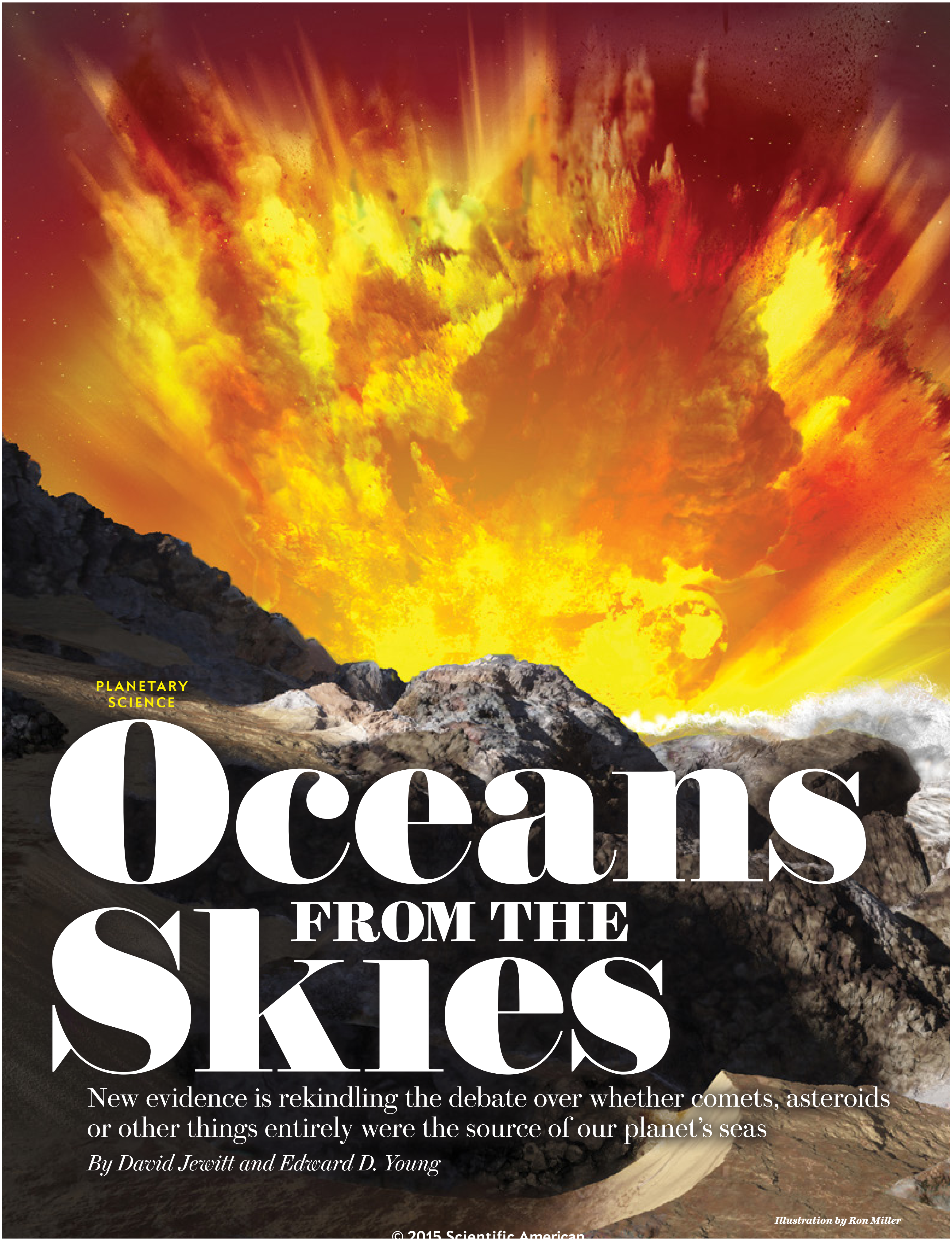
Scientific American,
2015 March issue, pages 36 - 43



PLANETARY SCIENCE

Oceans FROM THE Skies

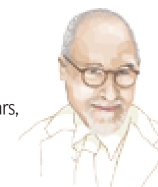
New evidence is rekindling the debate over whether comets, asteroids or other things entirely were the source of our planet's seas

By David Jewitt and Edward D. Young

Illustration by Ron Miller

David Jewitt traces his interest in astronomy to age seven, when he was astonished by a spectacular meteor shower over London. He is a member of the National Academy of Sciences and a professor at the University of California, Los Angeles. Jewitt drinks a lot of water (but only in the form of coffee).

Edward D. Young is a professor of geochemistry and cosmochemistry and a member of the Institute for Planets and Exoplanets at the University of California, Los Angeles. He searches for clues to the origins of the solar system by studying the chemistry of meteorites, the interstellar medium and other stars, using sophisticated laboratory instruments and the world's largest telescopes.



STANDING ON THE SEASHORE, WATCHING WAVES ROLL IN FROM OVER THE HORIZON—it is easy to see the ocean as something timeless. Our ancient ancestors certainly did. In numerous creation myths, a watery abyss was present before the emergence of land and even light. Today we realize that Earth's global ocean has not been around forever. Its water—as well as every drop of rain, every gust of humid air and every sip from your cup—is a memory from eons ago, when the seas literally fell from the sky.

All the water in our solar system can be traced to the giant primordial cloud of gas and dust that collapsed to form the sun and planets more than four and a half billion years ago. The cloud was rich with hydrogen and oxygen, the two atomic ingredients for water, H_2O. That enrichment is no surprise because hydrogen and oxygen are also the first and third most abundant elements in the universe (chemically inert helium is the second). Most of the gas was sopped up by the sun and the gas-giant planets, which formed earlier than the rocky planets. Much of the remaining oxygen bonded with other atoms, such as carbon and magnesium, but the hydrogen and oxygen left over were sufficient to produce several times more water than rock in our solar system.

And yet this is not what we see. Earth and its neighbors Mercury, Venus and Mars are rocky, not water worlds. Their relative lack of water is a product of where and how they were born. As the cloud that would become our solar system collapsed, its angular momentum flattened the material into a whirling disk, in which all the planets formed. The formation of rocky worlds is thought to be a progressive, step-by-step process where smaller objects in the disk collide and stick together to form larger ones: microscopic grains become pebbles, which become boulders, which become kilometer-scale planetary building blocks called planetesimals. Many of the planetesimals left over from planet formation then became the objects that we know today as asteroids and comets.

In the disk's inner regions near the sun, intense frictional heating of the gas and more sunlight probably cooked off hydrogen and other light elements, leaving only relatively dry material from which to form planets. As dry, rocky bodies were growing rapidly near the sun, farther out, somewhere in the vicinity of what is now the asteroid belt and Jupiter, temperatures in the disk were low enough to allow water and other volatiles to form ices. Astronomers call this transition point the "snow line," and conventional wisdom holds that most of Earth's water came from beyond it, in showers of icy asteroids and comets that were perhaps flung down into the inner solar system by the outer giant planets during the last gasps of planet formation.

Recently further evidence of snow lines and late-stage planetesimal collisions has emerged from observations of other stars in the midst of forming planets. Looking into the depths of interstellar space, we can see the same primordial processes that took place here in our own solar system unfolding far away, before our telescopic eyes. Even so, many aspects of the grand tale of our ocean's formation remain mysterious and are subjects of intensive ongoing research. As timeless and ineffable as

IN BRIEF

Intense heat and light near the young sun largely confined water to the outer solar system during planet formation, leading to relatively dry inner worlds.

Earth's water probably arrived late in the planet's development, via showers of asteroids or comets. But the data in hand leave room for alternative ideas.

Exactly how our water got here could remain an unsolved mystery for some time, pending the questions of when and if we will commence more robust exploration of the rest of the solar system.

A one-size-fits-all solution for the source of Earth's water may never be found.

Earth's oceans may seem, new evidence is bringing us closer to answering exactly how and when they formed and whether it was mostly comets, asteroids or some entirely different delivery mechanism that brought all that water to our once dry planet.

AN OCEAN PLANET DRIER THAN A BONE

AS VIEWED FROM SPACE, planet Earth might instead be "planet Ocean." Water covers more than two thirds of the surface and makes up more than two thirds of the typical earthling. The oceans, which have an average depth of four kilometers, hold enough water to fill a sphere more than 1,300 kilometers across. Yet many people are surprised to learn that all this ocean water constitutes only about 0.02 percent of the mass of Earth. Put another way, if our planet was a 300,000-kilogram Boeing 777, then all the water in the oceans would have the mass of a single passenger. Freshwater locked up in polar ice caps, clouds, rivers, lakes, soil and Earth's biota contributes only a tiny fraction to this total.

More water may lurk deep underneath our feet, in the planet's rocky mantle, which extends more than 3,000 kilometers from the crust down to the cusp of the liquid-iron core. Water there is not in liquid form. Instead it is bound into the molecular structure of "hydrated" rocks and minerals that have been dragged below the crust by tectonic processes. Some of this rock-locked moisture can escape from the mantle back to the surface through volcanoes, but a larger fraction is buried. Deeper still lies Earth's hefty nickel-iron core. Weighing in at about 30 percent of the planet's mass, the core potentially holds even more water than the mantle in the form of hydrogen that would otherwise bond with oxygen outside of the immense heat and pressure.

If Earth was a fully loaded Boeing 777, then its ocean would have the mass of a single passenger. As strange as it may seem, proportionally our planet is some 100 times drier than old bone.

No one knows just how much water our planet's interior holds. That uncertainty stems from a lack of direct samples, as well as a poor understanding of how efficiently water is transported to and from the surface. A reasonable guess is that the mantle alone contains at least another ocean's worth of water, effectively doubling Earth's total aquatic inventory. Even so, adding that water to the surface ocean accounts for only 0.04 percent of the planet's mass, equivalent to two passengers on a fully loaded 777. As strange as it may seem, in actuality, Earth is some 100 times drier than old bone, which contains only a tiny amount of water. Nevertheless, the question of how the water that we do possess got here demands an answer.

COMETS OR ASTEROIDS?

SINCE THE EARLY EARTH is generally thought to have been even drier than our planet is today, researchers investigating the origin of the world's water have focused on the relatively late stages of Earth's formation, after the moon came into being.

The freshly formed Earth, like the sun's other rocky planets, must have had at least a partly molten surface for, at minimum, tens of millions of years after its birth. That melting would have occurred from the immense energy pumped into our planet by infalling swarms of mountain-size planetesimals. Although there is geochemical evidence that Earth's magma ocean contained some water, hot molten rock is not very good at holding water, so much of the moisture from the proto-Earth and from the planetesimals would have been liberated as ionized gas and steam. Some of that material was lost to space, but some of it could also have fallen back to Earth to once again become locked in rock before being subsumed deep into the mantle.

Later, other huge impacts would have further altered the inventory of water at and near the terrestrial surface. In particular, Earth seems to have collided with a Mars-size body approximately 4.5 billion years ago, ejecting a plume of material that cooled and coalesced to become the moon. The energy of this global-scale impact would have swept away much of the atmosphere, flash-boiled any watery oceans and produced an ocean of magma hundreds of kilometers deep. Regardless of whether Earth formed wet or dry, the devastating blow of this moon-forming impact must have cleansed our planet of nearly all its primordial water.

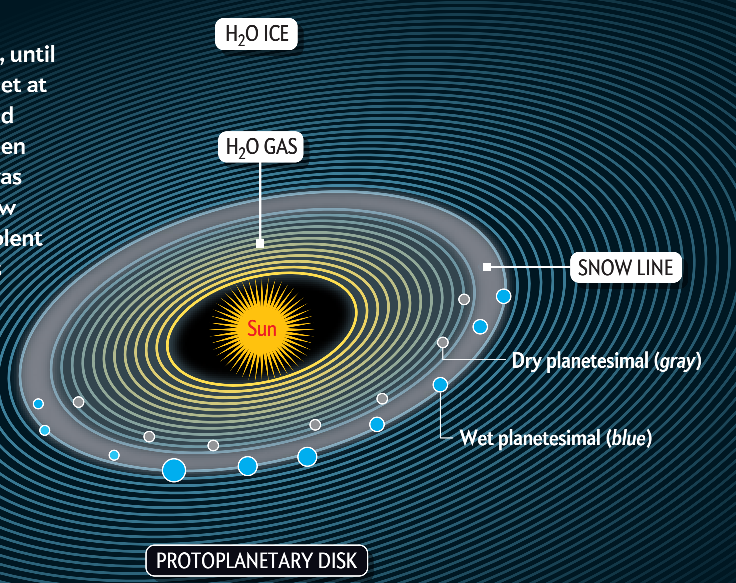
Knowing all this, scientists have long sought a source of water that could be delivered after the formation and cooling of the Earth-moon system. Comets have been known to be ice-rich since the 1950s, and they enter the inner solar system from two vast reservoirs in the outer solar system called the Kuiper belt (which begins around the current orbit of Pluto) and the Oort cloud (which begins far past the Kuiper belt and stretches perhaps halfway to the nearest star). Perhaps, many researchers have thought, comets were the dominant source of Earth's ocean.

But the notion hit some trouble in the 1980s and 1990s, when researchers made the first measurements of deuterium/hydrogen (D/H) ratios on comets from the Oort cloud. Deuterium is a heavier isotope of hydrogen, with a neutron in its nucleus, and its prevalence compared with that of normal hydrogen serves as a useful fingerprint for tracing an object's history. If Earth's ocean was made of melted comets, its D/H ratio should closely match those of comets we observe today. But the Oort cloud comets showed D/H ratios twice as high as that of ordinary seawater. Clearly, most of Earth's water must have come from elsewhere.

In the past few years, though, measurements of comets from the Kuiper belt showed D/H ratios similar to the ocean's, reinvigorating the case for comets delivering Earth's water. But now the pendulum is swinging away from comets once again. Late in 2014 findings from the European Space Agency's Rosetta spacecraft showed that the Kuiper belt–originating comet 67P/Churyumov-Gerasimenko possessed a D/H ratio three times greater than that of the ocean, providing another data point in

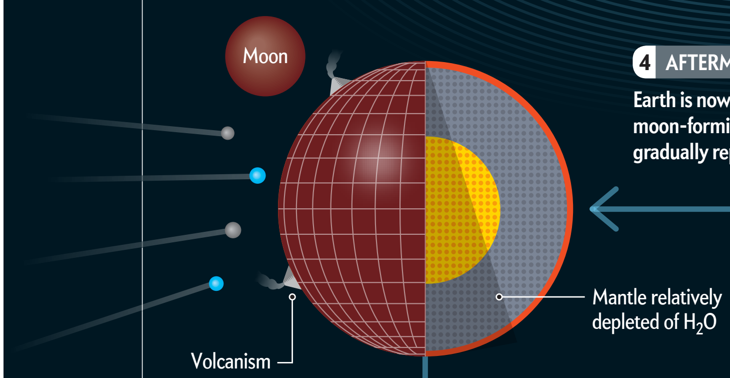
Water's Tumultuous History on Earth

Earth has not always been a planet with oceans. In fact, until about four and a half billion years ago, it was not a planet at all, having yet to coalesce from a swirling disk of gas and dust around the young sun. The disk was rich in hydrogen and oxygen, water's raw ingredients, but most water was relegated to the disk's cold outer regions, past the "snow line," where it existed as ice. Our world formed from violent collisions in the disk between planetary building blocks called planetesimals. Some were from close to the sun, and dry, but others were wet, from past the snow line, giving our infant planet some initial water. Getting today's oceans, however, took many more steps. Researchers generally agree on this scenario, although they argue over details, such as whether comets or asteroids brought more water to Earth.



4 AFTERMATH

Earth is now dry and slowly recovers from the moon-forming impact. Volcanoes and impactors gradually replenish the atmosphere.

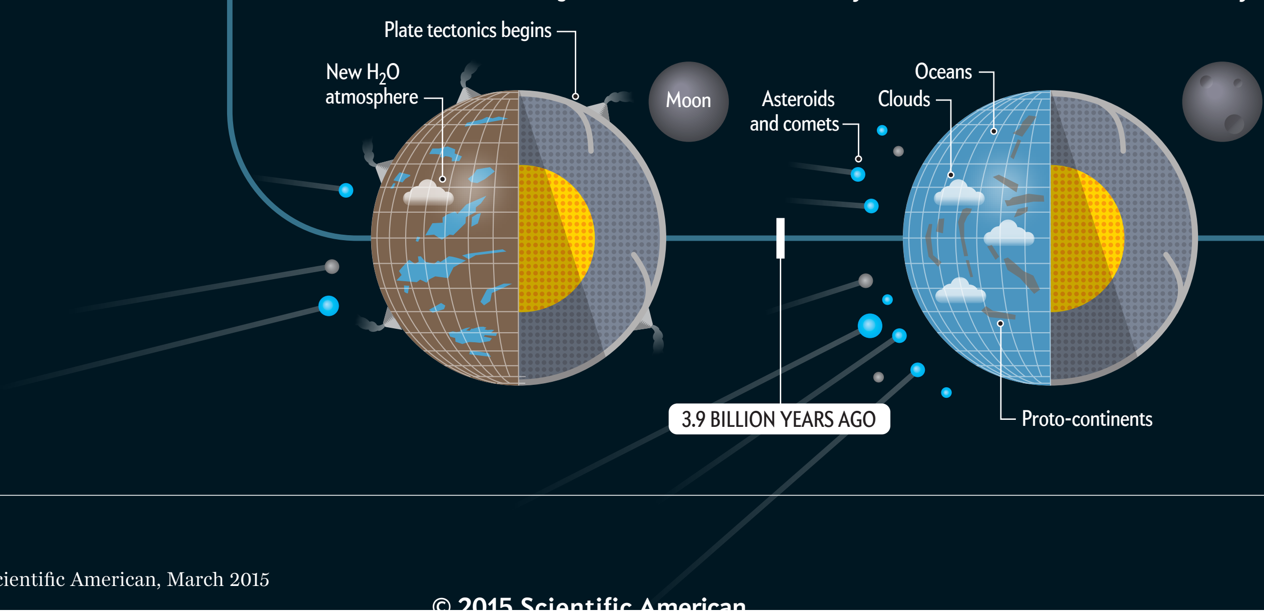


5 COOLING DOWN

Water from impactors and volcanic outgassing forms small seas on Earth's cooling surface.

6 LATE DELIVERY

A burst of leftover planetesimals (some mixture of asteroids and comets) bombards the planet from the water-rich outer solar system. The ocean rains out from a steam-filled sky.



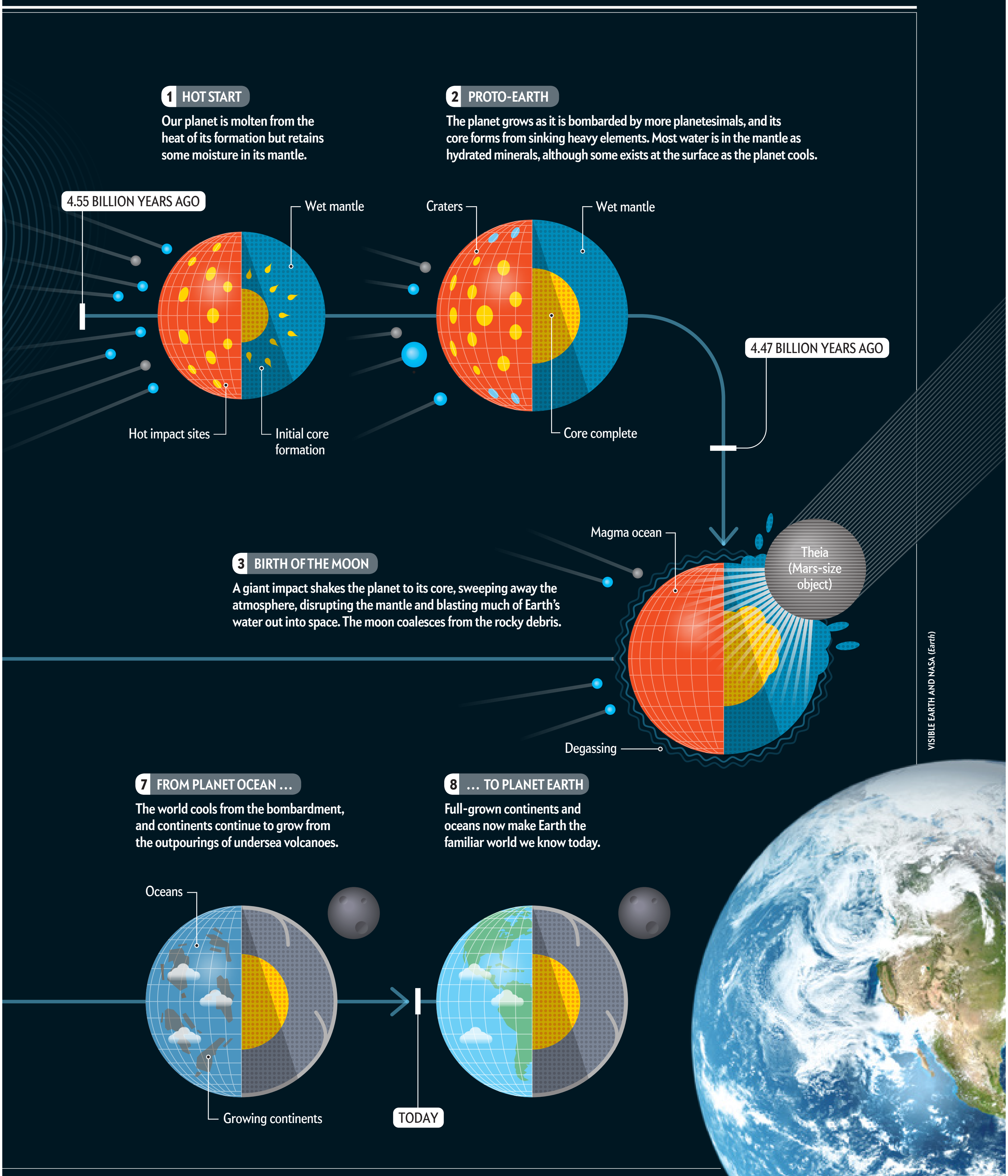


Illustration by John Grimwade

favor of some other extraterrestrial source for Earth's water. This result, paired with arguments based on the orbital dynamics of infalling bodies from comet-rich regions, suggests that although occasional comet impacts must have delivered water to Earth, this mechanism is unlikely to be the dominant source.

Asteroids are the obvious alternative, and today they are the consensus favorite for where most of Earth's water came from. Like comets, asteroids are also pieces of small planetesimals from which the planets were built. "Main belt" asteroids orbiting between Mars and Jupiter are far closer to Earth than the Kuiper belt is and, once displaced, have a much better chance than comets of hitting Earth. Proof of this is no farther away than the moon, which is pockmarked by craters from ancient asteroid impacts. Meteorites—rock chips from asteroids that have reached Earth's surface—also fill our science museums as potent reminders that Earth is still steadily bombarded with interplanetary debris. By studying these rare pieces of asteroids, we can glimpse their deeper histories and determine whether or not they might have filled Earth's ocean. Already studies of certain families of meteorites have shown that their D/H ratios align with that of seawater.

In the quest to distinguish between asteroids and comets as the sources for Earth's ocean, there are no easy solutions. The problem may not lie with nature but rather with the questions we ask of it.

Meteorites, like their parent asteroids, exhibit a range of compositions and water contents. Asteroids from the inner edge of the main belt, located out around twice the Earth-sun distance, generate many of the water-depleted rocky meteorites we study on Earth. On the other hand, asteroids from farther-out regions, more than halfway to Jupiter, are relatively wet. They tend to produce meteorites called carbonaceous chondrites—conglomerations of hydrated minerals and carbonates, in which water can make up several percent of the rock's mass. The history of water in these rocks has been a focus of the research of one of us (Young), which draws on observations of water coursing through rocks here on Earth. The water-rich minerals within a carbonaceous chondrite grew by reactions between the rock and either liquid or vaporous water, which take place at comparatively low temperatures of a few hundred degrees Celsius. On Earth, such minerals are produced when water percolates through porous rock. Within meteorites, they attest to a time when water ice melted and flowed through an asteroid's rocky matrix.

The heat source that melted all of this water ice was almost certainly a radioactive isotope of aluminum, ^{26}Al, which existed in abundance in the early solar system. ^{26}Al releases copious energy for a few million years as it decays into an isotope of magnesium, ^{26}Mg. In the cold outer reaches of the young solar system, past the snow line, the heat from decaying ^{26}Al was a potent but brief force shaping the geology and hydrology of volatile-rich asteroids. For a few million years after the sun formed, the water within many asteroids would have been liquid, sustaining hydrothermal circulation systems such as those now found at volcanic vents along Earth's mid-ocean ridges. Hydrated minerals and carbonates would have formed as warm brines percolated through the cracks and fissures within and around an asteroid's radioisotope-heated interior. In the very late stages of planet formation, the gravity of the outer giant planets scattered materials throughout the young solar system, flinging wet asteroids down from beyond the snow line to strike Earth and other rocky planets.

We see evidence for this late-stage reshuffling of material in the chemistry of Earth as well as in that of Mars. For example, the platinum group elements are "iron-loving," or siderophile, meaning they have a chemical affinity for iron and other metals rather than rock. On the newborn molten Earth, these elements should have been dragged down along with the dense, sinking plumes of iron and nickel that formed the planet's core. Instead a surprisingly substantial concentration of siderophile elements exists in the mantle and even the crust today, in amounts that are consistent with chondritelike material contributing approximately 1 percent of Earth's mass after our planet had cooled enough for the core to fully form. This "late veneer" of impactors explains how we have access to enough platinum to make rings for marriage ceremonies and catalytic converters for automobiles. It also could explain how we have enough water to fill Earth's ocean. In all likelihood, all the inner rocky worlds, not just Earth and Mars, were hit with this pulse of material from the asteroid belt during the final stages of planet formation.

There seems to be, however, one key flaw in this tidy picture of asteroids delivering the bulk of Earth's water. The problem becomes evident when investigators look at gaseous elements, such as xenon and argon, which are known as noble gases because they are spectacularly inert, scarcely reacting with any chemical compounds at all. This inertness enables noble gases to serve as a tracer of various physical processes, relatively free from the confusing effects of chemistry. If the rocky planets and the asteroids are closely related, then they should have similar proportions of most noble gases. But researchers studying ratios of xenon to argon in meteorites and planetary materials that have fallen to Earth have found that both Earth and Mars are depleted in these noble gases, relative to meteorites.

Numerous possible answers to this missing xenon problem have been suggested in recent years, including some that may tip the scales back toward comets as the de facto deliverers of water and other volatiles. As of this writing, researchers are eagerly awaiting the first measurements of a comet's noble gases, which should come from the Rosetta spacecraft's exploration of 67P/Churyumov-Gerasimenko. Such measurements may help us at last arrive at a definitive answer for the origin of Earth's ocean, but if past trends are any indication, they may instead only raise more difficult questions that keep the debate raging for decades more.

SCIENTIFIC AMERICAN ONLINE Learn more about a recent breakthrough in the search for the sources of Earth's water at ScientificAmerican.com/mar2015/ocean-origins

WATER'S WELLSPRING: Evidence from Comet 67P/Churyumov-Gerasimenko (*above*) suggests asteroids (*left*) may have delivered most of Earth's water.

COURTESY OF ESA, ROSETTA AND NAVCAM (*Comet 67P/Churyumov-Gerasimenko*); COURTESY OF NASA, JPL AND JOHNS HOPKINS UNIVERSITY (*Eros*)

A FALSE DICHOTOMY?

IN THE QUEST to distinguish between asteroids and comets as the sources for Earth's ocean, it seems there are no easy solutions. It may be that the problem lies not with nature but rather with the questions we ask of it. The dichotomy between asteroids and comets may not be as stark as was previously believed. One of us (Jewitt), along with Henry Hsieh of the Academia Sinica's Institute of Astronomy and Astrophysics in Taiwan, has recently discovered main-belt comets, objects that orbit in the asteroid belt but eject dust periodically in each orbit as ordinary comets do. These objects unexpectedly retain ice even though they orbit inside the sun-soaked, volatile-depleted snow line. Furthermore, as we have shown, the real question is arguably not why Earth has so much water but rather why it has so little. There are numerous pathways by which Earth's relatively small amount of water could have been delivered, and they depend intimately on the exact history of the planet, its impactors and their initial conditions of formation. All these ambiguities leave plenty of room for other, more exotic scenarios of water delivery that, though perhaps unlikely, cannot yet be definitively ruled out.

In theory, for instance, most of Earth's water could have been here almost since the planet's beginning. New research suggests that hydrogen ions from the solar wind could have accumulated to form hydrated minerals on the amorphous rims of interplanetary dust particles, which could then transport this watery material to planets and planetary building blocks early in their formation. Even so, it is difficult to conceive of exactly how such an early reservoir could persist deep in the mantle only to seep up after the great surface-scouring impacts that defined the end of the planet's formation.

Bodies larger than most comets and asteroids have also drawn attention of late. Consider the so-called dwarf planet Ceres, which at 900 kilometers wide is the largest asteroid in our solar system. Up to one half of the mass of Ceres is thought to be water. Early in 2014 researchers witnessed what seemed to be steam venting from the dwarf planet at a rate of some 20,000 kilograms an hour, providing crucial evidence that Ceres is water-rich. The mass of Earth is about 6,000 times that of Ceres. If, as many suspect, half of Ceres's mass is water, then Earth's total water inventory, subterranean and surface alike, corresponds to the water held within only about five Ceres-type bodies.

Such objects were much, much more common in the chaotic early solar system than they are today, and it is not hard to imagine that several Ceres-type bodies found their way into the inner solar system and on to Earth. Only a figurative handful of these objects would have been sufficient to give our planet the gift of the ocean, without a great need for further showers of small asteroids or comets. NASA's Dawn mission will rendezvous with Ceres this month, providing us with a new, up-close glimpse of its ice and outgassing and, undoubtedly, entirely new sets of surprises relating to the history of water both on and off our planet. SA

MORE TO EXPLORE

A Population of Comets in the Main Asteroid Belt. Henry H. Hsieh and David Jewitt in *Science,* Vol. 312, pages 561–563; March 23, 2006.

Water and Astrobiology. Michael J. Mottl, Brian T. Glazer, Ralf I. Kaiser and Karen J. Meech in *Chemie der Erde–Geochemistry,* Vol. 67, No. 4, pages 253-282; December 2007.

Detection of Solar Wind–Produced Water in Irradiated Rims on Silicate Minerals. John P. Bardley et al. in *Proceedings of the National Academy of Sciences USA,* Vol. 111, No. 5, pages 1732–1735; February 4, 2014.

67P/Churyumov-Gerasimenko, a Jupiter Family Comet with a High D/H Ratio. K. Altwegg et al. in *Science.* Published online December 10, 2014.

FROM OUR ARCHIVES

Comets. Fred L. Whipple; July 1951.

Secrets of Primitive Meteorites. Alan E. Rubin; February 2013.

Pluto and Beyond. Michael D. Lemonick; November 2014.

scientificamerican.com/magazine/sa