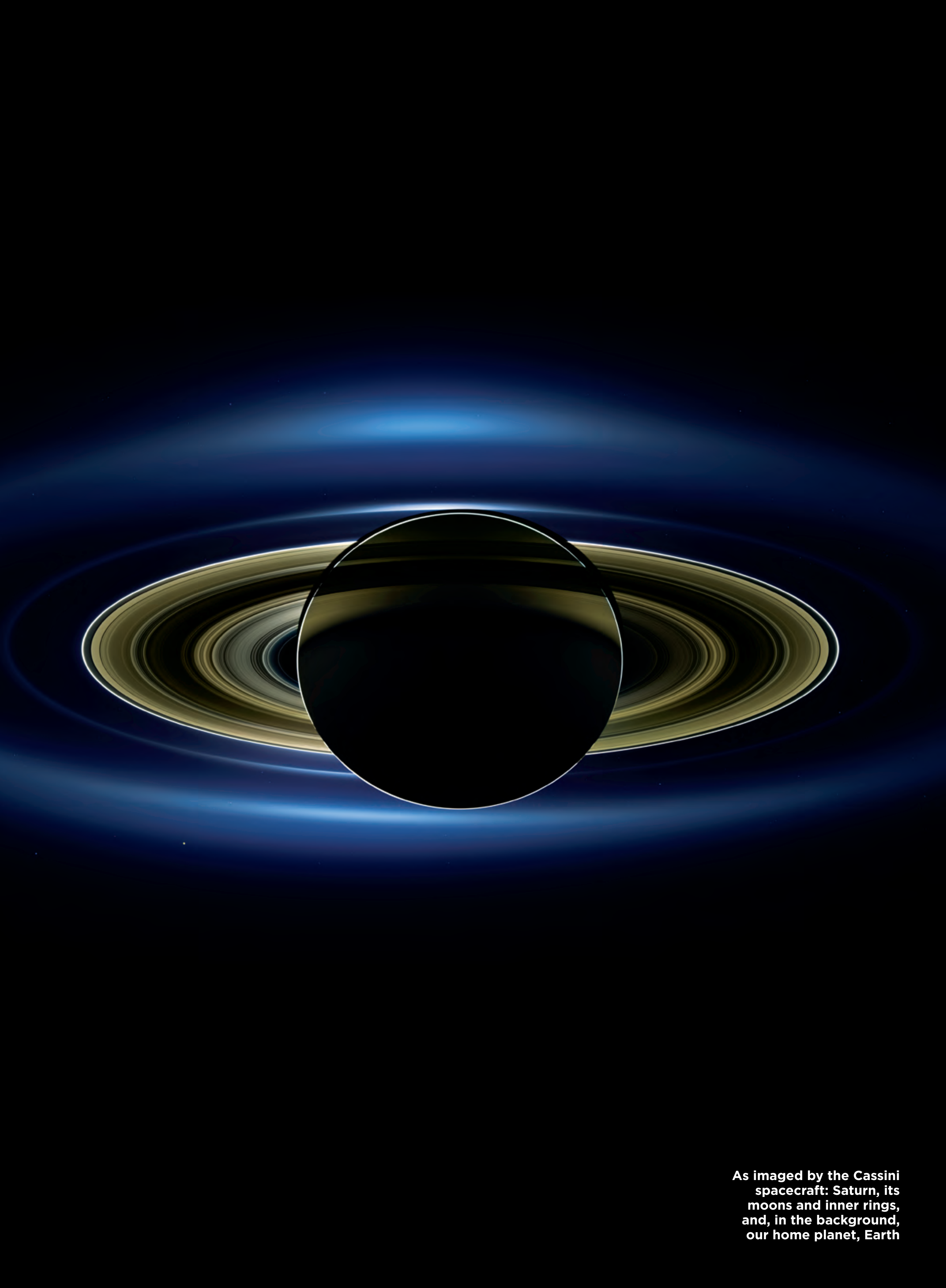
NATIONAL GEOGRAPHIC

Search for Life Across the Universe
Explore Our Sister Planets
Uncover Mysteries of Alien Worlds

THE NEXT EARTH

WHAT OUR WORLD CAN TEACH US ABOUT OTHER PLANETS

An artist's rendering of an exoplanet



As imaged by the Cassini spacecraft: Saturn, its moons and inner rings, and, in the background, our home planet, Earth

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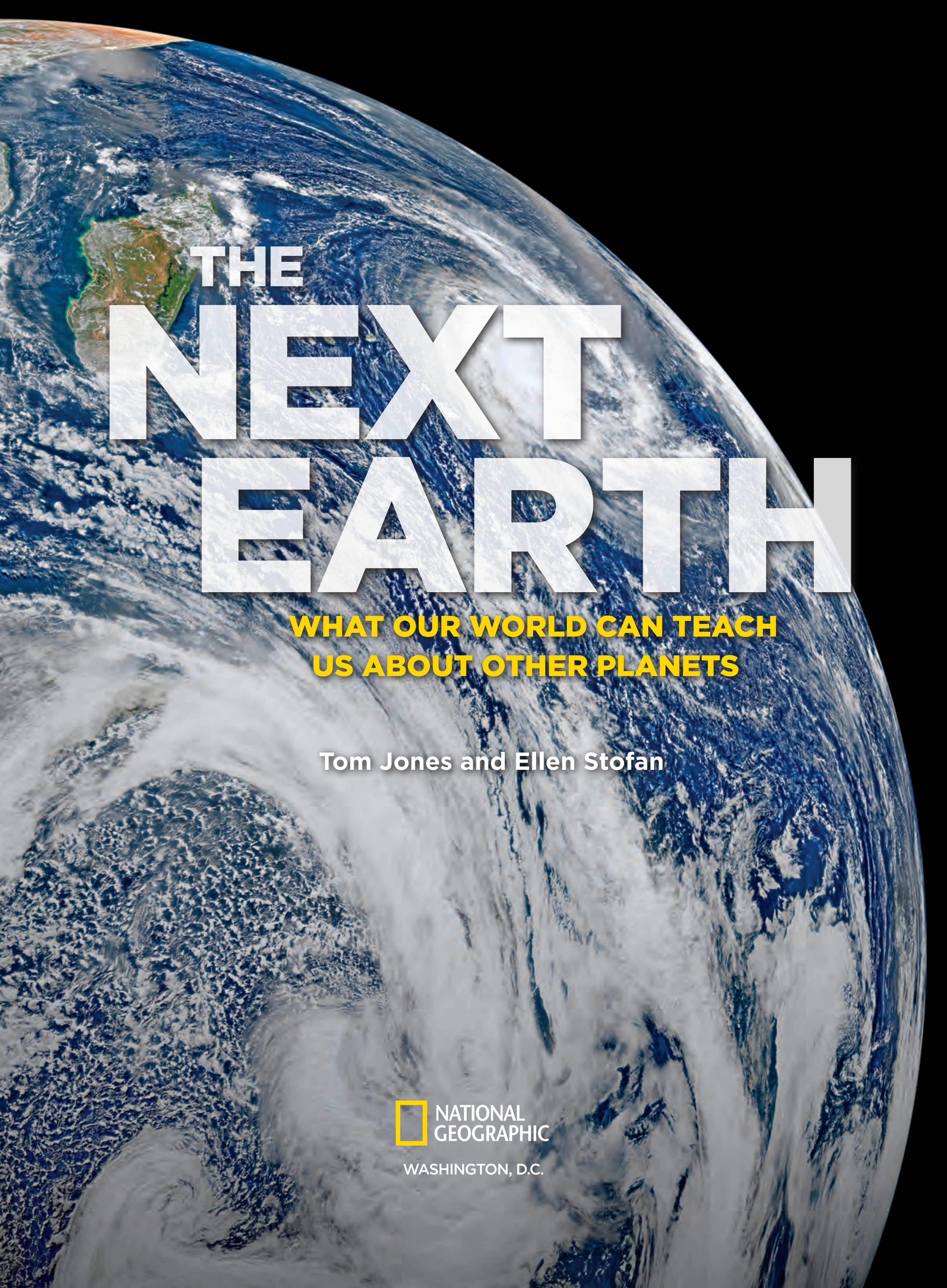

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▶ Previous pages: **In 2015 the Suomi NPP polar orbiter created this composite image of East Africa, Madagascar, and Tropical Cyclone Joalane amid the Indian Ocean.**

▶ **In less than 700,000 years, hotspot volcanoes—here, a Kilauea lava flow—have built the island of Hawaii, more than 32,800 feet (10,000 m) above the ocean floor.**

CONTENTS

The crescent moon, its shadowed face lit by earthshine, was viewed through our tenuous atmosphere in 2015 by astronauts aboard the International Space Station.

INTRODUCTION

UNLOCKING EARTH'S SECRETS

The more we learn about other worlds, the more we learn about our own.

The Next Earth presents a stunning look at our planet in the context of our solar system, seeing it as astronauts and spacecraft instruments do, and comparing those images to those of our sister planets to unlock Earth's secrets.

As space explorers, we both have long studied Earth and the planets. The spacecraft instruments with which we scout other worlds were developed from tools used to examine our own planet, outgrowths of satellite sensors that track hurricanes, scan polar holes in Earth's ozone layer, monitor rumbling volcanoes, and take our planet's temperature.

Exploring the sun's family of planets has taught humankind that ours is just one of many worlds in our solar system, among billions of solar systems in our galaxy, among billions of galaxies in the universe. Exploration has inspired a new appreciation of our Earth.

A doctor with only one patient might grow quite familiar with that patient's condition but, without examining others, would learn little about the normal state of humans or the complexities of diseases. Similarly, planetary scientists examine other worlds to develop a sharper picture of how planets work. Studying crustal faults on the icy moons of Uranus, sand dunes on ruddy Mars, or volcanoes on torrid Venus helps us understand the forces that create the same features on Earth.

As scientists and humans with a sense of wonder, we will enjoy traveling the solar system with you but always return our focus to home. As the poet T. S. Eliot wrote, "We shall not cease from exploration / And the end of all our exploring / Will be to arrive where we started / And know the place for the first time."

Anvil-top thunderstorms over the Pacific, imaged by astronauts at the International Space Station from low Earth orbit

• CHAPTER ONE •

EARTH:
KEY TO KNOWING OTHER WORLDS

Our ancestors observed the planets in the night sky and wondered if they might be worlds like our own. The telescope gave modern astronomers our first blurry glimpses of them, but only the advent of space exploration turned mystery into long-awaited facts.

Spacecraft images revealed connections between alien landscapes and Earth's dynamic surface. After spacecraft mapped craters from asteroid and comet strikes on the moon and Mars, geologists soon identified similar scars on Earth. The moon's "seas" are actually immense floods of cooled lava, like those found in Siberia, India, and the United States. Mars has volcanoes the size of Missouri, thick polar ice caps, and, as on Earth, valleys and channels seemingly cut by running water.

Examining the planets and comparing them to our own world has helped us understand the powerful geologic processes still at work here. With the solar system as our laboratory, we can begin to unlock Earth's persistent mysteries.

UNDERSTANDING OUR PLANET

A SHORT HISTORY OF EARTH

Earth, third planet from the sun, is the largest of the rocky, terrestrial planets: Mercury, Venus, Earth, and Mars. Orbiting 93 million miles (150 million km) from our star, Earth has a solid iron core, a liquid iron outer core, a semisolid mantle composing about two-thirds of its mass, and a thin, brittle crust. The crust ranges in thickness from about 18 miles (30 km) under the continents to just three miles (5 km) under the oceans.

That dynamic surface has been roiled by the hammer blows of celestial impacts and the motions of thin, rocky tectonic plates, which slide slowly across the globe, driven by relentless internal forces. Crustal movements are caused by the mantle, stretching 1,800 miles (2,897 km) from core to crust. Heated by radioactive elements like uranium, thorium, and potassium, it flows like warm molasses; rising mantle currents push and pull the crust, driving plate motions that lift mountains and fuel volcanoes. Where plates break apart along mid-ocean rifts, upwelling lavas form new crustal material. At some plate boundaries, called subduction zones, older crust plunges downward to merge into the mantle. This process destroys old ocean crust; most of the ocean floor is less than 200 million years old.

On the lighter, older continental plates, there are ancient remnants of the original crust: In Greenland, rocks as old as 4.2 billion years exist. Where continents collide, the crust crumples upward into mountain ranges like the Alps and Himalaya. Yet even the highest peaks succumb to erosion, as ice and water abrade them and carry the fragments to the oceans, to be deposited as new sedimentary rocks. We can investigate these same planet-shaping forces in our exploration of neighboring worlds.

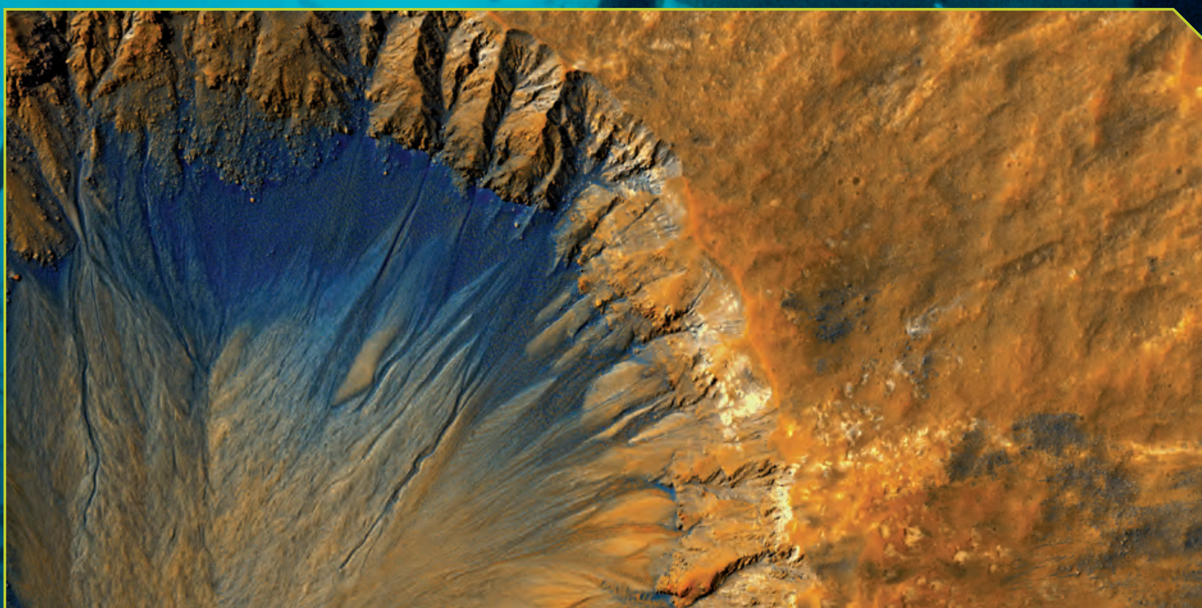
4.6 BILLION YEARS AGO
Solar system forms from a giant, swirling cloud of dust and gas.

4.5 BILLION YEARS AGO
Planets form. Earth struck by giant impact to form moon.

3.8 BILLION YEARS AGO
Atmosphere in place; heavy cosmic bombardment ends.

3.6 BILLION YEARS AGO
One-celled organisms arise.

Unlike on our blue planet, surface water is rare on Mars. Seasonal springs likely carved these gullies in a Sirenum Fossae crater (inset).



Explore More WHAT IS PLANETOLOGY?

Our exploration of the planets has yielded vital insights into the forces shaping Earth. In effect, the solar system is one big laboratory experiment, where we study how geologic forces operating on different worlds for billions of years created the planets we see today. The more planetary "experiments" we observe, the better we understand the internal and external processes that make our Earth tick. This systematic study of other worlds—their surfaces, interiors, composition, atmospheres, and geologic processes—is called planetary science, or planetology.

1 BILLION YEARS AGO
Multicelled organisms arise.

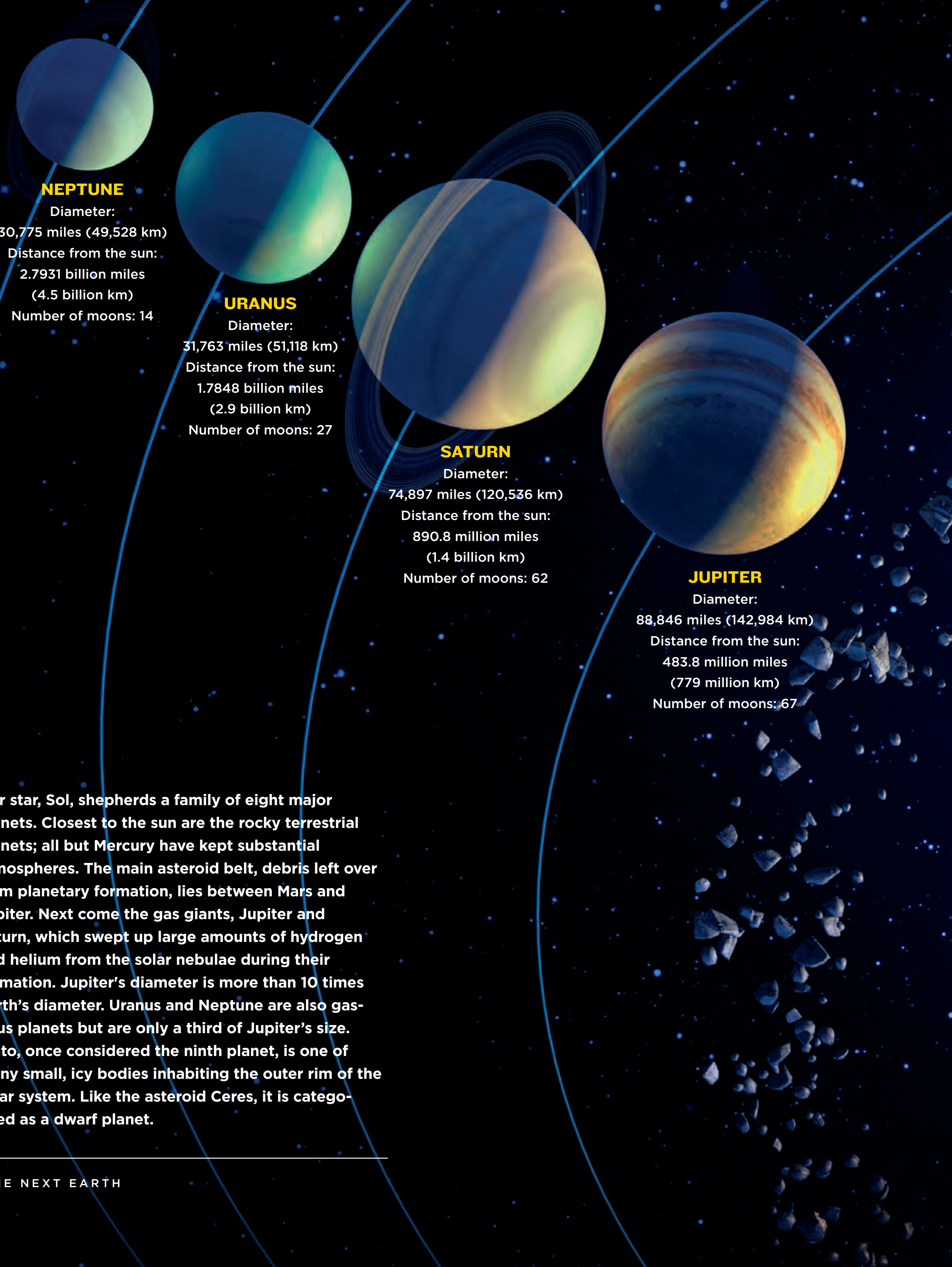
470 MILLION YEARS AGO
Land plants arise; fish are Earth's most advanced life-form.

250 MILLION YEARS AGO
Dinosaurs and first egg-laying mammals appear.

200 MILLION YEARS AGO
Primitive, true mammals spread.

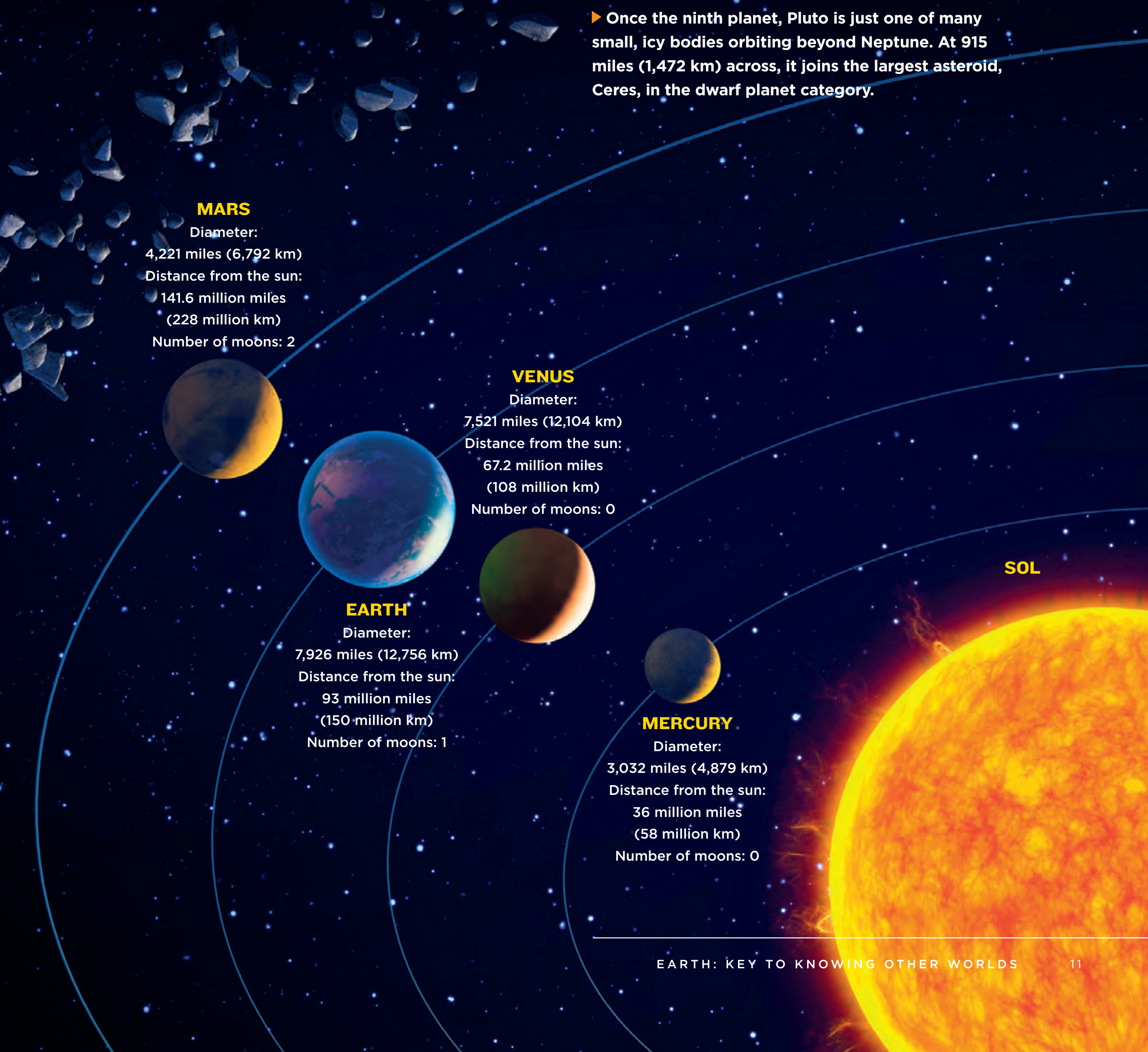
OUR PLANETARY FAMILY

THE SOLAR SYSTEM

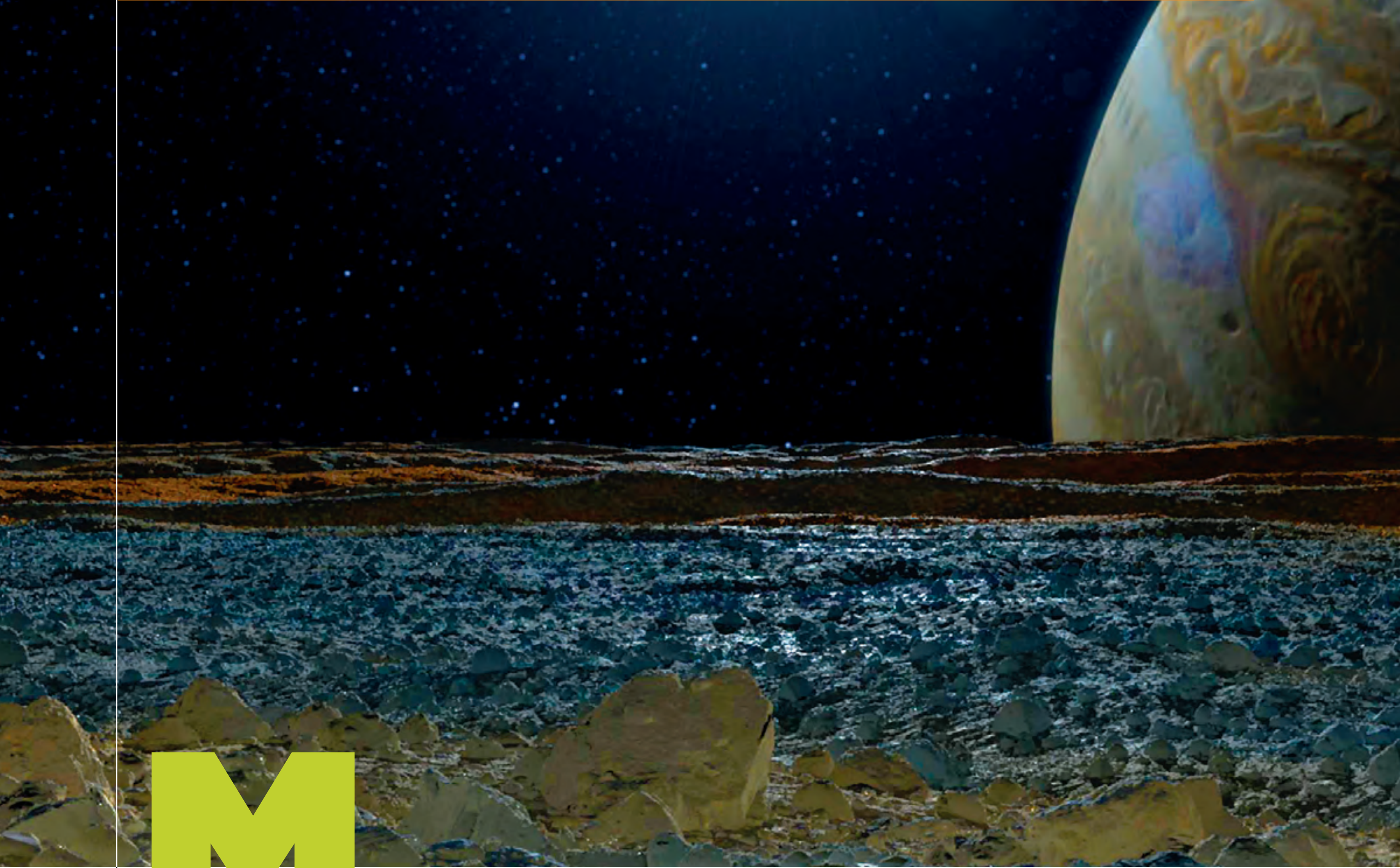


Our star, Sol, shepherds a family of eight major planets. Closest to the sun are the rocky terrestrial planets; all but Mercury have kept substantial atmospheres. The main asteroid belt, debris left over from planetary formation, lies between Mars and Jupiter. Next come the gas giants, Jupiter and Saturn, which swept up large amounts of hydrogen and helium from the solar nebulae during their formation. Jupiter's diameter is more than 10 times Earth's diameter. Uranus and Neptune are also gaseous planets but are only a third of Jupiter's size. Pluto, once considered the ninth planet, is one of many small, icy bodies inhabiting the outer rim of the solar system. Like the asteroid Ceres, it is categorized as a dwarf planet.

Once the ninth planet, Pluto is just one of many small, icy bodies orbiting beyond Neptune. At 915 miles (1,472 km) across, it joins the largest asteroid, Ceres, in the dwarf planet category.



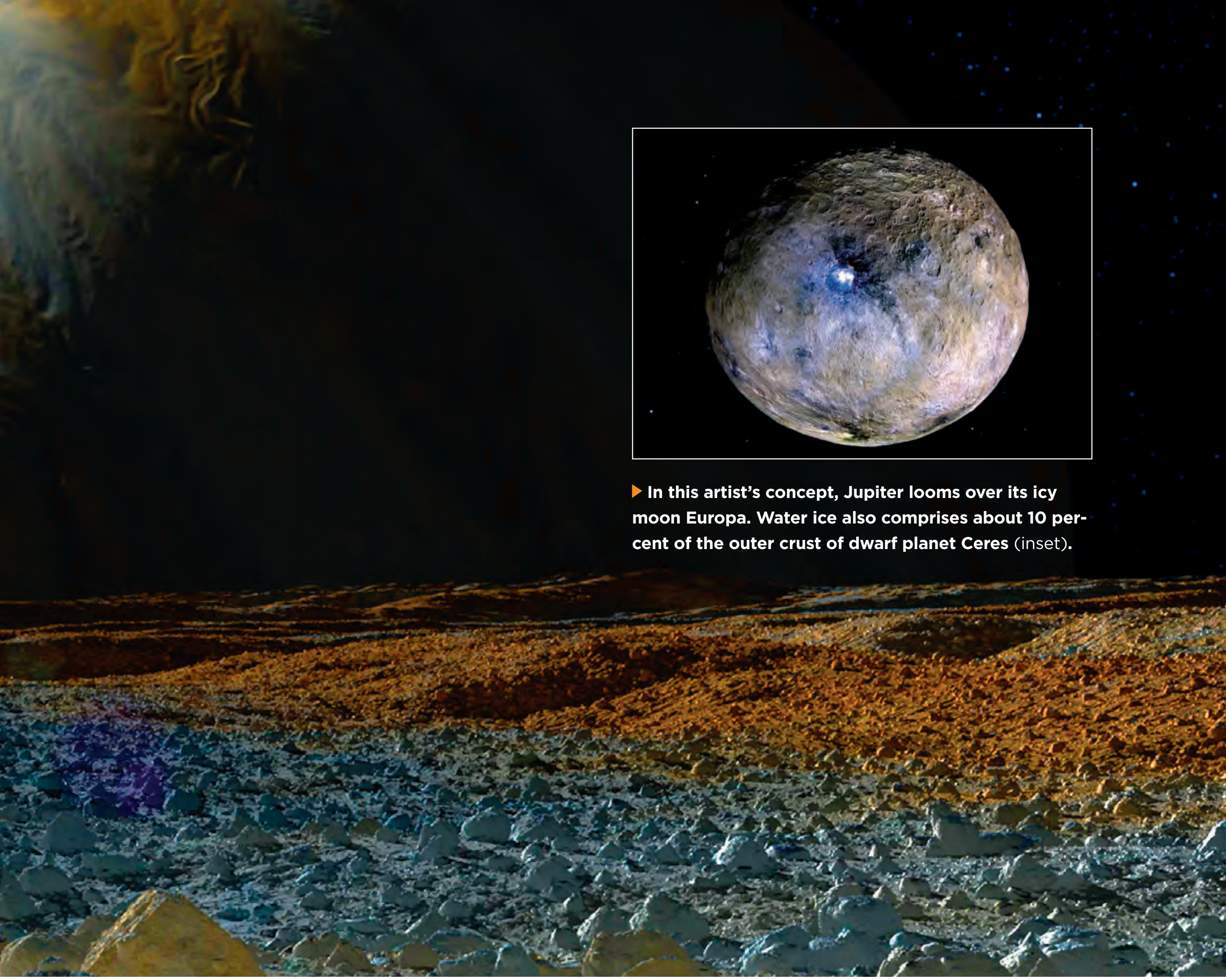
MOONS AND DWARF PLANETS



Moons are natural satellites that orbit their parent planet instead of the sun. Some, like Europa and Titan, formed from the disks of dust and gas spinning around newborn giants like Jupiter and Saturn. Some smaller moonlets may be asteroids or comets captured into orbit by their new planet's gravity. And a few, like our moon and possibly Mars's Phobos and Deimos, probably formed in violent collisions that blasted into orbit material from the parent planet and impactor.

OUTER PLANETS' MOONS

Jupiter's four biggest moons, the Galilean satellites, are named for the Italian astronomer Galileo, who first glimpsed them through a telescope in 1610. One of them, Io, stretched, flexed, and heated by Jupiter's massive tidal pull, erupts floods of molten sulfur and rock onto its ever changing surface. Another, Europa, has a thin, frozen crust underlain by a salty ocean 50 to 100 miles (80 to 160 km) deep—a possible abode for life. The ringed gas giant Saturn's family of 62 moons includes Titan, larger than the planet Mercury and cloaked in a smoggy nitrogen atmosphere. Titan's smaller, dynamic neighbor Enceladus spouts water geysers into space. And frozen Mimas was once nearly torn apart by a titanic impact; the resulting 86-mile-wide (139-km)



▶ **In this artist's concept, Jupiter looms over its icy moon Europa. Water ice also comprises about 10 percent of the outer crust of dwarf planet Ceres** (inset).

crater, Herschel, gives Mimas an eerie resemblance to the *Star Wars* Death Star.

Many icy satellites, like Jupiter's long-frozen Callisto, have ancient, stable surfaces that record billions of years of large and small impacts, preserving the solar system's history of cosmic bombardment. Pluto's moon Charon is about half its parent's size and exhibits mountains, canyons, and landslides. The sheer variety of moons—some surprisingly active—gives scientists many more "laboratories" to test our theories of comparative planetology.

»Explore More IT'S A SMALL WORLD

Astronomers in 2006 recognized a new planetary category—that of dwarf planet. Unlike moons, dwarf planets orbit the sun. They have enough mass (and thus gravity) to have tugged themselves into roughly spherical shapes but are not massive enough to sweep small asteroids or comets out of their path around the sun. Planetary scientists still debate Pluto's demotion to dwarf planet, but that title seems perfectly suited to the largest asteroid, Ceres, about as big across as Texas and circling the sun between Mars and Jupiter.

SIMILAR BUT UNIQUE

After the 1960s' space race took Apollo astronauts to the moon, Mars received the next round of attention: Its environment might once have been favorable for the emergence of life. Through the 1970s, geologists used terrestrial examples to interpret what they were seeing from Viking orbiters and landers at Mars. Its volcanoes and fluid-carved canyons, so like those on Earth, impressed planetary geologists. Yet the red planet's landscapes were uniquely distinctive.

Mars's volcanoes, for example, closely resembled some on Earth, with easy slopes and summit calderas like those of shield volcanoes in Hawaii and the Galápagos. But the Martian peaks were gigantic: The largest, Olympus Mons, was 374 miles (624 km) across, with 100 times the lava volume of Hawaii's Mauna Loa, Earth's most massive land volcano.

SIGNS OF WATER

Mariner and Viking imaged spectacular Mars canyons and networks of what appeared to be valleys formed by streams. On Earth, rain and running water carved these river valleys. Was the same true on Mars? Recent images from NASA's Mars Reconnaissance Orbiter show these gullies near the Gorgonum Chaos canyonlands in the planet's southern hemisphere. Flowing liquid—probably water—likely carved these ravines into the inner wall of an impact crater.

Boulders litter the ravines, as if the flow removed finer sediments and left larger, heavier rocks behind, and the gullies' overlapping courses suggest repeated erosive episodes. By comparing their depth and contours to ravines on Earth, we can learn whether rainfall or another process formed the channels. A leading theory is that infrequent outbursts of subsurface water, flowing from just below the crater's rim, carved these Martian gullies.

»Explore More

HOW WE OBSERVE OTHER PLANETS

Military reconnaissance satellites began peering down at Earth in the 1960s, followed by scientific spacecraft like Landsat and its successors. Ground-based telescopes were first to view the moon and planets, but spacecraft instruments gave us spectacular close encounters with planetary landscapes. Visible-light images show surface geology, but infrared sensors reveal the type and health of vegetation, distinguish rocks from soils and ice, and identify minerals. Similarly, radar echoes can expose landforms otherwise shrouded by haze or clouds.

▶ **Gullies on a crater wall in Mars's southern highlands resemble water-carved channels here. The Milky Way** (opposite) **harbors some 20 billion Earthlike worlds.**

EXPLORERS WILL TARGET INTERMITTENT MARTIAN SPRINGS IN A SEARCH FOR LIFE.

TIME LINE OF

SPACE EXPLORATION

CLYDE TOMBAUGH

VIKING

1609
Galileo Galilei perfects the telescope; his study of the moon reveals that its surface is not smooth, as previously believed.

GALILEO GALILEI

1659
Dutch astronomer Christiaan Huygens determines that the “arms” around Saturn are actually a ring.

1781
Musician and amateur astronomer Sir William Herschel discovers Uranus from his homebuilt observatory in Bath, England. Uranus is the first planet to be discovered with the aid of a telescope.

1930
American astronomer Clyde Tombaugh locates a distant world migrating across the night sky: Pluto.

1957
The Soviet Union successfully launches the Sputnik 1 satellite into Earth orbit, initiating the Cold War space race between the Soviets and the United States.

1961
Yuri Gagarin, a 27-year-old Soviet cosmonaut, becomes the first man in space. He orbits Earth for 108 minutes in a craft named Vostok 1 before reentering the atmosphere and ejecting to a parachute landing.

1962
American astronaut John Glenn equals Gagarin’s feat with three orbits of Earth in his Mercury spacecraft Friendship 7.

1965
Mariner 4 flies by Mars and photographs its surface. The images reveal a dry, desolate planet and effectively end decades of speculation that intelligent life exists on Mars.

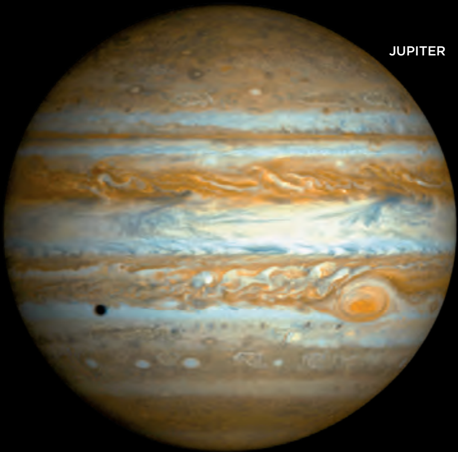
1966
The Soviet Luna 9 makes a successful soft landing on the moon, the first human-made object to land on another celestial body. The United States soon follows with the Surveyor 1 robot landing.

LUNA 9

1969
American astronauts Neil Armstrong and Buzz Aldrin are the first humans to explore another celestial body, our moon. Apollo 11 returns lunar samples and is followed by five additional piloted landings.

1973
NASA launches Mariner 10, the first mission to Mercury. It will make three flybys of the sun’s closest planet, measuring its mass and magnetic field.

1975
NASA launches Viking 1 and Viking 2 to map and land on Mars, analyzing surface conditions and testing for possible life. None is detected.



JUPITER

1979
Voyager 2 flies by Jupiter and spots a volcano erupting on Io, one of the moons Galileo discovered.

1989
NASA launches the Magellan probe to Venus. Its radar maps most of the planet's surface, charting volcanoes and "continents."

1989
NASA dispatches the Galileo spacecraft to Jupiter. Galileo sends a probe hurtling into Jupiter's cloud tops and discovers a subsurface liquid ocean on Europa.

1990
The space shuttle *Discovery* carries the Hubble Space Telescope into orbit. In the following three decades, Hubble greatly advances our knowledge of the universe.

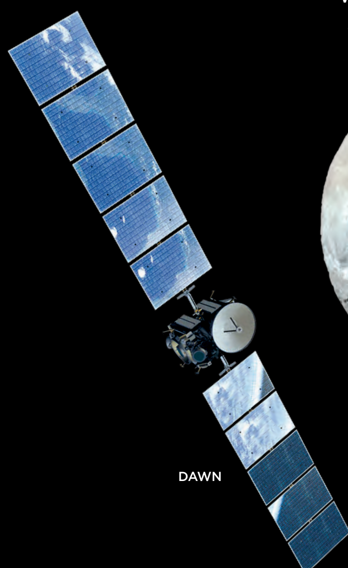
1997
The Mars Pathfinder lands on the red planet to explore it with a small rover.

1997
NASA launches the Cassini-Huygens probe toward Saturn, where it will study the planet's atmosphere and survey its many moons.

2004
Opportunity, one of NASA's Mars rovers, analyzes rock samples indicating that parts of Mars may have once been underwater.

2005
The Cassini orbiter images Saturn's moon Titan and finds seas filled not with water but with liquid ethane and methane. The Huygens probe parachutes to a landing on Titan's frigid surface.

2007
NASA launches the Dawn spacecraft to orbit Vesta and Ceres, two of the largest asteroids in the asteroid belt, and study their composition and history.



DAWN

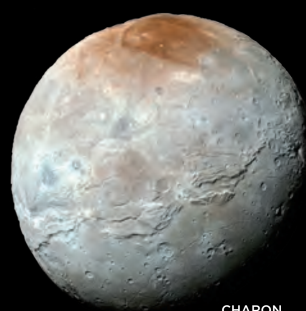
2009
NASA launches the Kepler telescope into orbit, searching for Earth-size worlds around other stars.

CURIOSITY

2012
NASA's Curiosity rover lands on Mars, discovering evidence of ancient running streams and a vanished lake bed at the base of Mount Sharp.

2014
The European Rosetta probe reaches comet 67P/Churyumov-Gerasimenko, maps its weird and jagged terrain, and drops the Philae lander to analyze the surface.

2015
NASA's New Horizons probe encounters dwarf planet Pluto and its moon Charon, revealing a surprisingly active body with frozen nitrogen plains and water-ice mountains.



CHARON

PUTTING IT ALL TOGETHER

Through two centuries of field observation and experiment, earth scientists have built theories about how and why mountains rise, volcanoes erupt, and earthquakes rumble. They apply these models to the landscapes seen on other planets; if our model explains those alien geologic features, we understand a bit more about how that world operates. And if other-world reality does not fit our Earth-based understanding, then the model needs revision. Geologists head back into the field for more observations, and theorists reassess their ideas explaining forces like impacts, volcanism, and erosion. With data and imagery from robot and astronaut visits to the planets, we not only learn more about them, we better understand Earth.

SURPRISES ABOUND

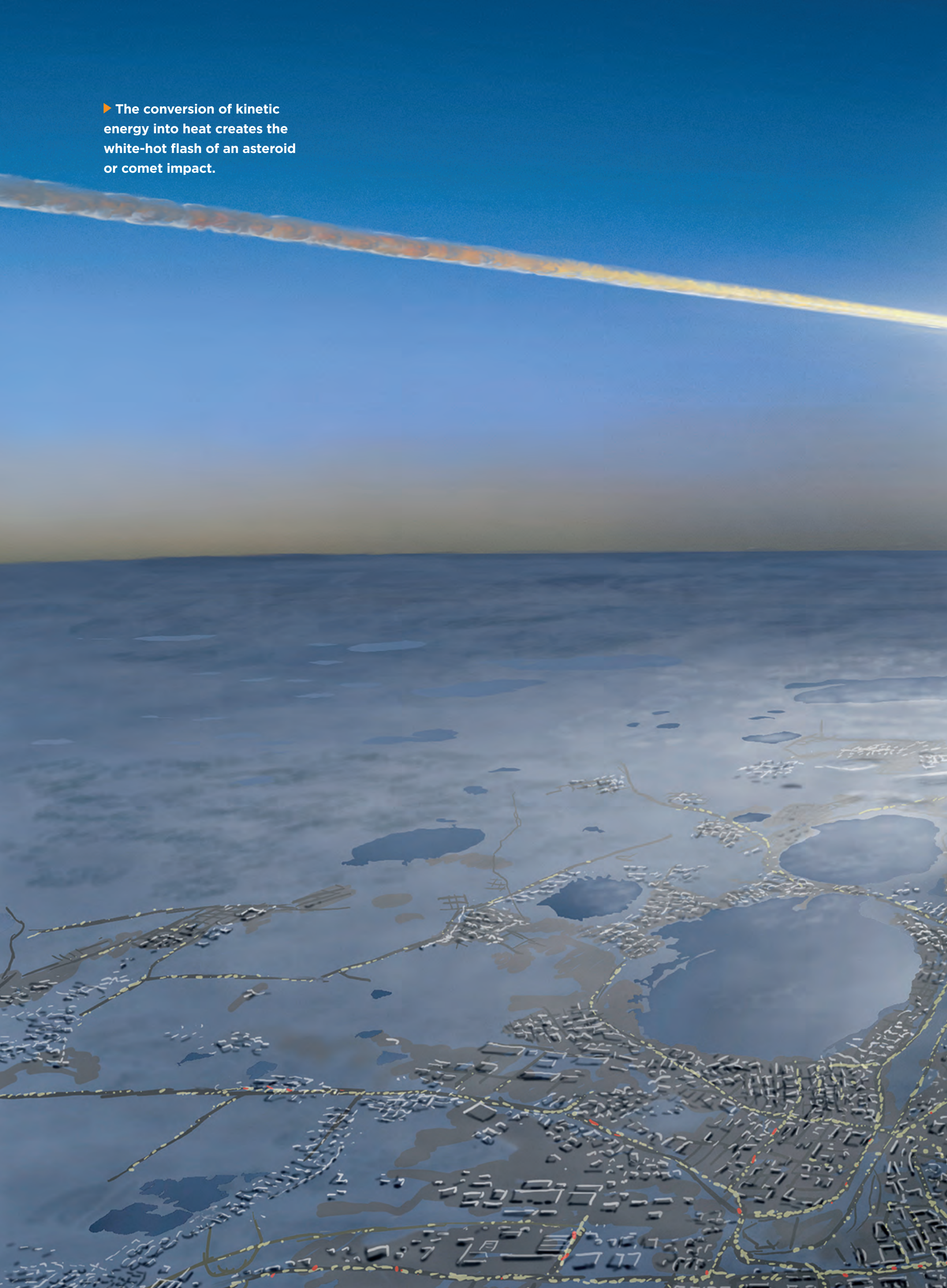
The joint American-European probe Cassini, in orbit around Saturn, has been studying that gas giant's supposedly frozen, long-dead moon Enceladus. Cassini images show fresh cracks in the moon's icy crust. From these so-called tiger stripes, watery geysers spray ice droplets into space. The source of the geysers? A subsurface ocean, warmed and kept liquid by the gravitational stretching and flexing of Enceladus's interior as it orbits Saturn.

Future explorers on Saturn's Arizona-size moon Enceladus will focus on geysers erupting from a subsurface ocean, a possible abode for life.

Cassini radar imagery has also revealed dark, smooth splotches on the icy surface of the large moon Titan. The splotches are actually lakes of liquid methane and ethane, rained out of Titan's frigid nitrogen atmosphere. The hydrocarbon lakes and the sooty fallout from Titan's smoggy skies resemble the complex chemistry present on early Earth. A future probe to Titan may sample the organic building blocks that might once have given rise to life on Earth. Life may even thrive on Titan today, hidden in a warm, salty subsurface ocean.

»Explore More APOLLO 8: OUR FIRST LOOK AT EARTH AS A PLANET

The Apollo 8 astronauts captured a stunning view of earthrise over the moon's ancient, rugged surface on December 24, 1968, during the first piloted mission to lunar orbit. Although satellite cameras had previously snapped global portraits of our planet, the Apollo 8 images first showed it as a fragile "blue marble" in a vast, inhospitable cosmos, inspiring the first Earth Day. For the first time, we saw Earth as a unique oasis in space, home to our human species and perhaps the only known harbor for life in our solar system.



The conversion of kinetic energy into heat creates the white-hot flash of an asteroid or comet impact.

• CHAPTER TWO •

COSMIC DEVASTATION

For 4.5 billion years, Earth has experienced many cosmic impacts. In the shooting gallery that is our solar system, the bullets are asteroids and comets, leftovers from the planets' formation. The rocky asteroids were the building blocks for a planet that tried to form between Mars and Jupiter. But Jupiter's rapid growth stirred the gravitational pot, preventing a planet from forming and scattering its remnants. They still pepper the surfaces of the four inner planets and Jupiter's satellites with destructive impacts.

Comets, snowballs of ice and dust, formed near Uranus and Neptune, whose gravity hurled them throughout the solar system. Most reside beyond Pluto today. Millions of asteroids and comets, from bodies the size of a house to that of Manhattan, still approach or cross Earth's orbit. In the rare event that a large object strikes, its mass and speed create a blast of heat and light, gouging a crater and wreaking global havoc.

COSMIC COLLISIONS

OUR SCARRED PLANET

3.8 BILLION YEARS AGO
Massive impacts by asteroids and comets batter the early solar system.

250 MILLION YEARS AGO
A giant asteroid impact and massive lava floods in Siberia combine to cause a devastating mass extinction.

108 MILLION YEARS AGO
An asteroid impact forms the striking, 53-mile-wide (86-km) Tycho crater on the moon's southern hemisphere.

66 MILLION YEARS AGO
A six-mile-wide (10-km) asteroid or comet smashes into the Yucatán Peninsula, triggering another extinction.

When a cosmic body collides with Earth at a typical velocity of 10 miles per second (16 km/s) or more, the impact generates a shock wave that instantaneously converts the energy of motion—kinetic energy—into heat. The intense heat largely vaporizes the impactor, melts the surrounding native rock, and creates a rapidly expanding fireball. A decompression wave following the shock hurls molten and shattered debris away from the impact site, leaving behind a bowl-shaped cavity—a crater.

In the 1960s, studies of Arizona's Meteor Crater gave us our first understanding of the physics of impact cratering. If the impact is from an object more than a mile or so in diameter, it forms not just a simple bowl-shaped cavity, as at Meteor Crater, but a more complex structure with a flat floor, a series of concentric terraces and rings, and a central peak.

The largest strikes create huge, multiringed features called impact basins. Giant impacts fracture the crust for hundreds of miles, shower the entire globe with scorching debris, and gouge so deeply that lavas flood the low-lying basin and cool into smooth plains. The most familiar examples are the dark lunar maria (seas) and the Vredefort basin in South Africa, but impact basins are common on all the rocky and icy bodies of the solar system.

Arizona's nearly mile-wide Meteor Crater is dwarfed by Canada's Clearwater Lakes (inset), whose west crater is 22 miles (36 km) wide and 290 million years old. The eastern scar is 16 miles (26 km) across and formed 470 million years ago.

15 MILLION YEARS AGO
An asteroid a mile wide (1.5 km) creates the 15-mile-wide (24-km) Ries crater in southern Germany.

50,000 YEARS AGO
A 164-foot-wide (50-m) iron-nickel asteroid slams into northern Arizona in a 20-megaton blast, excavating Meteor Crater.

1908
A 164-foot (50-m) asteroid explodes over the Tunguska region of Russia, with 5 megatons of energy, flattening 800 square miles (2,000 km^2) of Siberian forest.

2013
A 66-foot-wide (20-m) asteroid detonates over the Russian city of Chelyabinsk, injuring more than a thousand residents.

Studies of craters on the moon, Mars, Venus, and the icy satellites of the outer solar system have helped us refine our models of how impact basins form. The models allow us to predict the effects of a high-energy impact on Earth's surface and, critically, on its biosphere. Giant impacts have occurred repeatedly on Earth; the last one, 66 million years ago, reset life's future course by wiping out the dinosaurs.

»Explore More HOW OLD ARE EARTH AND THE SOLAR SYSTEM?

Earth's true age was revealed by the technique of radiometric dating, which uses the known rates of radioactive decay of elements like uranium or potassium to determine a formation age. The decay rate and the measured amounts of such radioactive elements in a rock tell us when the rock was formed.

Meteorites with radiometric ages of 4.6 billion years tell us when the planets formed. The oldest moon rocks collected by the Apollo astronauts are 4.4 to 4.5 billion years old. The oldest surviving Earth rocks formed just over 4 billion years ago.

THE NEAR-EARTH ASTEROIDS

WILD CARDS

Asteroids and comets are cosmic leftovers—chunks of dust, rock, and ice that failed to grow into full-size planets. Rocky asteroids in the millions orbit in the main belt between Mars and Jupiter. Jupiter, 11 times as wide and 318 times more massive than Earth, exerts a powerful gravitational influence that nudges objects out of the belt and into the path of other asteroids and the planets. Collisions between asteroids also create fragments that spin into the paths of the inner planets. Hundreds of thousands of objects greater than 328 feet (100 m) across approach Earth's orbit today.

Icy, dusty comets circle the sun beyond Pluto in the Kuiper belt and the more distant Oort cloud. Gravitational shoves from passing stars push some sunward along highly elliptical orbits; such long-period comets dive through the inner solar system at speeds of 25 miles per second (40 km/s) or higher. Earth sweeps up about 100 tons (91 metric tons) of comet and asteroid dust grains daily. Most, smaller than sand grains, are incinerated by atmospheric friction and seen as streaks of light in the night sky—meteors. Shards that are big enough to survive and strike the ground are called meteorites.

▶ Comet C/2001 Q4, an ancient relic from the outer solar system, displays an icy, solid nucleus, a sunlit gas cloud (the coma), and a lengthy, dusty tail.

The Galileo spacecraft imaged asteroid 243 Ida, 35 miles (56 km) across, and its moon, Dactyl. They orbit in the main asteroid belt, but thousands of smaller, closer objects threaten Earth.

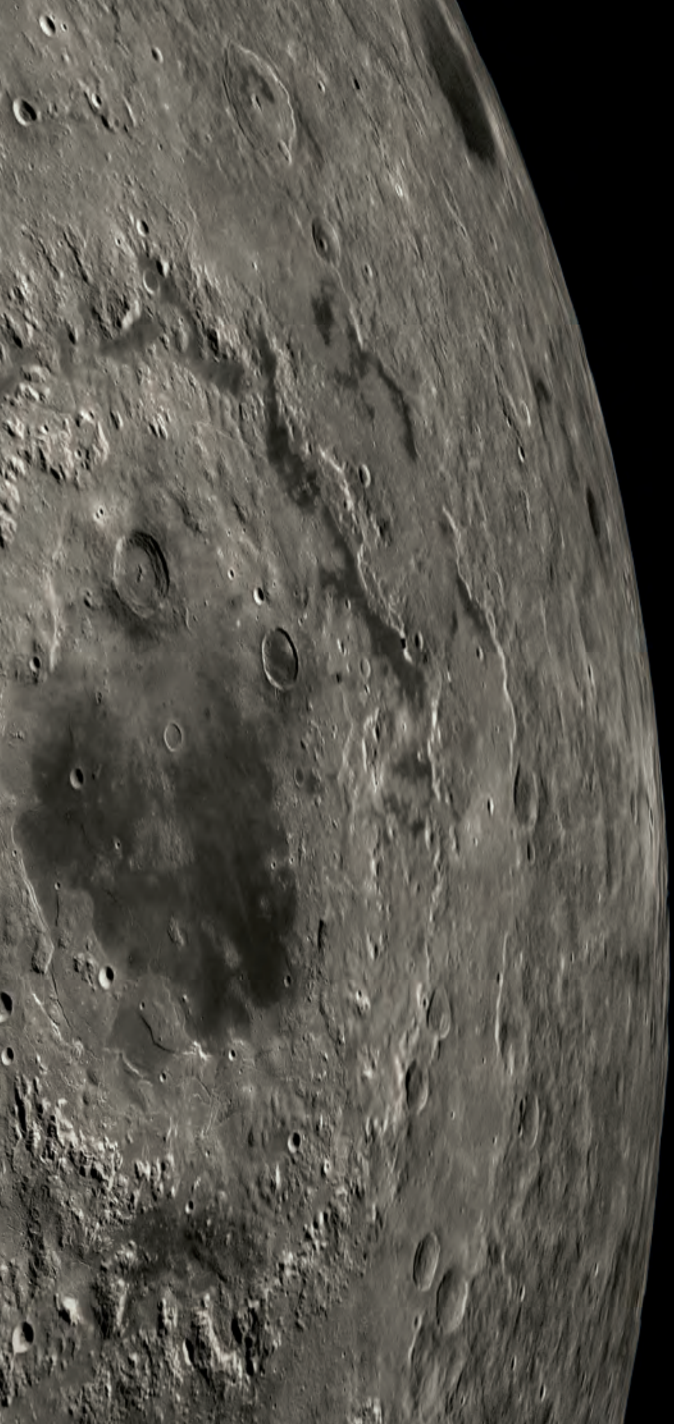
The Perseid meteor shower occurs each August as Earth crosses the orbit of comet Swift-Tuttle; its dusty debris burns up high in the atmosphere.

ANCIENT CRATERS

DEEP IMPACT

Asteroid and comet impacts weren't recognized as a major geologic force on Earth until the early 1960s, when geologist Gene Shoemaker proved the cosmic origin of Arizona's Meteor Crater. Why, with the moon's craters so easily visible, did it take us so long?

Plate tectonics, volcanoes, and erosion have obliterated most direct evidence of cosmic bombardment over Earth's history. Since Shoemaker's Meteor Crater finding, however, planetary scientists have identified about 190 terrestrial impact craters, usually through geologic sampling and mapping, or via aerial and satellite imagery. Most of these weathered scars, with exotic names like Manicouagan, Gosses Bluff, Sudbury, Clearwater Lakes, and Acraman, are preserved in the oldest continental rocks, like those found in northern Canada, Africa, and Australia.



Large asteroid or comet impacts create scars like the moon's Mare Orientale, 580 miles (930 km) wide, and Western Australia's Shoemaker crater (inset), **19 miles (~30 km) across.**

TELLTALE SCARS

Fortunately, the less active planets and moons preserve numerous ancient craters that reveal the history of cosmic bombardment during their first billion years. Examination of these impact scars enables us to estimate a surface's relative age.

For example, surfaces of the same age on different planets should show the same pattern of crater quantity and size. By carefully comparing the number and diameters of craters on the lunar plains—which Apollo 11 found were 3.6 to 3.9 billion years old—with similar regions on Mars, scientists estimate those Martian surfaces formed about the same time. Crater statistics also tell us that the red planet's battered southern hemisphere probably dates back 4 billion years, with its sparsely cratered northern volcanic plains perhaps only 1 to 2 billion years old. Rock samples returned from Mars will confirm or upset these educated guesses.

HEAVY BOMBARDMENT

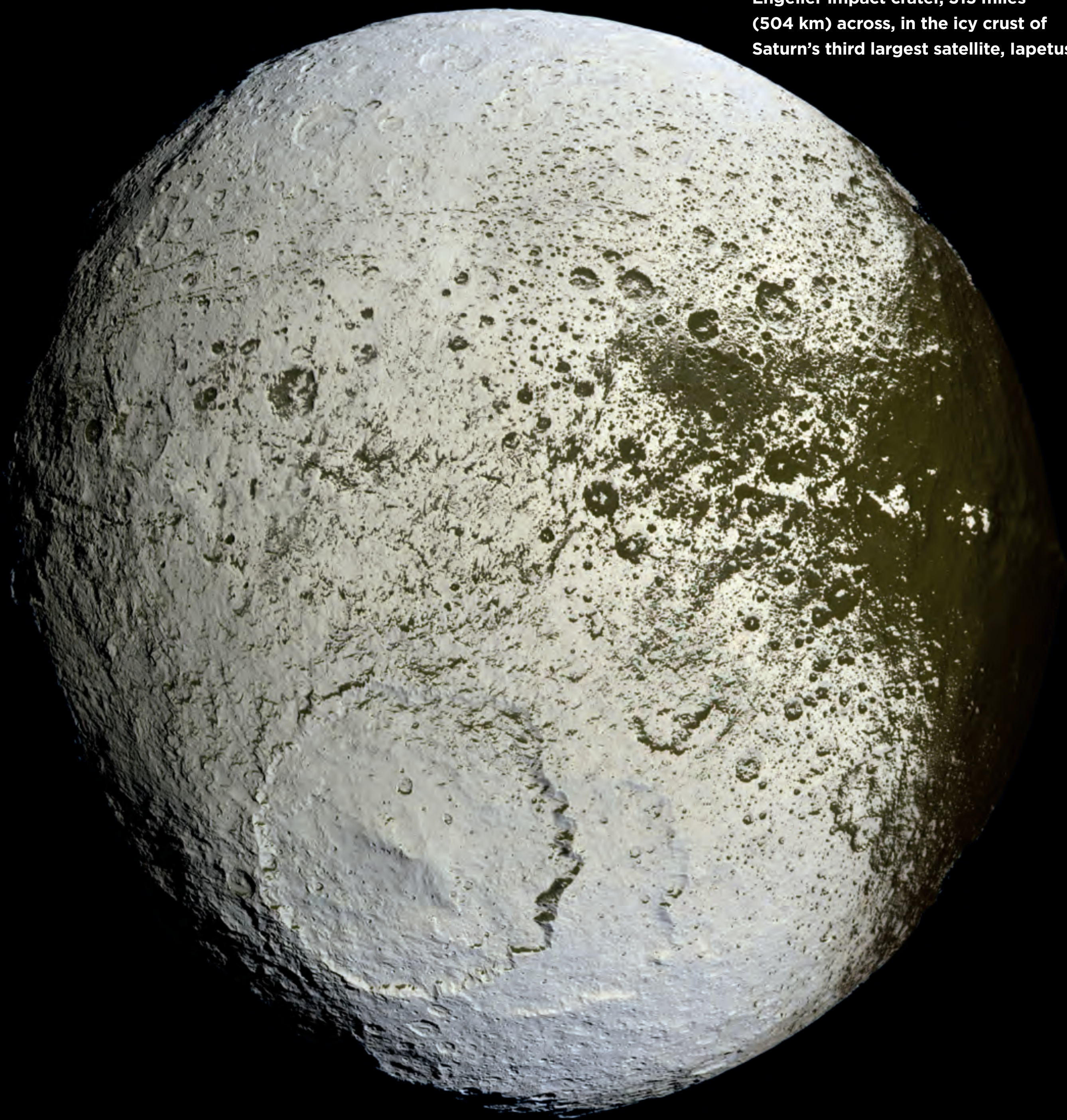
CRATERS ACROSS THE SOLAR SYSTEM

Since Galileo first trained his telescope on the moon in 1609, astronomers have debated the origin of the thousands of craters that pock its surface. Nineteenth-century scientists surmised that the craters were probably volcanic, but a few speculated that asteroid or comet impacts might be responsible. It was not until the early 1960s that geologist and astronomer Gene Shoemaker, examining Arizona's near-mile-wide (1.5-km) Meteor Crater, identified specific shocked quartz minerals in its rocks that could have formed only in an impact. Evidence pointed to a 160-foot-wide (50-m) iron-nickel asteroid fragment that slammed into Earth 50,000 years ago, carving out the crater in a 20-megaton blast. NASA's lunar exploration program confirmed that most of the moon's craters were likewise formed by asteroid or comet collisions. Geologists have since located more than 190 similar impact craters on Earth.

By mapping the moon's craters and comparing their distribution across the lunar surface to the ages of rocks returned by Apollo astronauts, geologists discovered that the early Earth, moon, and the other planets and moons from Jupiter inward were pummeled by a storm of colossal impacts early in their histories. The scars from this heavy bombardment, which ended about 3.9 billion years ago, are starkly visible on Earth's moon. On its southern highlands and most of its far side, craters overlap craters so thickly that the moon's original crust has been largely obliterated. The most violent of these collisions formed multiringed basins more than a thousand miles (1,600 km) across and flooded these deep crustal wounds with pools of lava. These are the lunar "seas." On Earth, nearly all evidence of this episode and later impacts has been erased by erosion and the recycling of oceanic crust via plate tectonics.

»Explore More IT'S ALL IN A NAME

Asteroid Eros, the moon's Copernicus crater, Venus's Maat Mons volcano—how did they get their names? As planetary features are discovered, the International Astronomical Union labels them according to themes assigned to each planet. Large lunar craters are named for deceased scientists, artists, and explorers; small Martian craters for modest-sized cities. Venus features get feminine monikers; Venusian craters are named for famous women who've died. To avoid controversy, the designation of planetary features is limited to deceased individuals.



A comet impact blasted out the Engelier impact crater, 313 miles (504 km) across, in the icy crust of Saturn's third largest satellite, Iapetus.

THE LATE HEAVY **BOMBARDMENT,** 4.1 TO 3.8 BILLION YEARS AGO, **SCARRED PLANETS** AND MOONS.

AN INEVITABLE STRIKE

TARGET: EARTH

Earth orbits the sun amid an asteroid swarm numbering in the millions. If Earth is struck by an asteroid 44 yards (40 m) or more across, it will penetrate the atmosphere to produce an explosion and perhaps a crater. An object that big collides with Earth once every 500 to 1,000 years; the last such blast was over the Tunguska region of Russia, in 1908, flattening 800 square miles (2,000 km^2) of forest.

MAKING THE MOON

Chemical analyses of lunar rocks returned by Apollo astronauts suggest that the moon formed after a Mars-size planetoid careened into a young Earth nearly 4.5 billion years ago. The explosion pulverized and melted our planet's outer crust and jetted vaporized and molten Earth rock high into space. This debris eventually settled into a transient, Earth-girdling ring and coalesced into the newborn moon.

As the moon began to cool, heavy materials sank to the interior to form the core and mantle; less dense minerals floated on top to create the lunar crust. Once its crust cooled and solidified, its rocks began to record the history of bombardment by asteroids and comets. Craters tell us how many asteroids and comets circulated through the solar system during its first billion years. Counting younger lunar

The asteroid that exploded above Chelyabinsk, Russia, in 2013 was 56 to 66 feet (17–20 m) wide. Debris from a giant impact 4.5 billion years ago (artist's concept, inset) formed our moon.

craters also tells us how many hits Earth should have sustained over the last few million years, and whether these estimates match actual impact scars here.

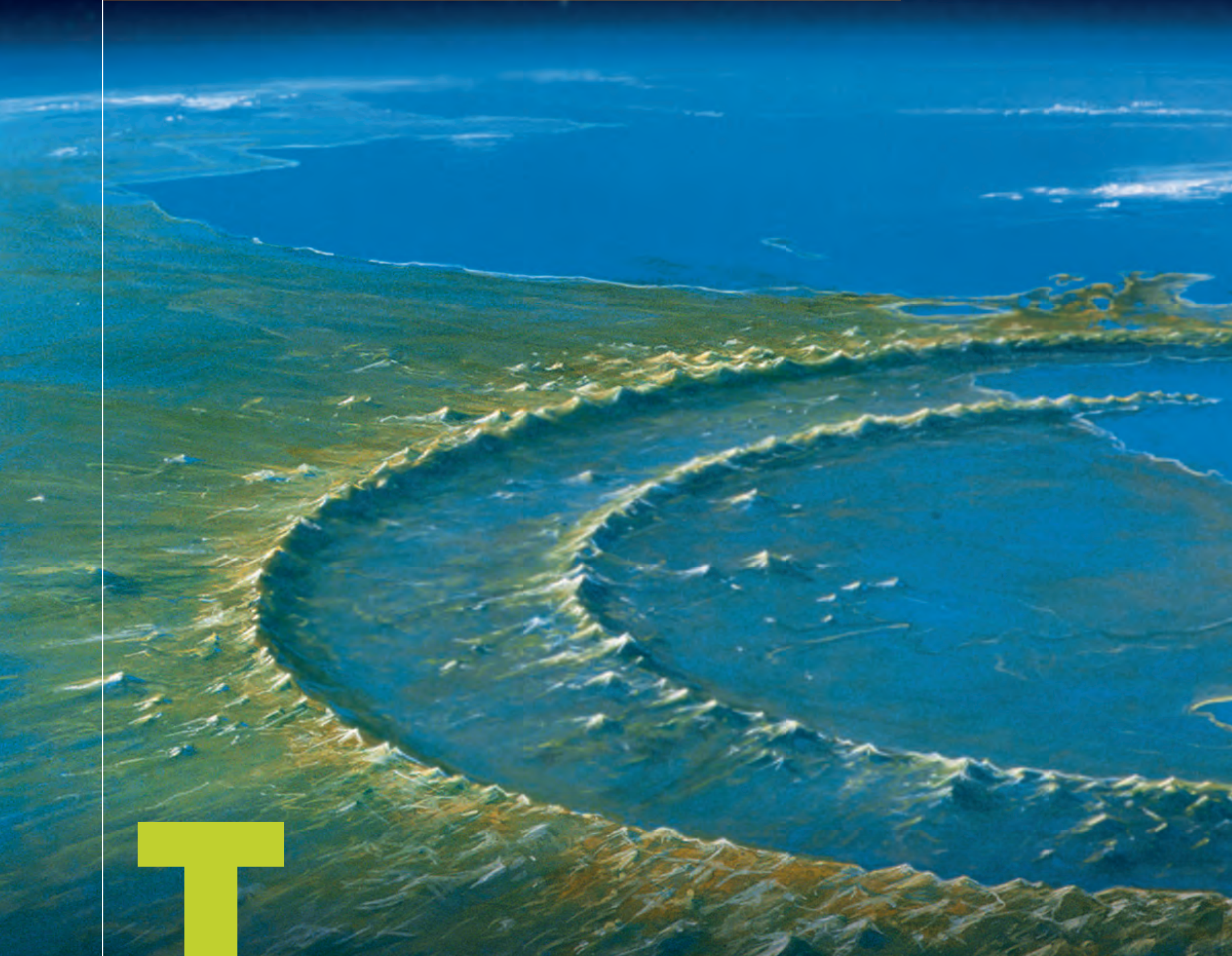
There are about a million near-Earth asteroids big enough to penetrate our atmosphere, but only those larger than two-thirds of a mile (1 km) would threaten global damage. NASA has found about 95 percent of those, and none pose an imminent threat. Your lifetime risk of dying from an asteroid strike is about 10 times less than perishing in a tornado.

»Explore More NASA'S PLAN TO RETURN TO THE MOON

NASA is intensively mapping the moon with its Lunar Reconnaissance Orbiter and will land a water-prospecting rover there in the early 2020s. Lunar ice may serve as a convenient source of rocket fuel for exploration. Astronauts may return in a decade to build an "international lunar village." Although Apollo samples helped reveal how the moon formed, many scientific questions remain. By obtaining ages for many of the larger lunar craters, we can calibrate dates of impact episodes throughout the solar system.

CHICXULUB

CATASTROPHIC IMPACT



The most infamous, if not the largest, crater on Earth is Chicxulub, a 112-mile-wide (180-km) basin buried a half mile (800 m) under the northwestern tip of Mexico's Yucatán Peninsula. Its catastrophic formation nearly 66 million years ago altered the very course of life on Earth.

In 1980 geochemists noted in sedimentary rocks all over the globe a thin clay layer containing the element iridium. Rare on Earth but enriched in meteorites, it was telltale evidence that a mountain-size asteroid or comet had struck our planet 66 million years ago. But where was the crater?

Geologists noted jumbled beds of 66-million-year-old sediments surrounding the Gulf of Mexico, along with tiny spheres of once molten impact glass, called tektites. In area gravity surveys, scientists found a central depression, buried rim, and outer rings that matched those

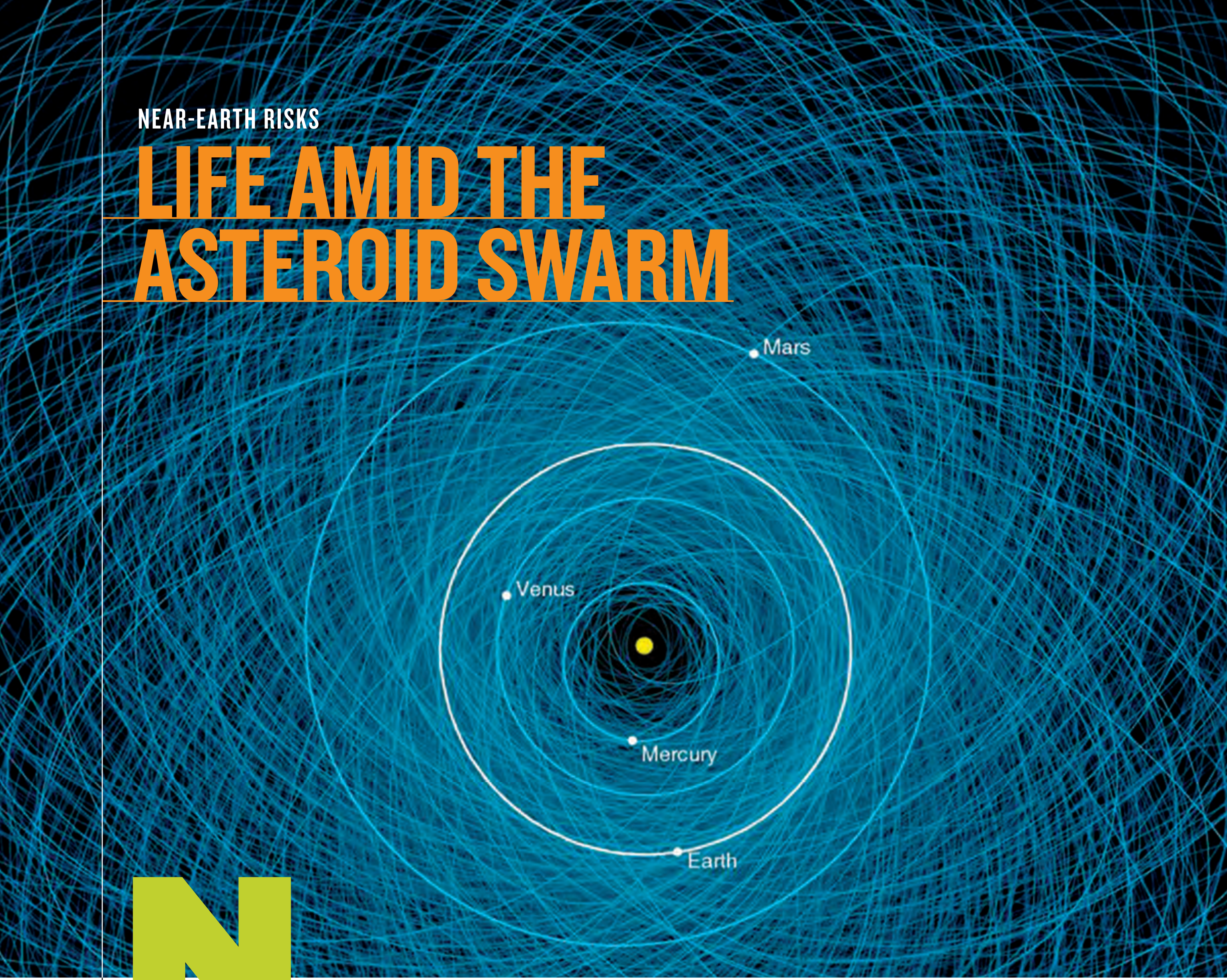
The Chicxulub crater was formed by an asteroid or comet impact (inset) **that caused the dinosaurs' extinction.**

of impact basins on the moon, Mercury, and Mars. Rocks retrieved during oil exploration confirmed Chicxulub was an impact crater, the smoking gun for one of the most dramatic mass extinction events in Earth's history.

The impact of a six-mile-wide (10-km) comet or asteroid created a searing fireball that killed everything within hundreds of miles and gouged a crater as wide as Long Island, throwing trillions of tons of dust and vapor into the atmosphere. Giant tsunamis tossed wave deposits dozens of miles inland. Water vapor and carbon dioxide generated by the impact raised global temperatures by nearly 20°F (7°C), and a drenching acid rain poisoned the oceans. Global fires, soot, and darkness killed vegetation. Roughly 80 percent of the planet's living species perished, the dinosaurs among them. Among the few survivors were early mammals—our ancestors.

NEAR-EARTH RISKS

LIFE AMID THE ASTEROID SWARM



NASA and its international partners are ramping up their search for near-Earth asteroids, finding about 2,000 per year from ground-based telescopes. Discoveries will accelerate as the new Large Synoptic Survey Telescope begins operations in Chile in 2022. But NASA will need a space-based, infrared-sensitive telescope to fulfill a congressional directive to find 90 percent of asteroids larger than 128 yards (140 m) across; an impact from one could devastate a multistate region. Asteroids that size and larger represent 90 percent of the current risk to Earth, but Congress has yet to fund this planetary defense mission.

DEFLECTING DISASTER

The technologies needed to divert a future asteroid collision include striking the object with a robotic hypervelocity "bullet," tweaking its orbit with a plume of exhaust from an ion engine, or slamming it off course with a nuclear explosive. All are feasible; NASA demonstrated the kinetic impact "bullet" approach during a 2005 comet science mission. NASA and the European Space Agency are discussing a joint deflection demonstration at asteroid Didymos in 2022, in which a NASA spacecraft would strike the asteroid's 525-foot-wide (160-m) moonlet while a European craft observes the impact's effects.

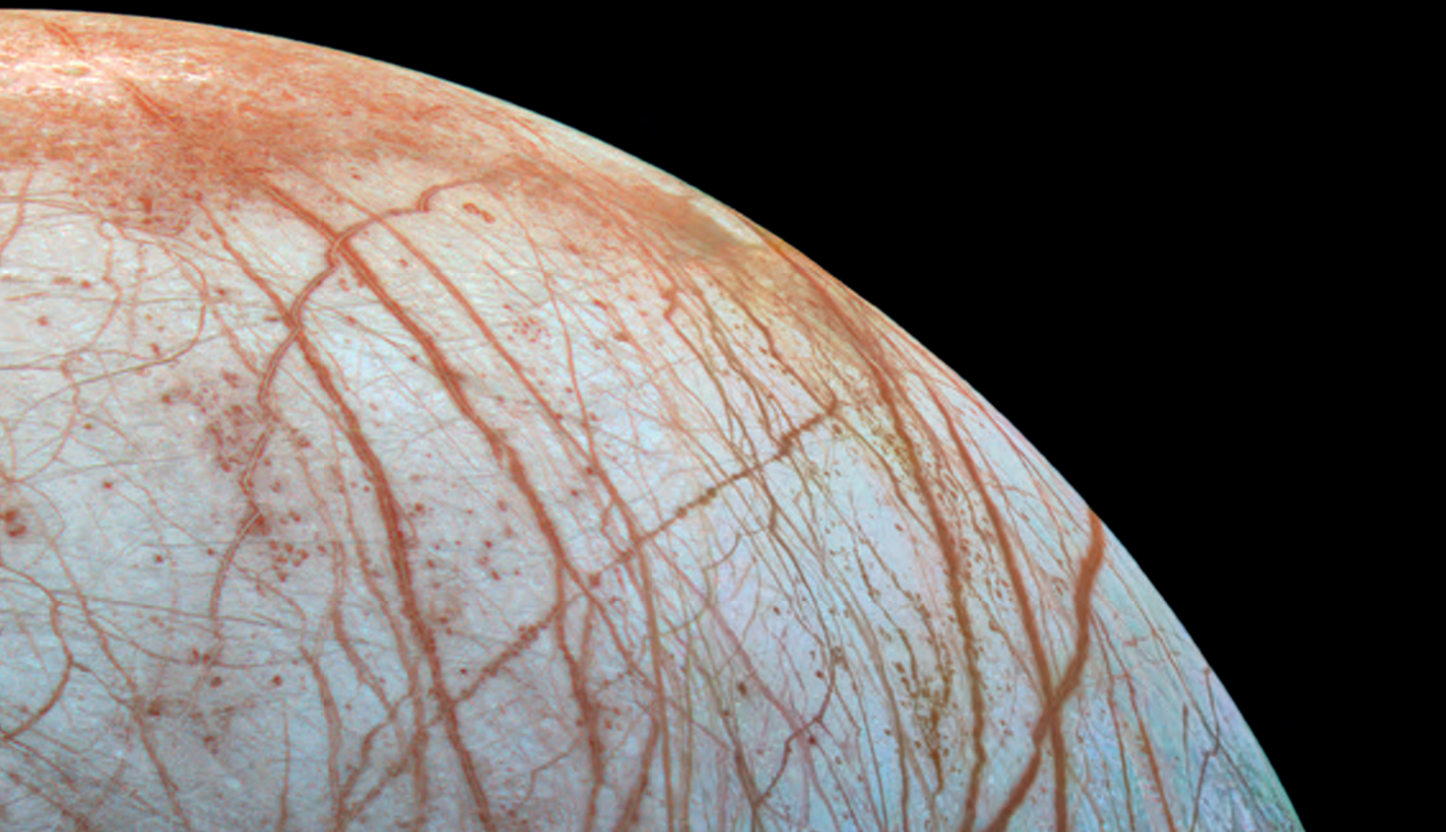
▸ **Thousands of potentially hazardous asteroids cross the inner solar system** (opposite), **many discovered by NASA's Pan-STARRS telescope, atop Maui's Haleakala volcano.**

NASA's Planetary Defense Coordination Office was set up in 2016 to guide U.S. efforts to discover and catalog near-Earth asteroids, predict possible collisions, and plan deflection missions to avert an impact. To learn more about objects that may threaten Earth, NASA launched the Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer mission in 2016 to examine the potentially hazardous asteroid Bennu. The OSIRIS-REx craft will map the possibly water-rich object and return a sample to Earth in 2023.

»Explore More THE OSIRIS-REX MISSION

The OSIRIS-REx spacecraft is headed to near-Earth asteroid Bennu to collect and return at least a 2.1-ounce sample. In 2018 OSIRIS-REx will approach Bennu—the size of a small mountain—and survey it while preparing to retrieve a sample. In 2020 the spacecraft will briefly touch down and shoot a jet of gas into the surface, scattering at least two ounces of surface material into a collection chamber. The return capsule will land in Utah in 2023, carrying the largest sample returned from space since Apollo's lunar missions.

▶ Cracks and ridges crisscross the icy surface of Jupiter's moon Europa and hint at the water ocean below.



• CHAPTER THREE •

SURFACES IN MOTION

Earthquakes, volcanic eruptions, and tsunamis that cause devastation and death are all the result of plate tectonics, the geologic process that dominates Earth and is driven by the heat of decaying radioactive elements in the mantle that melts rock. Hot, less dense material rises from the interior, cools, and then sinks again, producing slow convection currents on which the plates of Earth's outer crust ride. These crash into each other to form mountain ranges, dive under each other to create ocean trenches and volcanoes, and grind past each other along huge faults. Some plate motion is subtle and slow; when a major earthquake occurs, you are witnessing plate tectonics in violent action. We find analogs around the solar system, from Venus's giant fault systems to the massive chasms in Mars's crust. Ridges, rifts, mountains, and faults provide clues to planets' inner workings. Our goal is to learn how to live more safely on our own world in motion.

PLATE TECTONICS

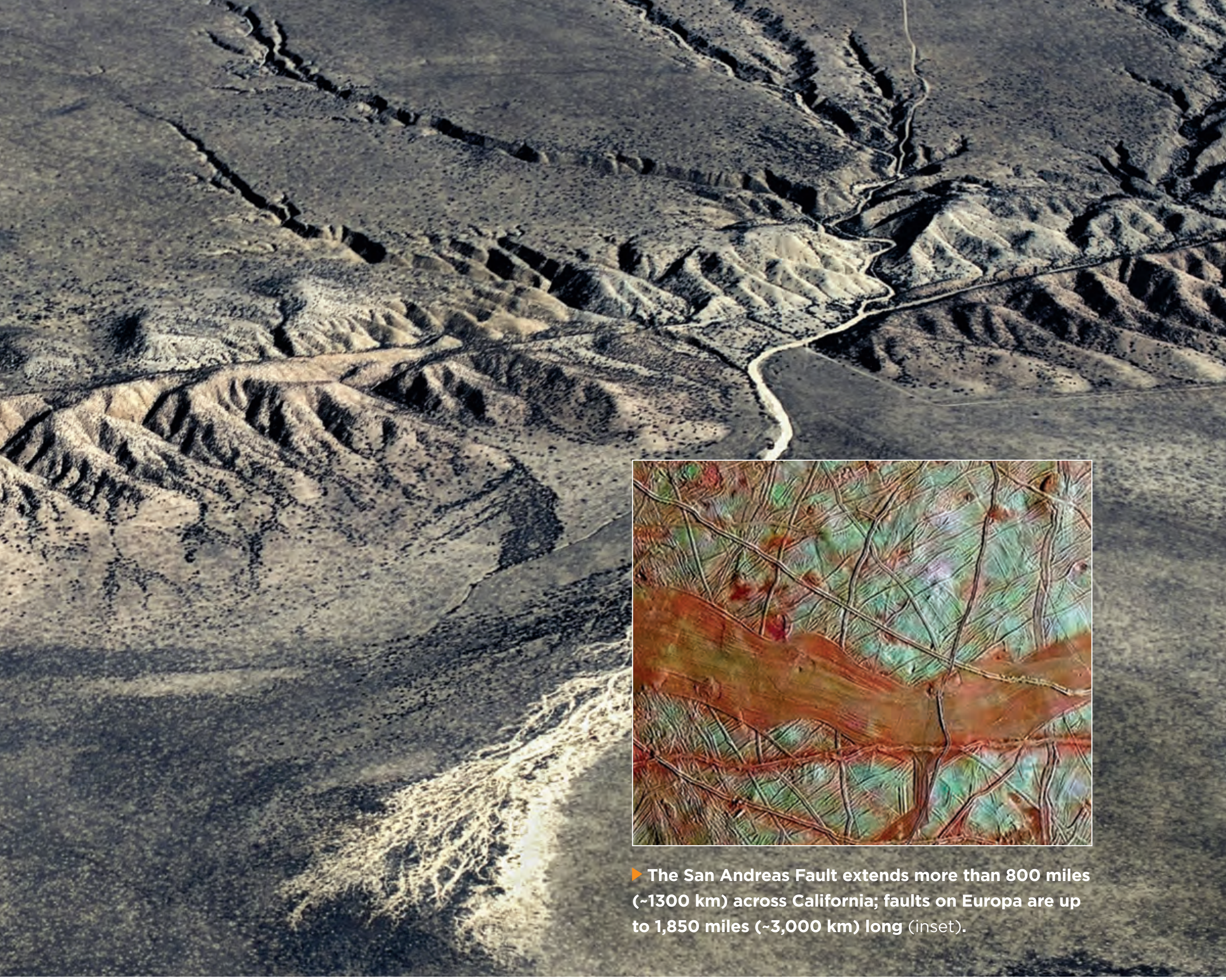
CONTINENTS, CRUSTS, AND COLLISIONS

Have you ever noticed how the mapped edges of South America and Africa look as if they could fit together like a puzzle? Several hundred million years ago, all land on Earth was massed in one large supercontinent called Pangaea, surrounded by a huge ocean. Over the last 230 million years or so, its pieces separated and drifted apart, riding on convection currents in the interior and producing the current pattern of continents. That they do look like they could fit back together like puzzle pieces led Alfred Wegener in 1915 to suggest the theory of continental drift, which was refined into the theory of plate tectonics in the 1960s.

SURFACE INSTABILITY

The pattern of continents we see today is unstable; active faults, mountain ranges, and volcanoes trace the plates' edges and demonstrate that the continents are in motion. Satellite observations and ground instruments can track strain accumulating along faults and the growth of active mountain ranges like the Himalaya. Very large earthquakes shake the entire planet, allowing seismologists to better understand how Earth's interior is layered.

Surprisingly, scientists haven't been able to confidently identify plate tectonics on any other body in the solar system, although



The San Andreas Fault extends more than 800 miles (~1300 km) across California; faults on Europa are up to 1,850 miles (~3,000 km) long (inset).

many planets and moons show evidence of surface movement, from faults to mountain ranges. While we cannot rule out that Venus and Mars had plate tectonics early in their histories, there's no clear evidence for active plate tectonics on their surfaces today, only limited motion. Jupiter's moon Europa has some features that resemble subduction zones and spreading centers; future missions to that moon may confirm a plate tectonic–like system that would help us understand better the forces that drive our world.

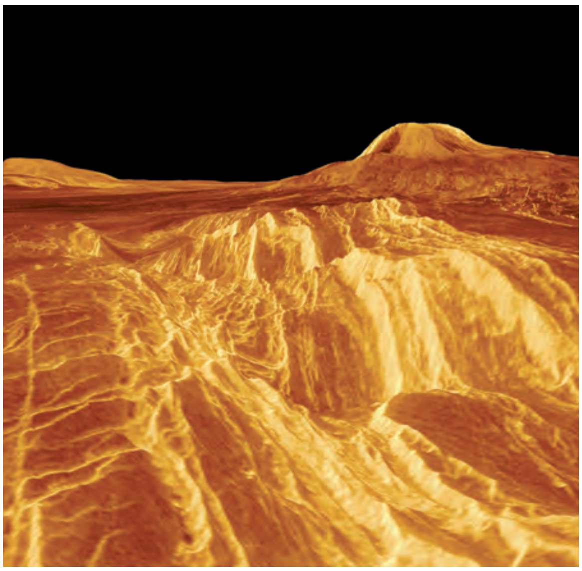
»Explore More RIDGES, FAULTS, AND SUBDUCTION ZONES

Spreading ridges, transform faults, and subduction zones are the three types of plate boundaries found here on Earth. Plates pull apart, and upwelling melted rock forms new crust at the mid-ocean spreading ridges. At transform boundaries, plates slide past each other to produce big earthquakes, as at the San Andreas Fault, along the boundary of the North American and Pacific plates. Subduction zones occur when two plates collide, forcing one below the other and producing melting that results in volcanoes like Mount Fuji in Japan.

CRACKS AND CANYONS

RIFTS ON EARTH, MARS, AND VENUS

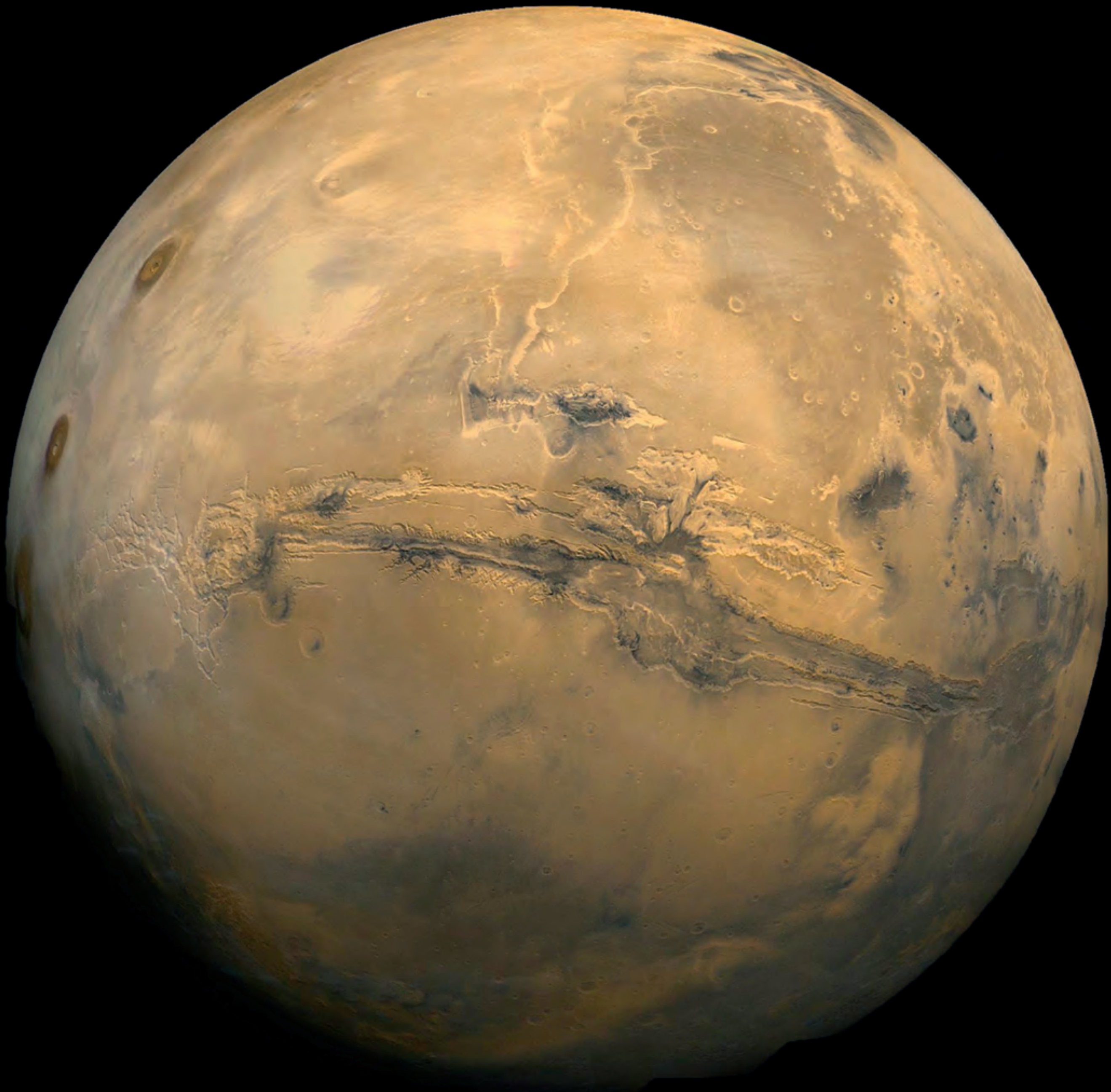
Giant cracks that are miles deep and hundreds of miles long signal the huge forces that can tear open the crust of a planet. These rifts are common on Earth, from the active spreading rift where new crust is created on the Atlantic Ocean seafloor to failed rifts that never spread very far, such as the East African Rift. The Tharsis bulge on Mars, a huge pile of volcanic material, produced stresses in the Martian crust and caused it to break. The result is the impressive rift Valles Marineris, a vast network of canyons, enlarged over time by erosion during Mars's wet past to about the width of the United States and more than four times the depth of the Grand Canyon. Mars's rift is not a spreading center; Mars cooled off too rapidly to have plate tectonics. Smaller rifts, called graben, formed when melted rock pushed up under the crust to stretch and crack it.



Radar and topographic data from the Magellan spacecraft of Venus's Guor Linea, a rift approximately 35 miles (56 km) across and a few hundred meters deep.

A PRISTINE RECORD

The rift systems on Venus are among the most extensive in the solar system, forming families of faults and troughs that run roughly the distance from New York City to Istanbul, and average about 155 miles (250 km) wide and several miles deep. The Venusian rifts are longer and more common than those on Mars, indicating a more active surface. And as on Earth, the cracks in the Venusian crust are caused by the flow of mantle material beneath it that transmits stress to the surface. But on dry Venus, the lack of water in the rocks may prevent subduction, in which one plate is shoved under another; the pull of the descending plate is a key driver of plate tectonics. Venus's lack of water also means that surface erosion is very slow, preserving its features and allowing geologists to study them in their pristine state.



Valles Marineris is Mars's Grand Canyon, stretching nearly a third of its circumference.

RIFTS TAKE **MILLIONS OF YEARS** TO FORM, AS THE **CRUST** SLOWLY PULLS **APART.**

SUN-STARVED SATELLITES

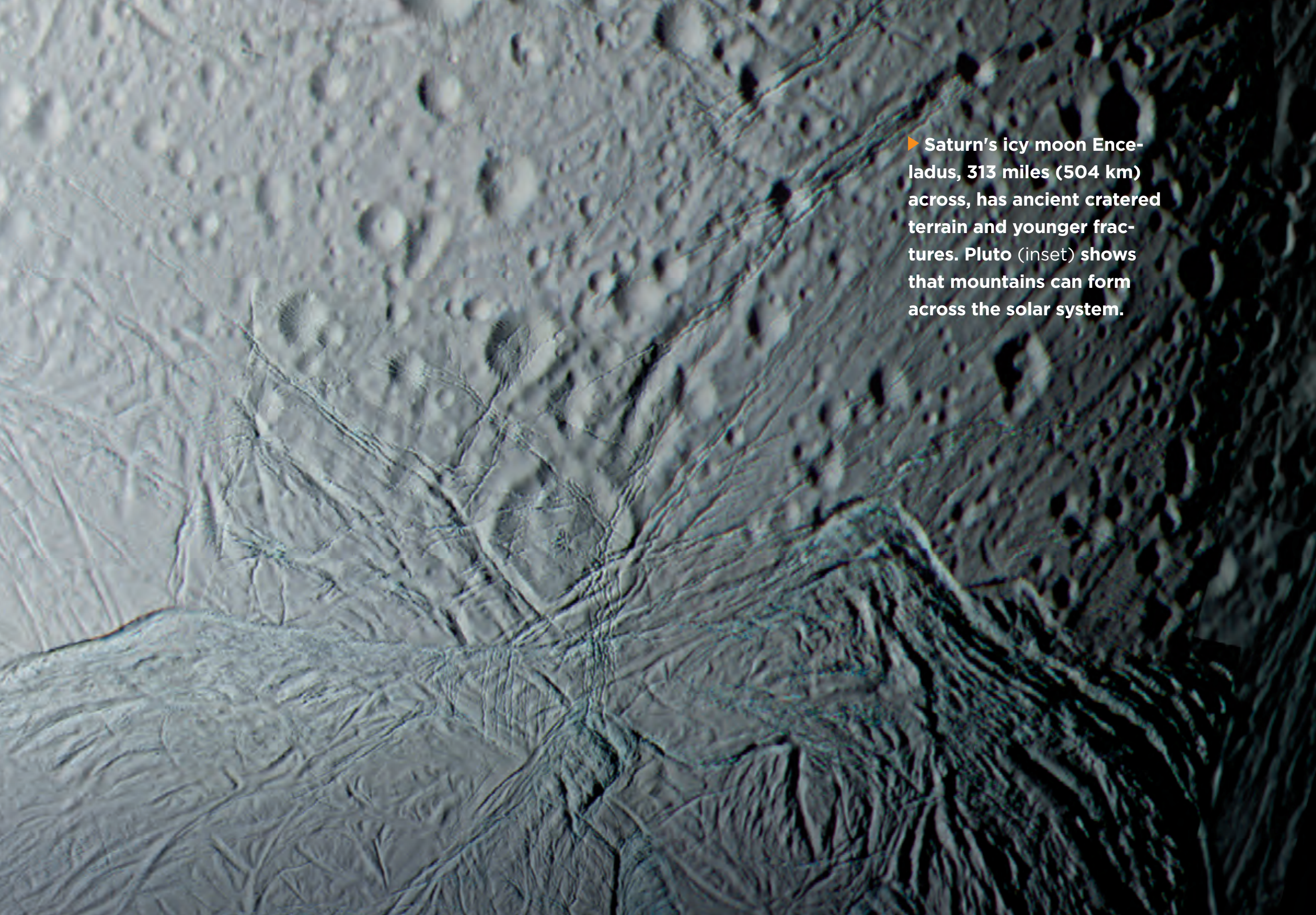
ICY WORLDS

Far from the sun in the outer solar system, the satellites of Jupiter, Saturn, Uranus, and Neptune are composed of rock and water ice. The extremely cold temperatures result in crusts of strong ice that behave like rock, producing mountains, rifts, and faults similar to those found on Earth or Mars but formed by a very different process. What causes these frigid surfaces to deform without plate tectonics? The rocky cores of these outer-planet satellites do contain radioactive elements but do not generate enough heat to produce what we observe. Instead, the nearby giant planet tugs strongly on its satellites, producing tidal flexing or motion in their interiors and creating frictional heat. But instead of melting rock, this tidal heat melts water ice beneath the crust, producing a liquid, subsurface ocean.

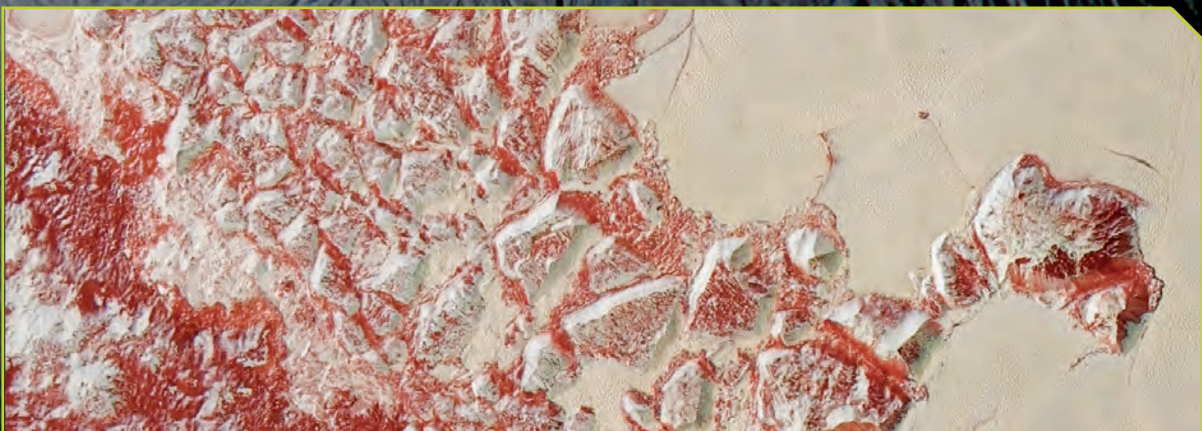
The surfaces of Jupiter's moons Ganymede and Europa have pulled apart in many places, forming belts of grooves. When cracks open, a water-ice slush wells up to create new crust. The motions of oceans beneath the moons' icy crusts, produced by Jupiter's tidal pull as they revolve around the giant planet, extend and compress the icy outer shell. Europa's surface rises and falls almost a hundred feet (30 m) between high and low tides.

Saturn's satellite Enceladus is cut by chasms, some up to 124 miles (200 km) long and more than a half mile (800 m) deep; Saturn's Dione has similar fissures. Messy, fractured moons are found even farther out in the solar system, including Miranda at Uranus and Triton at Neptune.

Even more puzzling are the cracked surfaces of Pluto and its moon Charon. The source of heating that drives crustal motions on these bodies has confounded scientists since New Horizons first imaged them in 2015.



Saturn's icy moon Enceladus, 313 miles (504 km) across, has ancient cratered terrain and younger fractures. Pluto (inset) shows that mountains can form across the solar system.



» Explore More MOUNTAINS IN THE SOLAR SYSTEM

Mountains rise when continents slam together, pushing up the crust. Mountains can also be built from immense piles of lava. The tallest mountain in the solar system is a volcano, Mars's Olympus Mons, at 15.5 miles (25 km) high. Maxwell Montes on Venus comes in second at 6.8 miles (11 km), and may be a sign that Venus had plate tectonics early in its history, when it was wetter. Earth's Mount Everest seems small at 5.5 miles (8.9 km) tall. Satellites also have mountains, such as 3-mile-high (4.9-km) Verona Rupes on Uranus's Miranda, and our own moon's Huygens Mons, 2.9 miles (4.7 km) high.

DEVASTATING ACTION

EARTH'S MOTION

Breaking, cracking apart, smashing together—the rocks on Earth's surface are in motion. The resulting rifts and mountains reveal how a planet is layered, what the layers are made of, and why and when they break. Geophysicists measure the strength of rocks under different conditions in laboratories and combine this information with models to decipher what these features tell us about the planet's upper layers and the forces that have reshaped them. Each planet has a unique set of materials, bending and breaking under different conditions. A rock on Earth will not deform the same way as one on hot, dry Venus, where the lack of water makes rocks stronger. Getting a model to work under different planetary conditions and produce results that match observations helps improve our understanding of the often violent forces that shape Earth's surface.

▶ The remains of a house dangle from a cliff in Christchurch, New Zealand, after a major earthquake in 2011.

OBSERVABLE YET UNPREDICTABLE

There are several million earthquakes on Earth every year. Scientists can identify where they are more likely to happen, as well as study the history of a particular fault to forecast when another damaging quake might occur. But scientists can't predict the exact timing and magnitude, even for well-studied faults like the San Andreas, and often devastating earthquakes occur on unknown or less scrutinized sites, such as the 1994 Northridge, California, earthquake.

While mountain ranges, rifts, and faults are common across the solar system and useful for geologists, we find no easy parallels when it comes to studying the process that really controls how our planet works: plate tectonics. Earth appears to be the only world where plates grow, shift, and dive back down into the mantle. Europa remains our only hope!

Chile's Calbuco volcano, erupting in 2015; lightning in its plume is triggered as ash, rock, and ice collide.

• CHAPTER FOUR •

FIRE FROM WITHIN: VOLCANOES

Volcanoes are the planetary world's smoking guns, showing that a planet is still active. They are found across the solar system, most bearing witness to an active past rather than a fiery present. Lava flows reshape landscapes, and eruption plumes alter atmospheres by injecting gas and ash. Some eruptions last for years, even decades; others, only days. Earth volcanoes create dramatic scenery, from island paradises like Hawaii to towering peaks like Mount Fuji. But they also pose deadly dangers: Lava flows damage and destroy property and life, and eruptive clouds and plumes of ash can disrupt aviation for weeks. Volcanologists compare terrestrial volcanoes to those on other planets and moons to understand the factors that control why, how, and when a volcano will erupt. In turn, our studies of Earth's volcanoes help us interpret what the lava flows we see on surfaces from Mercury to Pluto reveal about that planet's past, present, and future.

INTERNAL HEAT

DEADLY DRAMA

Buoyant melted rock, driven by trapped gases, bursts upward through a crack in a planet's surface, creating fountains and rivers of fire. Some planetary bodies, like Mars and Mercury, did not have enough internal heat to keep their volcanic engines going over their 4.5-billion-year history, and thus ended volcanic activity long ago. Earth and Venus, larger and with more internal heat-producing elements, are active, while Jupiter's volcano-rich moon Io is heated internally by tides raised by the giant planet.

HOTSPOTS AND BOUNDARIES

Where you find a volcano on a planetary surface tells you about how that planet works internally, as well as the kind of rocks that likely make up the volcano. On Earth, volcanoes are concentrated along plate boundaries; those on the land surfaces of continents tend to have silica-rich magma that erupts explosively, such as at Mount St. Helens. Volcanoes also form over rising plumes from the interior called hotspots, giving rise to chains of volcanoes as the plate moves over the hotspot, as in the Galápagos Islands.

The lava of volcanoes on oceanic crust is less silica-rich and erupts more gently, forming long lava flows and gradually sloping volcanoes. The largest eruption in North America in the last million years occurred when a hotspot pierced the continent at Yellowstone, burying much of the Great Plains under yards of volcanic ash.

TEMPERATURE GAUGE

No other planet has chains of volcanoes marking plate boundaries like Earth. Volcanoes on other worlds are instead scattered across their surfaces, indicating interiors dominated by hotspot plumes. By counting impact craters on planetary lava flows, we can establish the history of volcanism on that body, determining when—or if—its volcanic heat engine shut down.

»Explore More LETHAL RATINGS

Over human history, large volcanic eruptions have wreaked havoc, killing thousands and even disrupting the course of civilizations. Eruptions can be rated on a scale from 0 to 8 (the most destructive). Over the last 10,000 years, there have been no 8s and one 7: the 1815 eruption of Mount Tambora, which killed 92,000 people and produced the "year without a summer" in 1816. Other notables: Krakatoa, rated 6; Pompeii, 5. But a volcano's lethality also relates to how it erupts: Mount Vesuvius produced a searing cloud of hot gas and ash that engulfed Pompeii.

The volcanoes of the Galápagos Islands, seen from the STS-108 space shuttle mission, are built of long lava flows erupted from the summit calderas.

MERCURY, THE MOON, **EARTH**, MARS, AND VENUS HAVE **BASALTIC** SHIELD **VOLCANOES.**

HEATED TRANSFORMATION

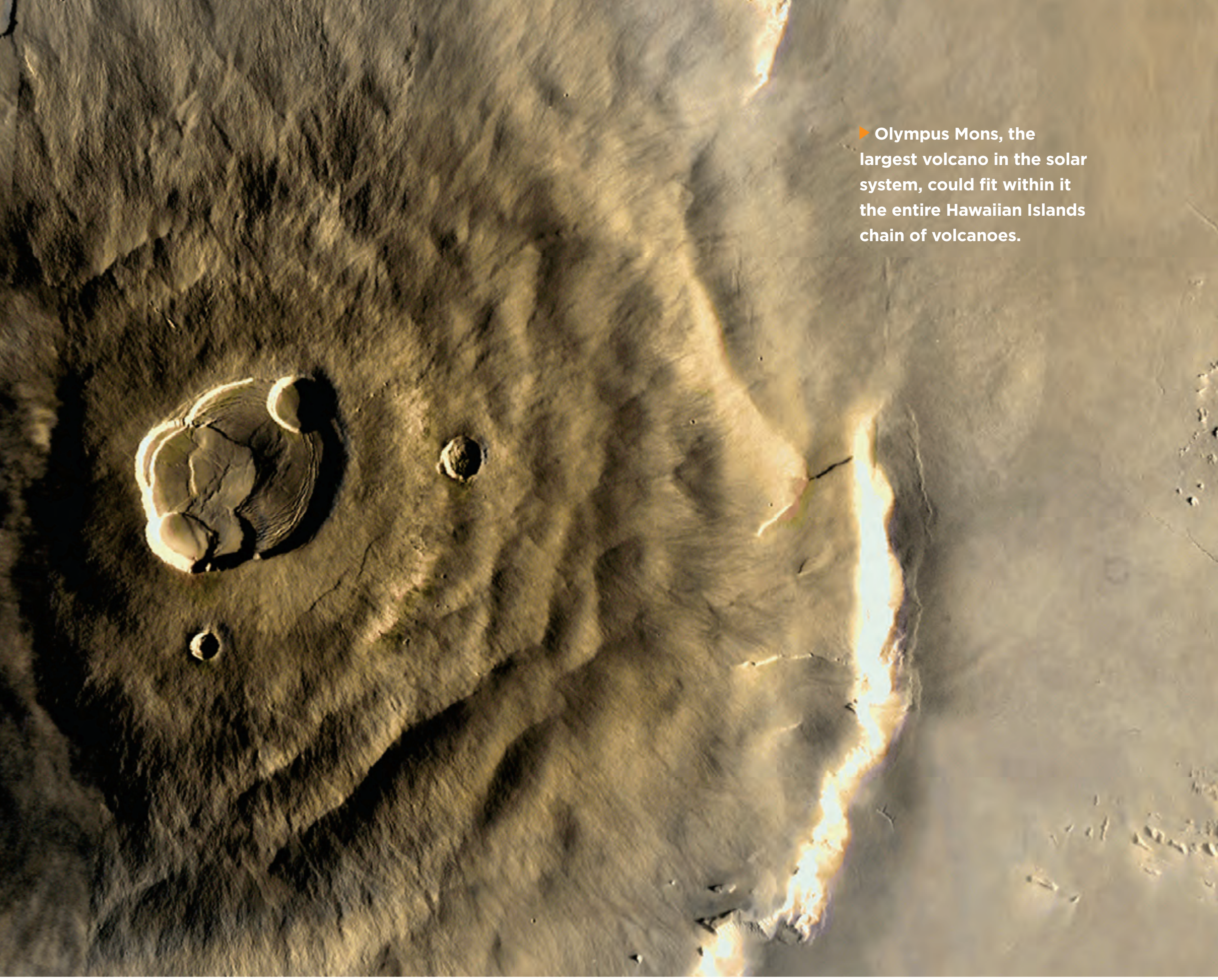
SUPERVOLCANOES

Floods of lava that covered the state of Washington and California's explosive Long Valley caldera, which dropped ash more than 30 feet (9 m) thick as far away as Kansas, are supervolcanoes. Most of these huge eruptions have occurred over hotspots or at the start of a continent's ripping apart. We have not witnessed one in human history, but a supervolcano will erupt again, so we must understand them.

FLOOD BASALTS

About 16 million years ago, a massive eruption in the Pacific Northwest piled layer after layer of lava to a depth of more than two miles (3.3 km), covering more than 63,300 square miles (163,946 km^2). These are the Columbia River basalts, totaling more than 42,000 cubic miles (175,063 km^3) of lava. Flood basalt eruptions are the largest volcanic events on Earth; by comparison, Mount St. Helens in 1980 released only one-third of a cubic mile (1.4 km^3) of lava. India's Deccan Traps, which formed 65 to 60 million years ago, and the Siberian Traps, some 251 million years ago, are flood basalts linked to massive extinctions of life on Earth.

Flood basalts on Earth's moon, called the lunar maria, or seas, formed billions of years ago. Mars, Venus, and even Jupiter's moon Io have flood lavas that cover thousands of



Olympus Mons, the largest volcano in the solar system, could fit within it the entire Hawaiian Islands chain of volcanoes.

square miles. Volcanoes on other planets are truly super: One of the largest calderas on Venus, Sacajawea Patera, is 200 times larger than Earth's largest active volcano. On bodies like the moon and Venus, with no erosion by flowing water or rain, we can study these floods of lava in their pristine state to better understand how and when they form. Scientists debate how quickly Earth's flood basalts were emitted; faster formation would have had much more intense effects through rapid, massive release of toxic, climate-changing gases.

»Explore More VOLCANOLOGISTS

Volcanologists like co-author Ellen Stofan get out into the field to study active and ancient volcanoes. Whether in Iceland, or on Mount Etna in Sicily, or Kilauea in Hawaii, volcanologists watch how a flow forms in real time, sometimes backing away from its searing heat as they attempt to measure how fast the crust forms on the liquid flow and what shapes it takes. Then they compare that information to models and lava flows on other planets to understand how to keep people living near volcanoes safe during eruptions.

OTHERWORLDLY ACTIVITY

VOLCANOES OF THE SOLAR SYSTEM

Towering 15 miles (24.1 km) above the surface of Mars, Olympus Mons dwarfs every other volcano and mountain peak in the solar system. At 374 miles (624 km) across, it would nearly cover the state of Arizona. Olympus Mons sat atop an active hotspot for about a billion years, building up an enormous pile of lava—so massive that at one point part of the volcano collapsed under its own weight. Mars's two groups of large volcanoes ceased activity millions of years ago, which we know from counting the number of impact craters.

Venus has more volcanoes than any other planet; its tallest, Maat Mons, rises 4.8 miles (7.7 km) above the surface and is about 480 miles (773 km) across. Venus has flat volcanoes shaped like pancakes and thousands of small, shield-shaped volcanoes. They may still be active; with Venus's thick cloud cover, we can't see active flows or eruption plumes, though we have measured changes in atmospheric gases that could indicate recent eruptions.

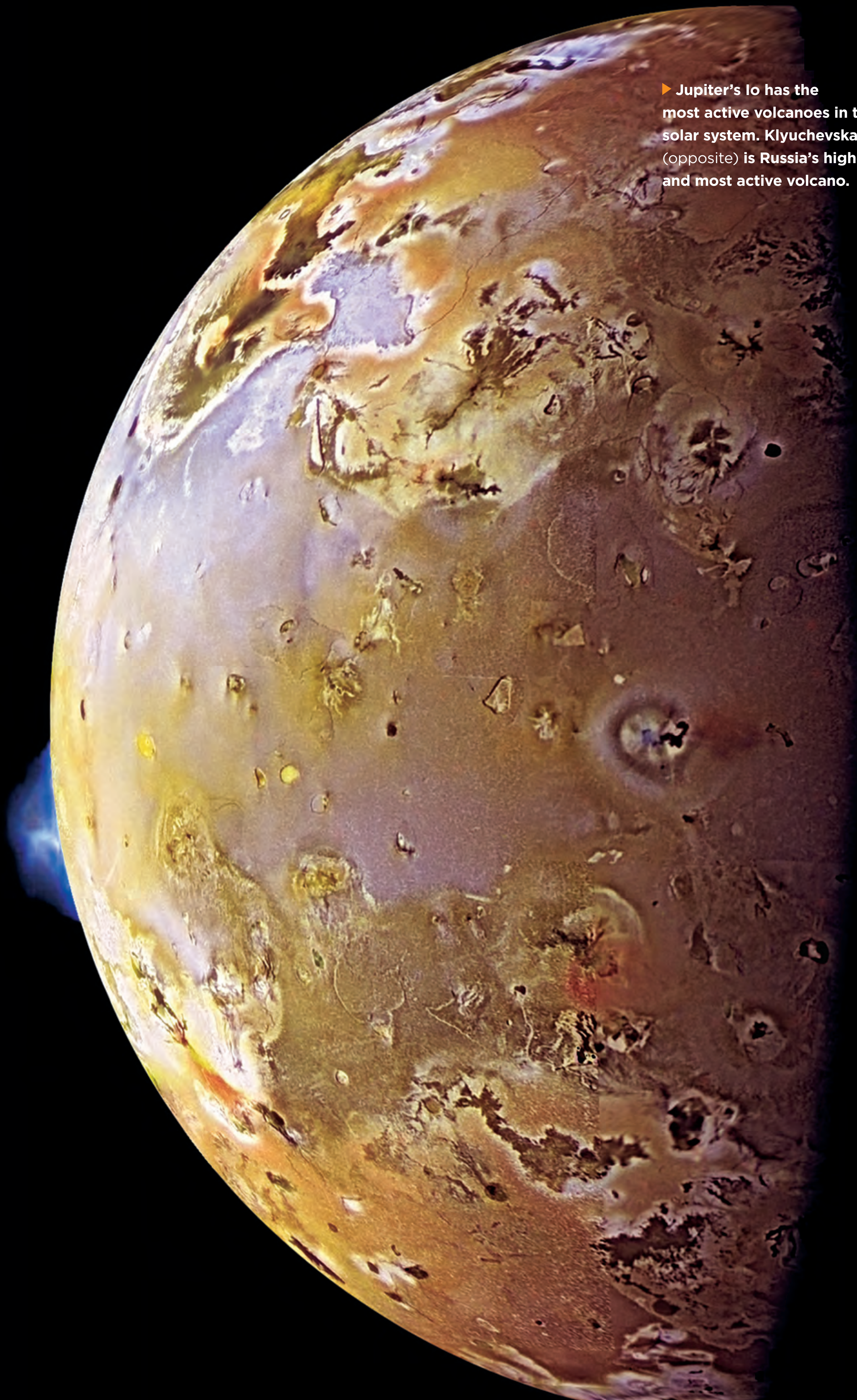
Io, rent by tides induced by giant Jupiter, is the most volcanically active body in the solar system, and the only body with no identified impact craters. This pizza-hued moon gets its color from sulfur in the lava flows, but high temperatures measured by the Galileo spacecraft indicate that they are also silica-rich. Of Io's 350 volcanoes, more than 70 are erupting, and some contain lava lakes, just like those on Earth.

Farther out in the solar system, we find exotic ice volcanoes, such as the newly discovered Wright Mons on Pluto. At temperatures far below zero, erupting water-ice "cryolavas" flow like silica lavas elsewhere.

»Explore More

CATCHING A VOLCANO IN THE ACT

At any time, 40 volcanoes are erupting across Earth. The ancient Greeks first described long-erupting Mount Etna; Hawaii's Kilauea has been active for decades. From orbit, the most identifiable sign is the towering plume. Major eruptions produce clouds of ash that can circle the globe in days. Volcanoes release about 220 million tons (200 million metric tons) of carbon dioxide per year, while humans produce more than 39.8 billion tons (36.1 billion metric tons) of carbon emissions.



Jupiter's Io has the most active volcanoes in the solar system. Klyuchevskaya (opposite) is Russia's highest and most active volcano.

WATCHFUL WAITING

IN A VOLCANO'S SHADOW

Along with Venus and Jupiter's moon Io, Earth is an active volcanic body. Somewhere on Earth right now, a volcano is erupting, causing people to evacuate—and possibly lose—their homes and businesses. In places like Naples, Italy, home to Mount Vesuvius, and Seattle, Washington, where Mount Rainier sits, residents eye local volcanoes with trepidation, knowing they have caused destruction in the past and will do so again. Volcanologists work with local officials to plan for future damaging eruptions.

The diverse array of volcanic features that we see across the solar system, from towering shield volcanoes to small volcanic domes, informs us about what the planet is made up of, and tells us that volcanism is one of the most significant processes in shaping planetary surfaces. Supervolcanoes dot the surfaces of most of the planets, warning us of future megaeruptions but also helping us prepare. By studying the sequence and style of volcanic activity on a planet's surface, we can map the history of its interior.

The more we scrutinize these volcanoes, the more we learn about how high the plumes of ash and gas from an eruption will rise, how far and how fast an erupting lava flow will travel, and, most important, when a volcano might erupt. We can never hope to stop a volcanic eruption, but we can learn how to prevent loss of life and minimize property damage. Studying the full array of the solar system's volcanoes helps us understand and eventually improve predictions of the behavior of these awesome but destructive planetary actors.

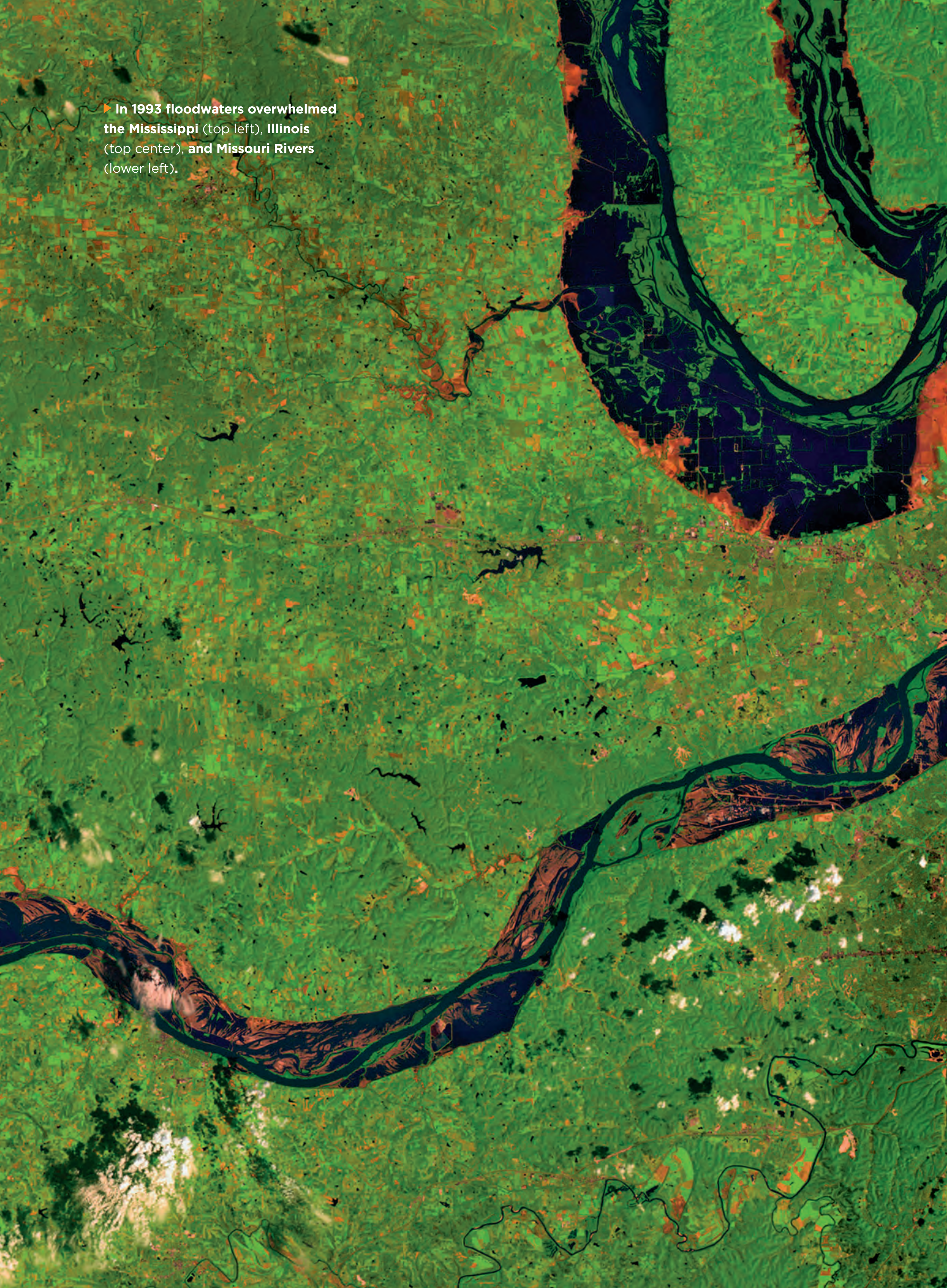
» Explore More

DANGEROUS VOLCANOES

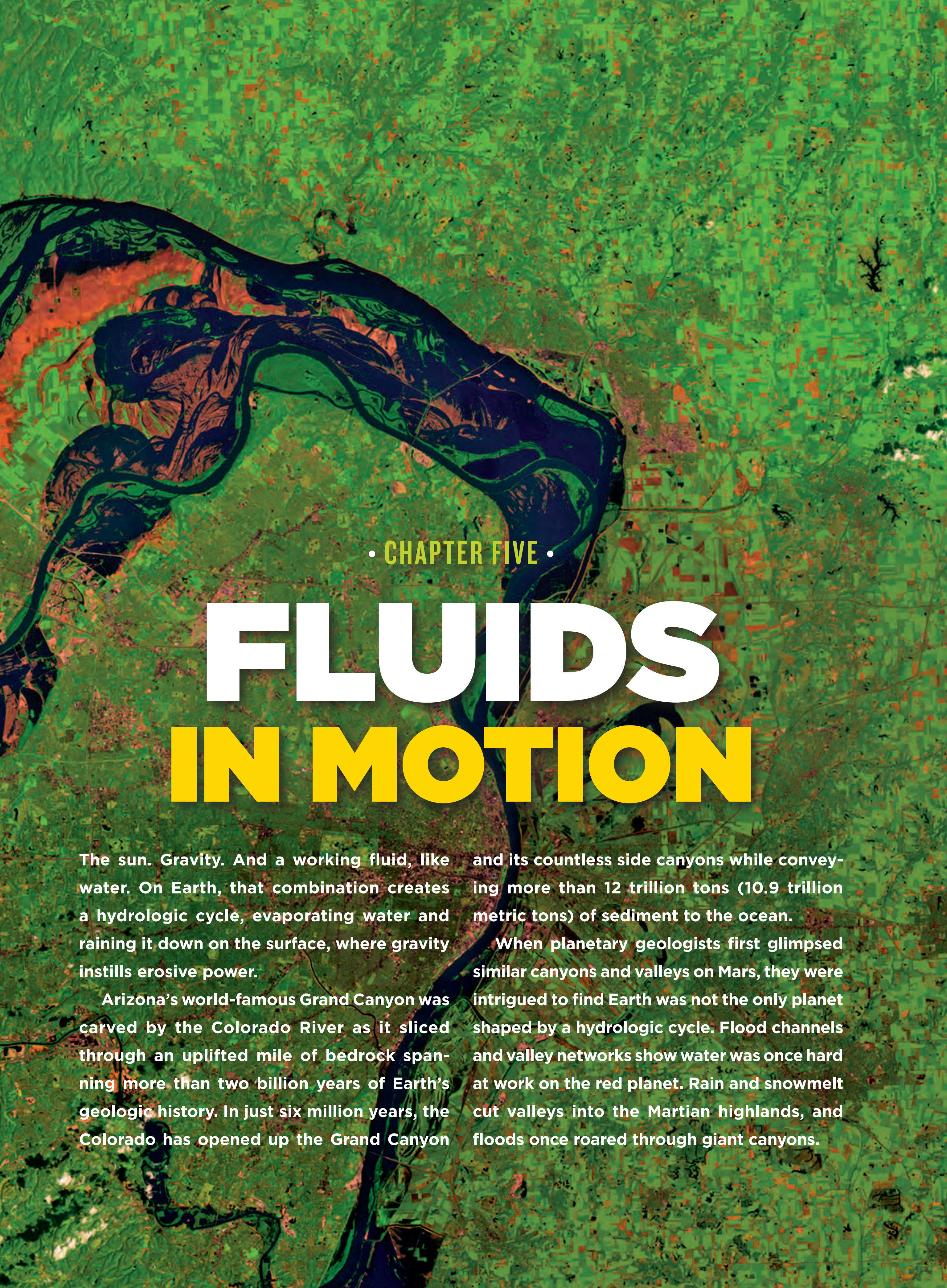
These are some of the most hazardous volcanoes on Earth, posing multiple dangers to populated regions. All have been active recently.

Avachinsky-Koryaksky, Kamchatka, Russia
Colima, Jalisco, Mexico
Mount Etna, Sicily, Italy
Galeras, Colombia
Mauna Loa, Hawaii, U.S.A.
Mount Merapi, Central Java, Indonesia
Mount Nyiragongo, Democratic Republic of the Congo
Mount Rainier, Washington State, U.S.A.

▶ **The 1973 eruption of Iceland's Eldfell volcano threatened homes and farmland, while in 2010 Indonesia's Mount Merapi** (opposite) **produced significant ash.**



In 1993 floodwaters overwhelmed the Mississippi (top left), Illinois (top center), and Missouri Rivers (lower left).



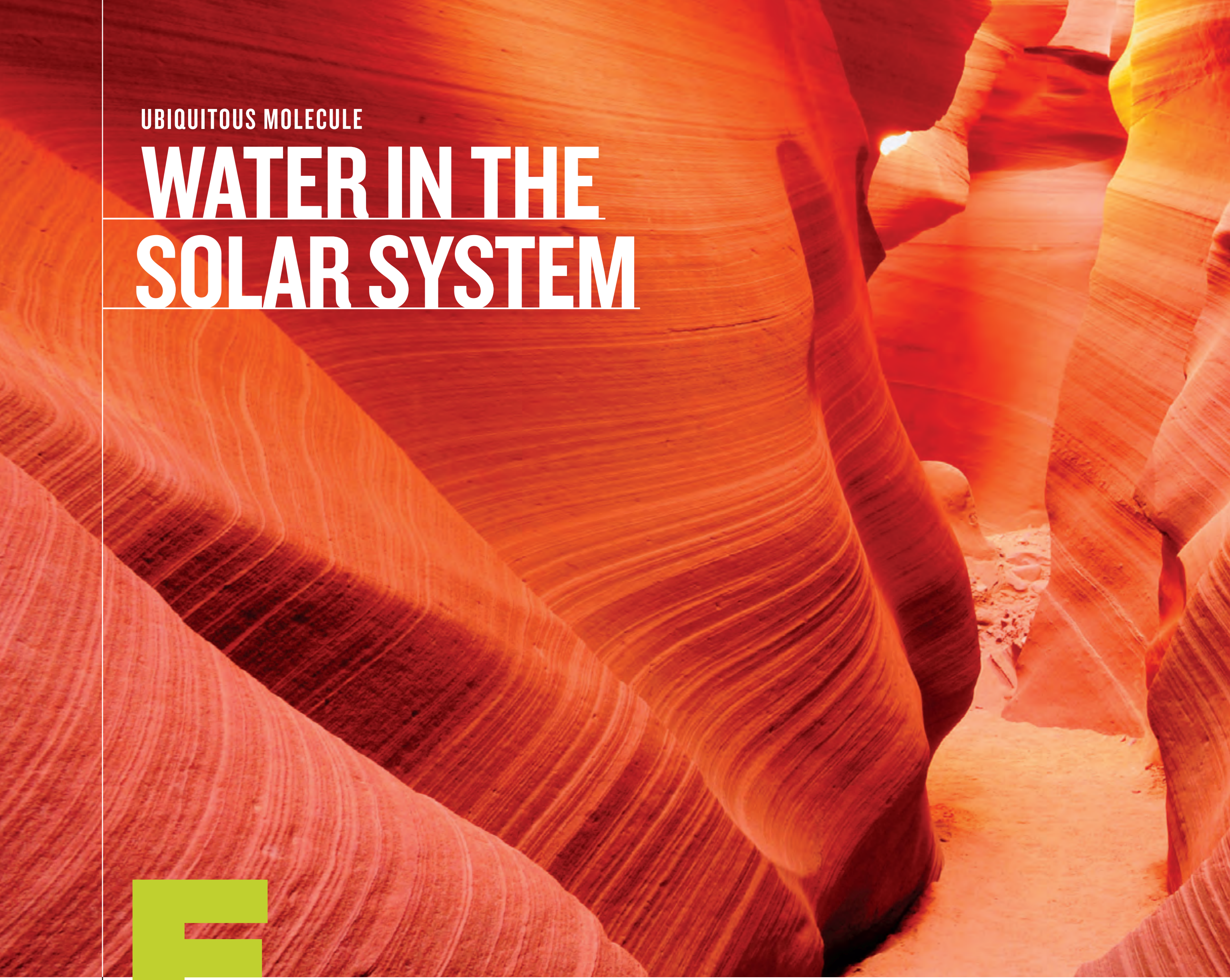
• CHAPTER FIVE •

FLUIDS IN MOTION

The sun. Gravity. And a working fluid, like water. On Earth, that combination creates a hydrologic cycle, evaporating water and raining it down on the surface, where gravity instills erosive power.

Arizona's world-famous Grand Canyon was carved by the Colorado River as it sliced through an uplifted mile of bedrock spanning more than two billion years of Earth's geologic history. In just six million years, the Colorado has opened up the Grand Canyon and its countless side canyons while conveying more than 12 trillion tons (10.9 trillion metric tons) of sediment to the ocean.

When planetary geologists first glimpsed similar canyons and valleys on Mars, they were intrigued to find Earth was not the only planet shaped by a hydrologic cycle. Flood channels and valley networks show water was once hard at work on the red planet. Rain and snowmelt cut valleys into the Martian highlands, and floods once roared through giant canyons.



UBIQUITOUS MOLECULE

WATER IN THE SOLAR SYSTEM

Earth is a water planet. Seventy percent of its surface is covered by oceans. All that H_2O gives our world the deep blue tint seen by robotic spacecraft and marveled at by lunar explorers almost 50 years ago.

Our world is the showcase for the power of water in shaping a planetary landscape. H_2O is found throughout the solar system, but only on Earth is it stable in all three forms—gas, solid, and liquid. Close to the sun, at Mercury, water delivered by comet or asteroid impacts survives as ice in shadowed craters at the poles. Any evaporating molecules break down under solar radiation into free oxygen and hydrogen, inevitably escaping into space. Venus may once have possessed an ocean, but its thick, superheated greenhouse atmosphere has long since sizzled away any water at the surface and desiccated its crust.

SOLAR-DRIVEN CYCLES

At Mars and beyond, temperatures are too cold or pressures are too low for liquid water to exist at the surface. (The average Mars temperature is minus 81°F/minus 63°C; on Saturn, minus 290°F/minus 179°C.) In the outer solar system—in comets or on dozens of moons—surface water exists only as ice since it can remain stable for millions of years at low temperatures.

Flash floods scoured Antelope Canyon from beds of Arizona sandstone. Glacial meltwater carries pulverized rock seaward from New Zealand's Mount Cook (inset).

Oceans of liquid water lie under the icy crusts of several moons around Jupiter, Saturn, and Neptune. Even Pluto may have a slushy sea beneath its frigid crust.

In Earth's hydrologic cycle, water evaporated by the sun condenses as rain, which collects in rivers, lakes, oceans, or underground aquifers. A water molecule resides in the ocean for an average of 3,200 years before evaporating again. That perpetual cycle, driven by solar energy and gravity, is what makes water such a powerful, erosive agent.

»Explore More EROSION BY WATER

Atop mountains, rain joins with melting ice and snow to seep into every hairline crack or crevice, only to freeze again as temperatures drop. Expanding ice widens fractures, splitting rocks apart. Rivulets carry the debris onto a liquid conveyor belt headed to deposit sand and silt in valleys or oceans. Rivers carry about 20 billion tons (18.1 billion metric tons) of eroded material a year, enough to lower continents by about an inch every thousand years. On Earth, water erases the work of tectonics, volcanism, and impact, whose traces are so visible on other planets.

LANDSCAPING FORCES

MAJOR RIVERS OF EARTH

Rivers carry most of the continents' eroded debris seaward. The Mississippi and Amazon are mature river systems; they transport vast amounts of water and sediment across nearly flat plains, marked by oxbow lakes and old flood channels. The 6,570-mile-long (10,573-km) Amazon, fed by Andean snows and South America's tropical rains, dumps 1.2 billion tons (1.1 billion metric tons) of sediment annually into the Atlantic, along with one-fifth of all the freshwater entering the world's oceans.

THE MISSISSIPPI AND MISSOURI

Nearly as long as the Amazon, the Mississippi-Missouri drains Earth's second largest watershed but pumps into the Gulf of Mexico just one-twelfth the Amazon's water output. The Mississippi's massive, miles-deep sedimentary deposits actually depress the continental crust. Even mature rivers like the Mississippi continually shift into new channels and alter deltas.

Draining the northern Rockies, the middle-aged lower Missouri River slices through the badlands of the Dakotas and cuts cliffs into surrounding plateaus. The Missouri supplies most of the sediment carried by the Mississippi after their junction at St. Louis.

RIVERBORNE SEDIMENT

Young rivers like the Brahmaputra and Ganges of India and Bangladesh drain the towering Himalaya. Fed by powerful monsoons and snowmelt, this pair discharges into the Bay of Bengal a sediment load 20 times that of the Amazon.

On Earth, floods occur when rain, or melting snow in spring, overwhelms the drainage system's capacity. The Mississippi floods about twice a decade; in spring 1993, it breached many of its protective levees and inundated the St. Louis area. Floods scour upstream sediments, cut new channels, and dump silt to remake islands, build levees, and spread nutrients across adjacent floodplains.

»Explore More SCORCHING RIVERS: LAVA ON HAWAII

Scorching rivers of lava have cut their way through older lava plains at the Pu'u 'O'o vent on Kilauea volcano on Hawaii's Big Island. A much larger flow cut the moon's Hadley Rille, a channel some 80 miles (129 km) long and about a thousand feet (300 m) deep; the Apollo 15 astronauts landed here and sampled its cooled basalt layers. The moon's lava-carved rilles, easily visible in small telescopes, stretch farther than any found on Earth. Radar images of Venus have revealed more than 200 similar lava channels; one, Baltis Vallis, stretches more than 4,000 miles (6,440 km).

Sediment carried by the Mississippi River—more than 90 million tons (82 million metric tons) annually—built its levees and delta over the past 7,000 years.

IT WOULD TAKE **12.4 MISSISSIPPIS** TO MATCH THE AMAZON'S AVERAGE **OUTFLOW.**

INTRICATE VALLEYS

MARS SCULPTED BY WATER

In the late 1800s, astronomer Percival Lowell claimed he'd seen linear "canals" on Mars, interpreted as irrigation channels built by alien beings. His writings fed popular speculation for decades, until Mariner 4 in 1965 imaged a battered, desolate world and dashed hopes of finding Martians. However, in 1971 Mariner 9 did find an unmistakable pattern of small stream networks on the red planet, feeding into successively larger canyons. The delicate branching pattern of these slender, sinuous channels, like those on Earth, suggests that rainfall or flowing spring water had created the valley networks. Their narrow width (less than a mile, or 1.6 km), the intricate tributary system, and the fact that the valleys increase in size heading downstream imply that they were cut slowly by running water over time, and not by rare, large floods.

In Mars's current thin atmosphere and dry, cold climate, liquid water cannot exist on the surface—it would freeze and quickly sublime into the thin atmosphere. So the presence of water-cut valleys means Mars must have once been warmer, with an atmosphere thick enough to allow rainfall. And because the valleys appear almost entirely in the older, cratered highlands of Mars, the warm conditions and valley formation must have

▶ Streams once flowed into Gale crater, depositing sand and gravel, as shown in this artist's concept. The Curiosity rover is exploring this once wet Mars environment.

occurred in the first few billion years of its geologic history.

This hospitable climate didn't last long. The valley networks didn't lengthen into major river drainages or cut tributaries that captured the flow from adjacent watersheds. Most Martian valley formation must have ended billions of years ago, as the atmosphere thinned and temperatures dropped. Water survives today in polar ice caps and buried ice sheets, but liquid water can exist only underground, trickling occasionally onto the surface.

»Explore More WATER ON MARS TODAY

On cold, dry Mars, liquid water is only belowground. But in 2010 the Mars Reconnaissance Orbiter imaged dark, narrow streaks, 2 to 15 feet wide (0.6 m–4.5 m) and up to several hundred yards long, on a few sunlit crater walls. The streaks form repeatedly when spring and summer temperatures climb above minus 10°F (-23°C). Geologists suspect they form seasonally when briny water flows from a subsurface aquifer. Hydrated salts on these slopes, detected from orbit, are further evidence that the streaks form when salty water trickles downhill, then evaporates.

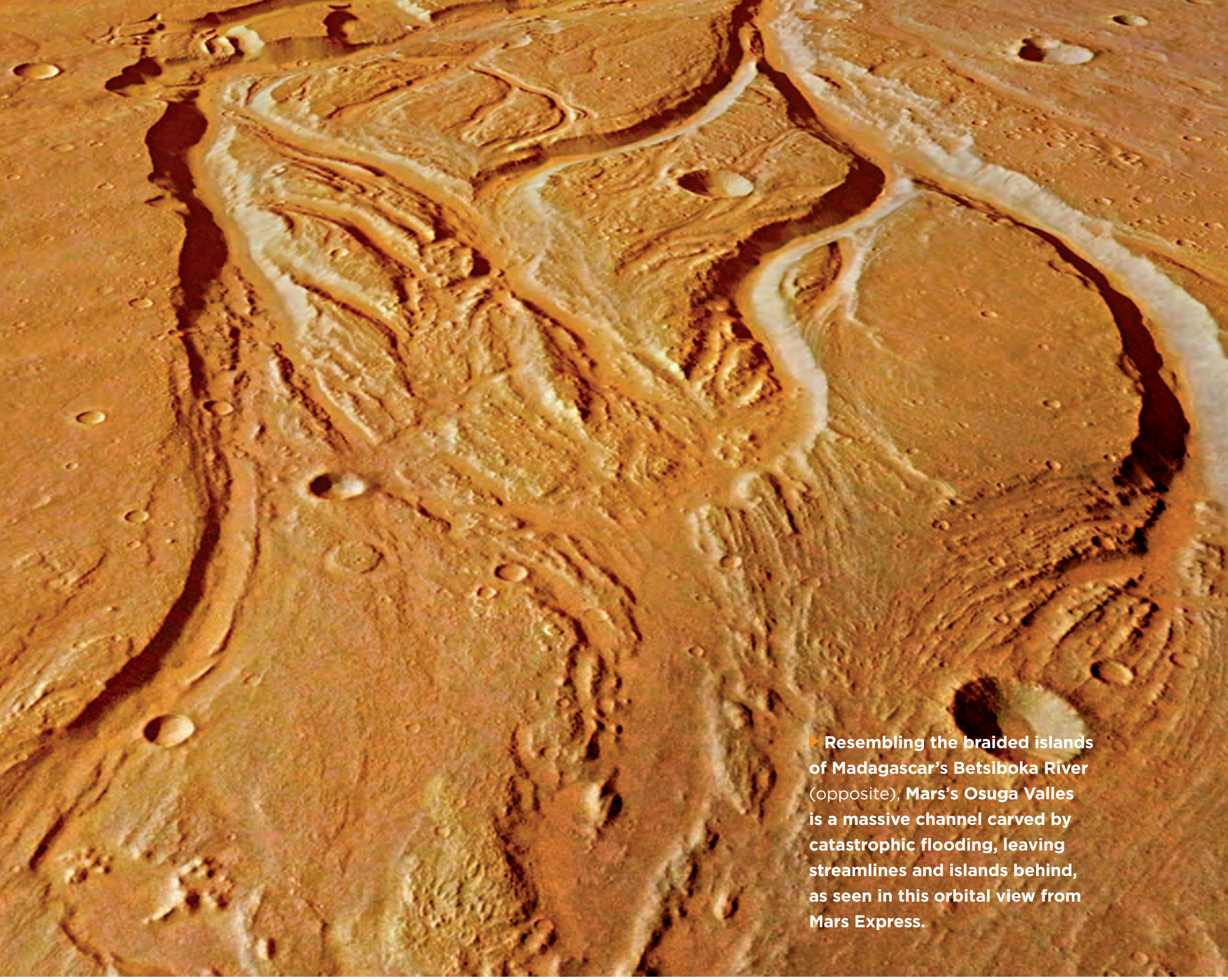
MARTIAN CHANNELS

CARVED BY FLOODS

The solar system's grandest canyon—named Valles Marineris after its robot discoverer, Mariner 9—is a crustal rift valley that stretches 2,500 miles (4,023 km) across Mars's equatorial region. But Valles Marineris, as well as dozens of large canyons across the planet, shows unmistakable signs of massive floods. These channels rise abruptly from broad depressions littered with jumbled blocks of bedrock. Some extend thousands of miles from their source regions until they merge with low-lying plains high in the northern hemisphere. The channels possess few tributaries and appear to emerge at full width from the chaotic terrain. They are marked by dramatic flow lines, scour marks, and teardrop-shaped islands, just like those in sandy-bottomed terrestrial streams. But these Mars floods carried huge volumes of water—the peak flow of the Ares Vallis channel exceeded that of a thousand Mississippi Rivers.

GARGANTUAN OUTBURSTS

The Mars channels are strikingly similar to outsize flood features in eastern Washington State. But unlike those, carved by a series of glacial ice-dam collapses during the last ice age, the Martian flood channels were probably created when trapped



Resembling the braided islands of Madagascar's Betsiboka River (opposite), Mars's Osuga Valles is a massive channel carved by catastrophic flooding, leaving streamlines and islands behind, as seen in this orbital view from Mars Express.

groundwater erupted from beneath a frozen permafrost layer, perhaps released by faulting or an asteroid impact. The gargantuan outbursts collapsed and eroded the overlying rock and sediment, leaving wildly jumbled blocks behind as floodwaters rushed downstream. Rocky barriers created temporary lakes; when these Martian dams failed, a series of cascading, catastrophic floods occurred. Canyon walls in Valles Marineris show layered deposits, possibly created by these short-lived lakes.

»Explore More ANCIENT LAKES

Mars floodwaters ponded in lowlands to form broad lakes or even shallow seas. Orbital imagery shows layered lake sediments and terraces, many within large craters. At Gale crater, the Curiosity rover analyzed stacked, pancake-like layers of gravel and mudstone at the base of Mount Sharp and found they were laid down by streams flowing into a lake between 3.8 and 3.3 billion years ago. The deposits are up to 650 feet (200 m) thick, implying that for at least half a billion years, Mars enjoyed a warmer and wetter climate, perhaps suitable for life.

THE SEARCH ON MARS CONTINUES

WATERY WORLDS

The 2004 Mars exploration rover Opportunity found that the bedrock of Meridiani Planum was once drenched in salty water, either by an aquifer or on the floor of a shallow sea, like Utah's Great Salt Lake. Rock outcrops contain the mineral jarosite, typically formed when rocks are saturated in sulfate-rich standing water. Opportunity also found the surface littered with thousands of tiny spherules nicknamed "blueberries," products of mineral formation and dissolution in a long-lasting subsurface aquifer. That water has long since disappeared, perhaps into underground aquifers, ice sheets, and the polar caps. Hydrologists estimate that if all that ice melted, the water would submerge the entire Martian surface to a depth of more than 30 feet (9 m)!

Curiosity, roving the slopes of Gale crater since 2012, has identified gravels deposited by a stream flowing along the crater floor billions of years ago. Sediments ranging in size from sand grains to golf balls were washed in from beyond the crater rim and then into its interior, forming an alluvial fan spreading onto the crater floor. The grain sizes tell us that water once flowed in the stream at around three feet (~1 m) per second, and was anywhere from ankle to hip deep. The crater's overlapping stream

Titan's north polar lakes of methane and ethane (inset, imaged by Cassini) **dwarf Lake Superior, lapping Michigan's Pictured Rocks National Lakeshore.**

channels indicate that water flowed into Gale for a long time, perhaps millions of years. Curiosity also detected the presence of very thin films of briny water, condensing like dew on rocks each night, then evaporating after dawn.

Mars has gone from a youthful period of massive floods to today's mere trace of liquid water. As on Earth, the story of this planet and its suitability for life has been carried along by the flow of water.

» Explore More COLD LAKES ON SATURN

Beyond Mars, the outer solar system is simply too cold for liquid water. Yet on Saturn's largest moon, Titan, we find evidence of erosion by moving fluids. It can't be liquid water; Titan's surface, at minus 289°F (-178°C), is far too cold. But that's warm enough for liquid methane, raining from the smoggy skies, carving channels in the icy crust, and filling lakes. One of the lakes found by Cassini's radar imager is Kraken Mare, near Titan's north pole. At least 115 feet (35 m) deep and covering 154,000 square miles (~399,000 km^2), it's about five times as large as Lake Superior.

▶ **Ice is common in the solar system, but only Earth has inhabitants like these chinstrap penguins near the Antarctic Peninsula.**

• CHAPTER SIX •

ICE-CARVED LANDSCAPES

Imagine, instead of a familiar blue marble, an Earth dominated by white. Some 20,000 years ago, ice sheets extended from the North Pole to the Great Lakes and covered most of northern Europe. Today they are confined to the poles and Greenland. But these sheets, called glaciers when in motion, carved modern landscapes. About 90 percent of Earth's freshwater is stored in ice caps and glaciers; if all melted, sea levels would rise as much as 230 feet (70 m).

Ice has been detected on Mercury and the moon, as well as on the satellites of Jupiter, Saturn, Uranus, and Neptune, and on dwarf planet Pluto. On Mars, polar caps hint at an icier past, and images show surfaces possibly carved by glaciers. The frozen landscapes of other worlds help us understand the role of water in their formation and evolution, and provide evidence of past climate. And while we study natural climate change on other planets, we worry most about human-induced change on Earth.

A PERMANENT FREEZE

EARTH'S ICY PAST

Polar exploration enthralled the public in the early 1900s. Norwegian Roald Amundsen reached the South Pole in 1911, while American Robert Peary probably reached the North Pole in 1909. Planets' polar regions receive only slanting, indirect sunlight, making them much colder than the equatorial regions. The tilt of Earth's axis produces darkness for much of a polar winter, lowering temperatures further. Near-constant freezing conditions have produced the ice sheet over Antarctica and the ice cap over the Arctic Ocean.

AGED ICE

A balmy day at the South Pole sees the temperature rise only to about minus 12°F (-24°C). Earth's polar regions are covered by ice accumulated by precipitation: Snow that falls on the ice cap or sheet is compacted over time to form layers of ice. The ice at the bottom is very old; some from Antarctica

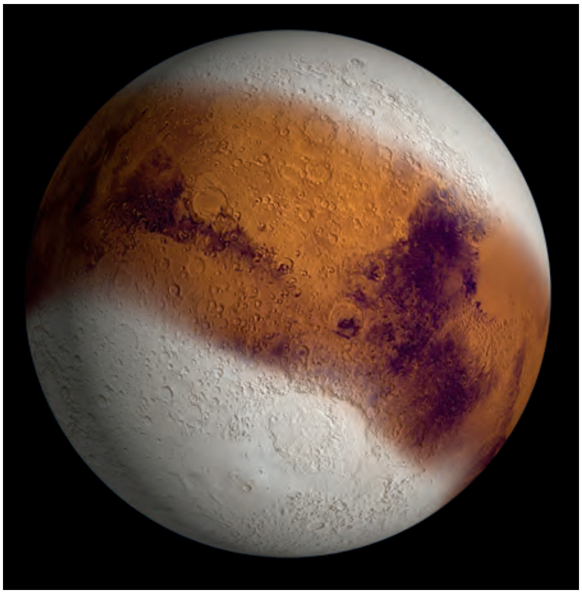
▶ **Steenstrup Glacier on the northwest coast of Greenland has retreated 6.2 miles (10 km) over the past 60 years.**

froze more than 750,000 years ago. Ancient ice can contain trapped air bubbles that allow scientists to study how Earth's atmosphere has changed. The ice ages, when the caps grew, are linked to small changes in Earth's orbit, called Milankovitch cycles. Western Antarctic ice sheets, Greenlandic ice sheets, and Arctic sea ice are shrinking due to global warming, caused largely by human carbon emissions. The Arctic may be free of ice in summer by 2050.

The weight of the giant ice sheets causes Earth's crust to bend downward. Greenland's center has been depressed below sea level by the overlying sheet, almost two miles (3.2 km) thick in places. As the ice melts, which is happening quite dramatically in Greenland, the pressure is relieved and the land springs back at a rate of about a half inch (~1 cm) per year, a process called isostatic rebound. Rebound after the last ice age resulted in Iron Age coastal villages in Sweden now being located far inland.

POLAR ICE ON MARS

Bright blue-white ice against red rocks and dust—this is the dramatic scenery at the poles of Mars. Caps of frozen water and carbon dioxide cover both Martian poles, with the northern cap primarily water ice, and the southern cap primarily carbon dioxide. In the winter, both poles accumulate several feet (~1 m) of carbon dioxide ice from the atmosphere, which then sublimes away—turns directly from a solid into a gas—in summer. It is never warm enough for the water ice in the caps on Mars to melt; instead, their evaporation each summer is the result of the planet's low atmospheric pressure, which is only about 0.6 percent of Earth's atmospheric pressure at sea level.

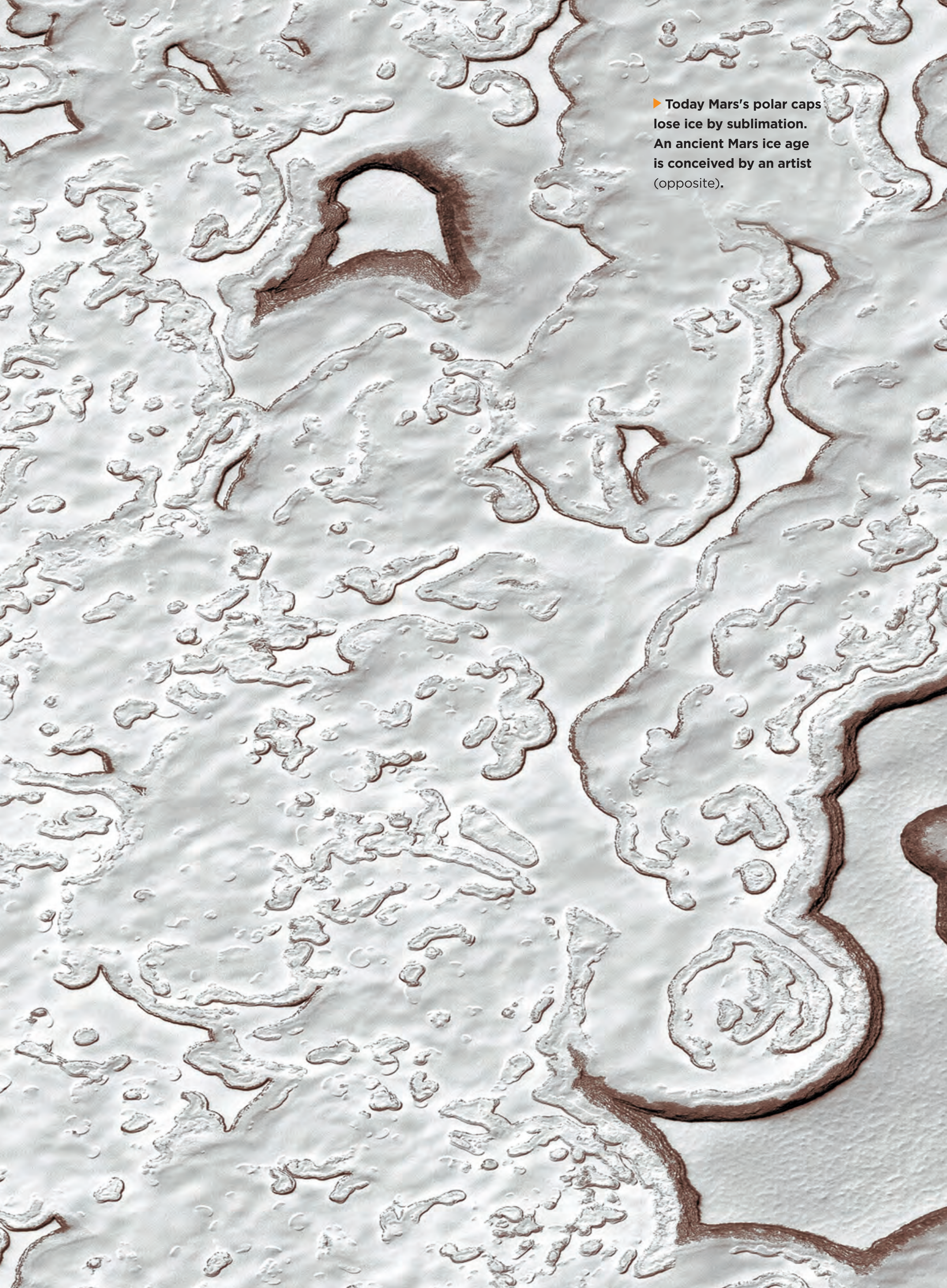


GLACIAL MOVEMENT

The layers of ice, rock, and dust at Mars's poles have been revealed by ice-penetrating radar instruments on both European and NASA spacecraft. These layers, some as thin as a few feet (~1 m) and some more than 1,000 feet (~300 m) thick, record climate changes likely caused by slight shifts in Mars's orbit around the sun—similar to what caused Earth's ice ages. Both caps have long, curving canyons a half mile (0.8 km) deep and up to 60 miles (97 km) wide, incised in a spiral pattern probably carved by Martian glaciers or meltwater. The largest such valley at the north pole is called Chasma Boreale; at the south pole, Chasma Australe. If the canyons were cut by water flowing from the polar caps, that suggests past periods of much warmer temperatures.

CARBON DIOXIDE ICE, ALSO KNOWN AS DRY ICE, FREEZES AT MINUS 193°F (-125°C).

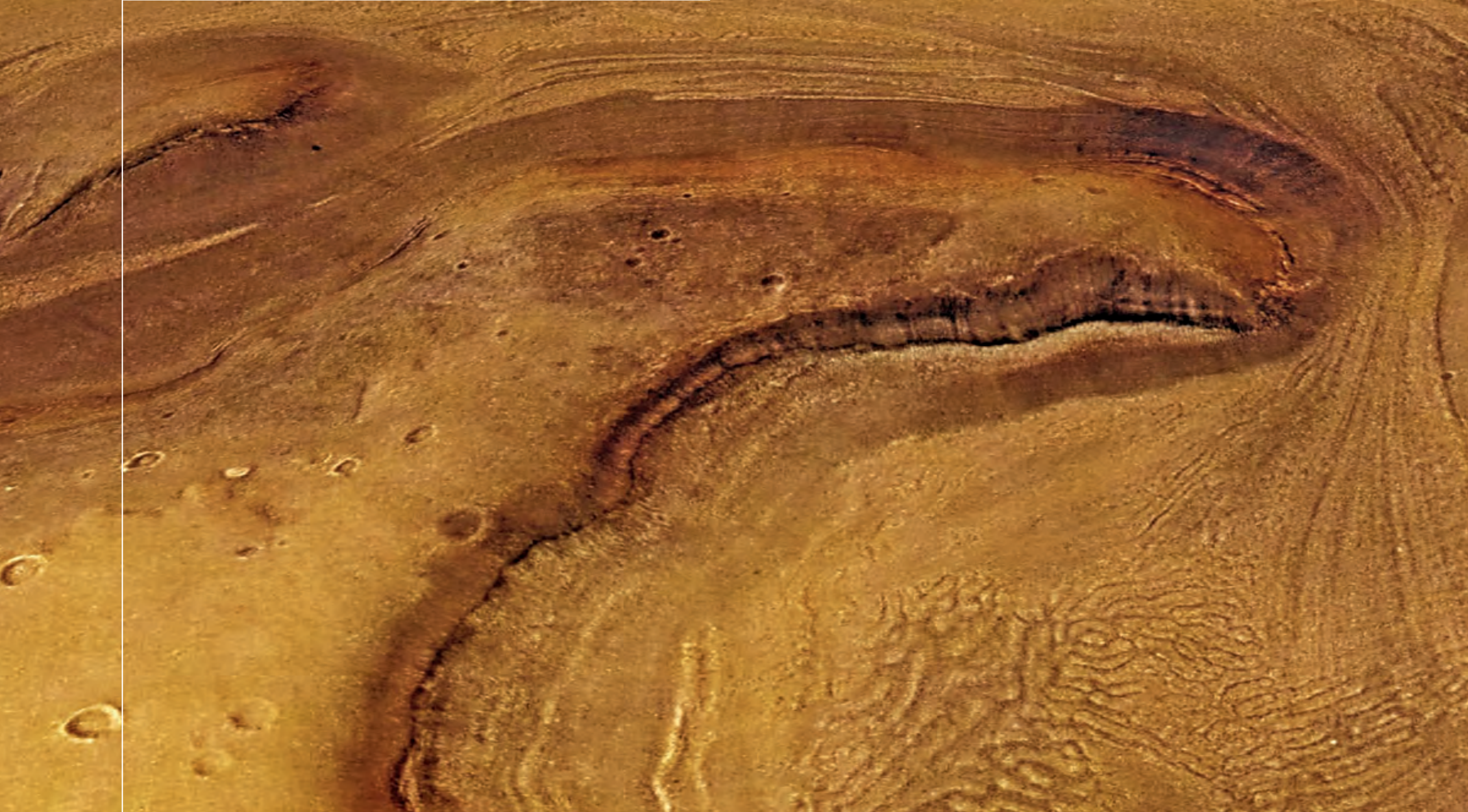
While the heavily cratered surfaces of the moon and Mercury seem unlikely places to find ice caps, evidence of water ice has been detected at their poles. Permanently shadowed impact craters on both contain deposits of water ice likely brought by comets. On the moon, this ice could be a source of water or rocket fuel for future explorers.



▶ Today Mars's polar caps lose ice by sublimation. An ancient Mars ice age is conceived by an artist (opposite).

GLACIERS

RIVERS OF ICE



Emerging from the melting ice of a glacier were the remains of a human—but how old? Ötzi the Iceman, recovered from a glacier in the Austrian Alps in 1991, turned out to have been murdered around 3300 B.C. The ice had preserved not just his clothes and the contents of his stomach but also evidence that he had suffered a head wound, as well as an arrow to the shoulder.

Earth is home to more than 67,000 glaciers, rivers of ice in motion that cover about 10 percent of the land area; during the last ice age, they covered about 30 percent. The longest in North America is Alaska's Bering Glacier, 126 miles (203 km) long. But most of Earth's glaciers are retreating as the climate warms. By 2030 Mount Kilimanjaro in Kenya may lose its famous glacier, and Glacier National Park in Montana may also be ice free.

Like ice fields, glaciers during the winter accumulate snow and ice that form compacted layers of ice. Glaciers flow down valleys and mountains, eroding the underlying rock and scouring out boulders that help grind the surface as they go. Glaciers proceed at varying rates, from as little as 6.5 feet (2 m) to as much as 5 miles (8 km) in a year, depending on the slope, thickness, temperature, and type of surface they rest on. A sudden, rapid downslope

Deuteronilus Mensae, in the northern plains of Mars, resembles the Taylor Glacier in Antarctica (inset). Ice may still be trapped beneath Mars's red dust.

movement, called a surge, can carry a glacier dozens of feet in a single day.

As a glacier melts, it leaves behind a landscape characterized by U-shaped valleys, such as Yosemite Valley in Yosemite National Park, and mounds and hills of rock and dirt, plowed up by the glacier. One in Farmingville, New York, called Bald Hill, was deposited 21,000 years ago. Glaciers also scoop out lakes and ponds, among them the Great Lakes of North America.

» Explore More ICE ON MARS

Did glaciers carve landscapes on Mars, as they did on Earth? Hills in the northern plains of Mars resemble those left behind on Earth after its ice ages, the last ending about 11,700 years ago. Deuteronilus Mensae is remarkably similar in appearance to Taylor Glacier in Antarctica. On Mars, the top layers of ice may have sublimed away before being buried by layers and layers of dust, which preserved some of the ice below. Some of these possible dust-covered glacier remnants are near the Martian equator, where they could provide water to future astronauts.

CLIMATE CHANGE

THE FUTURE OF ICE

Earth's climate has fluctuated over the history of the planet. A temperature decrease of 7° to 9°F (4° to 5°C) and an increase in snowfall marked the start of an ice age caused by natural changes in Earth's orbit around the sun. But the modern rise in our world's global average surface temperature, about 1.4°F (0.8°C) since 1880, is driven by human-induced processes.

Our atmosphere contains a mixture of greenhouse gases, including carbon dioxide, that allows the sun's light to pass through and traps heat radiated from Earth's surface. Without atmospheric greenhouse gases, our planet's temperature would be 60°F (33°C) cooler. Venus's carbon dioxide is mostly all in its atmosphere, resulting in surface temperatures near 900°F (482°C). While early Earth was warmer, with an atmosphere richer in carbon dioxide, the evolution of living organisms incorporated carbon dioxide into shells and coral reefs, removing CO_2 from the atmosphere and cooling Earth.

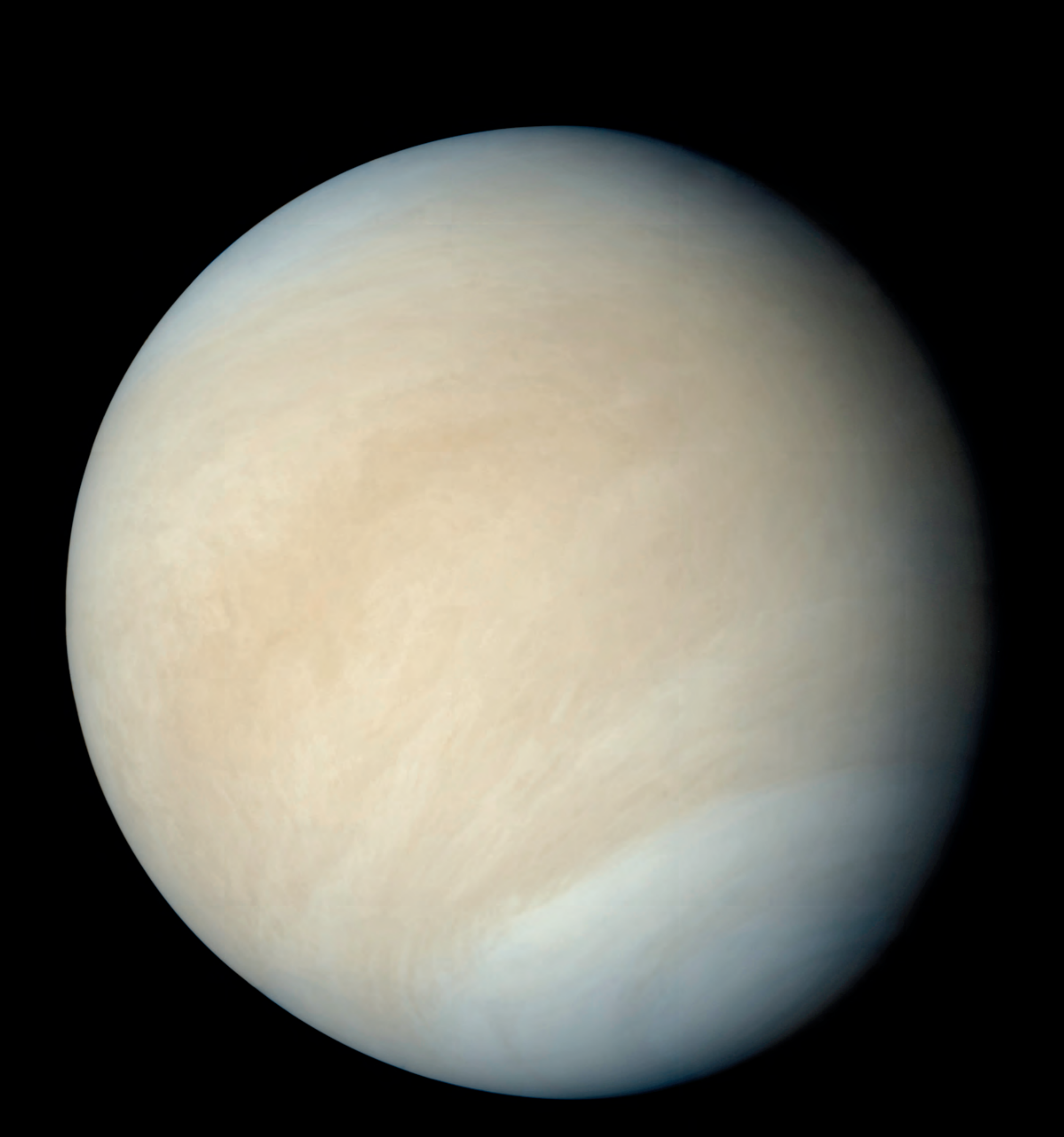
HUMAN EFFECTS

Since the industrial revolution, human activity has injected increasing amounts of CO_2 into the atmosphere through our burning of fossil fuels, increasing the pace of climate change. Its impact is evident: There is a dramatic loss of ice in the Arctic; regular flooding in low-lying regions as sea levels rise, the oceans thermally expand, and land ice melts; and more incidences of extreme weather, such as prolonged droughts, excessive rainfall, and unusually heavy snowfall. Rising temperatures put at least 30 percent of species at risk of extinction, and will affect our food supply and the crops we can plant. Reducing carbon emissions by shifting to renewable and nuclear energy would help mitigate some effects of climate change.

»Explore More

SNOW TO WATER

In California and elsewhere, estimating the equivalent water volume of the snowpack with airborne or spaceborne instruments is critical for farmers and city dwellers who depend on the yearly snowmelt. In 1994 the Space Radar Lab used Mammoth Mountain in California as a test site. While the shuttle radar measured water volume from space, ground readings verified the space-based data. As rain and snowfall patterns shift with changing climate, global measurements of snowpack inform us of the future availability of water supplies.



▶ **Studying the runaway greenhouse atmosphere of Venus helps us understand climate change, which is causing alpine glaciers to melt as Earth warms** (opposite)**.**

A dust storm blankets Australia’s outback. Wind-borne particles build dunes and abrade rock across the solar system.

• CHAPTER SEVEN •

TOUCHED BY THE WIND

The wind can't raise continents or plunge oceanic crust into the mantle, but given time it can reshape Earth landscapes. A nearly transparent film of gases just one-millionth the mass of our planet itself, the atmosphere in motion can easily lift soils and dust from the surface.

Heated by the tropical sun, equatorial air rises and spreads north and south, transporting energy toward the poles. Earth's spin deflects the flow even as it slides over cooler air, causing the energetic circulation we call "winds."

Storm winds can pound shorelines, devastate forests, and flatten buildings; they have been clocked at more than 231 miles per hour (372 kph), at New Hampshire's Mount Washington in 1934. Less dramatically, steady winds raise dust storms that carry sand and fine soils over long distances. Although windborne particles work more slowly than waterborne silt, over time they can erode rocks and build impressive dunes.

ON EARTH, MARS, AND VENUS

AN INVISIBLE, IRRESISTIBLE FORCE

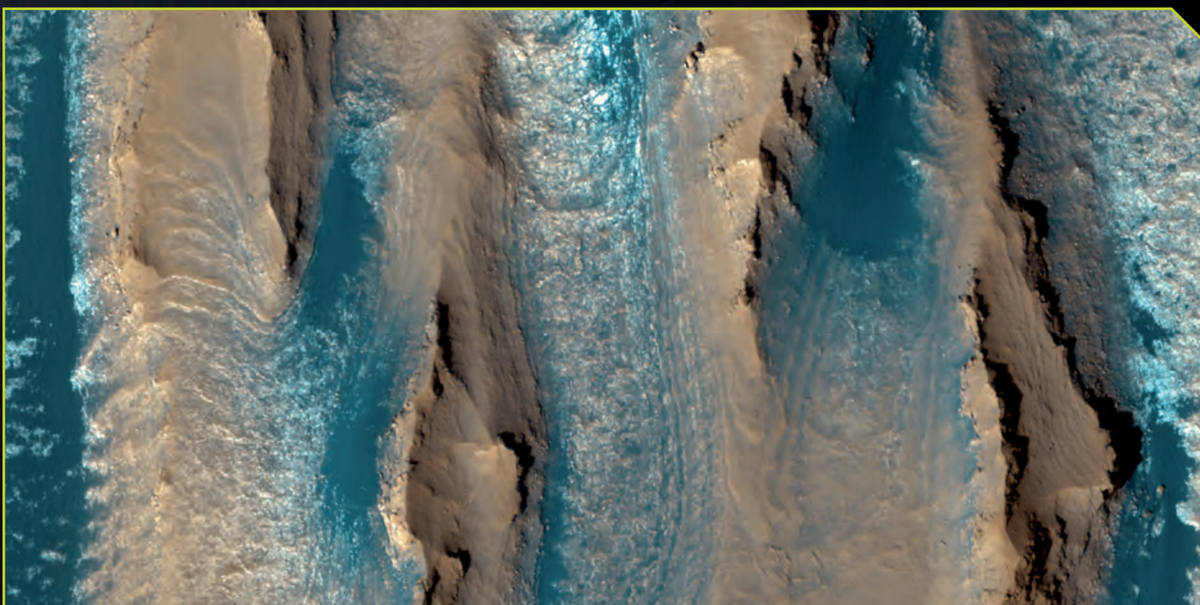
Earth's neighboring worlds possess very different atmospheres. Venus is cloaked in a superheated CO_2 blanket so massive that the surface pressure is 90 times that of Earth's, equal to the water pressure at an ocean depth of more than half a mile. That much CO_2 and the sun's proximity create a runaway greenhouse effect that heats Venus's surface to 900°F (482°C), hot enough to melt lead.

Exerting just one-third of Earth's gravity, Mars has a CO_2 atmosphere with a surface pressure less than one percent that of our planet. At Mars's equator, 141 million miles (227 million km) from the sun, temperatures barely reach 70°F (21°C) and plunge to minus 195°F (-126°C) at the poles. The thin air and low temperatures don't seem conducive to strong wind action, but when Mariner 9 arrived in 1971, it found the red planet masked in a dust storm. It later imaged dark streaks and rippling sand dunes, proof that wind was at work.

When the two Viking landers arrived on Mars in 1976, their cameras showed drifts of fine-grained dust and wind-scoured faces of rocks. But how? Wind speeds were measured at only about 11 miles per hour (18 kph), hardly enough to nudge a Martian sand grain.

The answer was solar energy—and time. The nearly six-month-long Martian summer traps enough heat to generate strong winds, and Mars's lower gravity, at 38 percent of Earth's, helps the dust get airborne and stay aloft. Given hundreds of millions of years, Martian wind storms created vast dune fields and cloaked the planet in orange-red dust—hence its nickname. Over time, steady winds have carved bedrock into fluted landforms aligned with prevailing breezes. The thin Martian air still has power.

▶ **The gauzy layers of Earth's atmosphere belie the change that winds produce on a surface, like wind-carved ridges on Mars called yardangs** (inset).



» Explore More WIND-CARVED LANDFORMS ON EARTH AND MARS

Wind removes loose surface material, leaving behind shallow basins in a process called deflation. Heavier remaining rocks accumulate into a layer of packed pebbles called desert pavement, common on both Earth and Mars. Over time, abrasive, wind-blown sand slowly erodes resistant bedrock into long, streamlined ridges called yardangs (Turkish for "steep banks"), resembling an overturned ship's hull. Earth yardangs can grow 100 yards (91 m) high and stretch along the prevailing wind direction for several miles—even farther on Mars.

WINDSWEPT

DUST STORMS AND LOESS DEPOSITS

Every year, strong winds sweep about 40 million tons (36 million metric tons) of Sahara desert dust to the Amazon Basin, supplying important mineral nutrients to the rain forest ecosystem. About half of the annual dust falling on the Amazon emanates from a single African source, the Bodele Depression, northeast of Lake Chad. A mountain gap upwind of the depression funnels strong surface winds across it, lifting an average of 700,000 tons (635,000 metric tons) of dust daily.

DUST STORMS AND DEPOSITS

Martian dust storms dwarf even the legendary sandstorms of the Sahara and China's expansive Gobi. A typical Mars dust grain is just one micron across, as fine as the particles in cigarette smoke, so even weak winds send them aloft. Local Mars dust storms typically stretch 60 to 600 miles (~97 to 970 km) but occasionally grow into a planetwide shroud of orange-yellow haze. Dust from a 2007 global storm reduced power from the Opportunity rover's solar panels to critically low levels. Luckily, passing dust devils (whirlwinds) swept off the grit, restoring adequate electricity.

As winds subside, the suspended material falls to the ground, forming deposits of sand and dust. Prevailing winds can build up uniform deposits called loess (German for "loose"),

Sand seas cover a quarter of the Sahara and contribute dust, shown blowing westward. Dust deposits (inset) in China's Loess Plateau are up to 656 feet (200 m) deep.

a thick blanket of fine dust, clay, and sand. On Earth, loess underlies rich farmlands in areas like Washington's Palouse region, the upper Midwest, and the Loess Plateau of central China.

The ice ages exposed to scouring winds vast quantities of rock, which were ground by glaciers to fine powder, then picked up and later deposited as loess. The Missouri River of eastern Nebraska carved steep-sided bluffs in loess deposits that are roughly 12,000 years old and more than 60 feet (18 m) thick, similar to those found along the Rhine and Danube Rivers.

»Explore More WIND: ABOVE IT ALL

Seen from orbit, our atmosphere is a gauzy layer of blue separating Earth from the utter black of space. But wind's work is plainly visible: Centuries of unceasing winds have built endless ranks of orange dunes in the Algerian Sahara. In China's Gobi, powerful storm fronts have churned sand into the air, veiling thousands of square miles in a dull yellow haze. In Australia's outback, blowing sand has carved fluted yardangs into rust-red bedrock. Across the planet, storms and wind-carved landscapes are graphic proof of the power of moving air.

SOARING HILLS OF SAND

DUNES

Dunes are born when winds strike an obstacle, slowing them down and dumping sand grains to the ground. The growing pile creates a bigger disturbance, dropping more windborne sand. The sand drifts into a gently sloped, windward face; as grains bounce over the top, they avalanche down the steeper rear face of the dune.

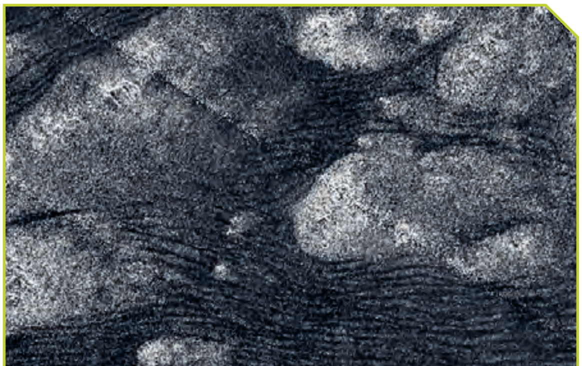
Earth sand dunes can reach heights of 100 to 300 feet (30–91 m), but some in the Alashan Plain of western China soar to more than a thousand feet (~300 m). There are five basic types: barchan, which are crescent-shaped with downwind horns; transverse, with a sinuous crest perpendicular to the wind; linear, with a crest aligned between two prevailing wind directions; star, isolated sand hills with central peaks, built by multidirectional winds; and parabolic, which are U- or V-shaped, with arms opening upwind.

Where sand is plentiful, as in deserts, dune fields can form extensive ergs, or sand seas, like those found in the Sahara, Australia's outback, and the Arabian Peninsula.

OTHERWORLDLY DUNES

Dunes form from Venus to Mars and beyond, wherever wind can deposit fine materials and drift them into hills. Some Martian dunes top 20 feet (~6 m) in height, but due to the thin atmosphere and low wind speeds, most form and migrate very slowly. On present-day Mars, sand takes some 50,000 years to drift into a classic dune shape. Winds of 75 miles per hour (~120 kph) are needed to move even a three-foot-tall (1-m) dune, and it may take 1,000 years to migrate just a few feet.

Dune fields cover the floors of some craters near Mars's south pole and sweep more than halfway around its north polar cap. These shifting sand seas exhibit subtle annual changes.



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TITAN DUNES

Dunes on a world made of ice? The Cassini orbiter at Saturn used radar to image smooth ridges hundreds of miles long on the giant moon Titan. Spaced about two miles (3.2 km) apart, these longitudinal dunes are probably composed not of sand but of solid organic particles or ice grains coated with organics. The organic compounds are products of the breakdown of methane and ethane by sunlight high in the atmosphere. Astronomer Carl Sagan called them tholins, after the Greek word for "muddy." Titan is likely coated with this fine, sooty fallout.

Nili Patera is an active dune field on Mars; these barchan dunes have shifted over a period of a year or two. On Titan's Shangri-La Sand Sea (opposite), winds blow hydrocarbon grains into flowing, linear dunes 300 feet (91 m) high.

ACTIVE DUNES ON MARS MAY MIGRATE SEVERAL YARDS IN JUST A FEW MONTHS.

▶ The evolution of life may have begun in hot springs similar to Yellowstone's Grand Prismatic Spring.

• CHAPTER EIGHT •

ARE WE ALONE?

THE SEARCH FOR LIFE

Looking up at the blaze of stars against the night sky, humans have long wondered if we are alone. Is there life warmed by the light of some of these stars? To answer this question, we need to understand the origin of life here and the presence or absence of life on other worlds.

Life on Earth is split into three groups: bacteria, archaea, and eukaryota (to which humans belong), each originating from a common ancestor. All cellular life-forms store genetic information in RNA and DNA; as species become more complex, they evolve more genes to support new functions and forms. All life shares a number of common genes and uses about 20 amino acids, although more than 500 are known. Amino acids have been detected in interstellar clouds and comets, and meteorites have been found to carry some of the amino acids that make up DNA. The ubiquity of these building blocks suggests that life beyond our world may not be that dissimilar to life here on Earth.

CRITICAL COMPONENTS

THE RISE OF LIFE

Our understanding of how life evolves is biased by the only example we know—our Earth. Three major components are considered necessary for life: carbon, which, with hydrogen and oxygen, makes up the organic molecules that are the building blocks of life; liquid water; and a source of energy. These are the ingredients we look for in places beyond Earth.

Life originated in Earth's oceans from complex chemical reactions between the building-block organic molecules that were likely delivered by comets and asteroids. Ribonucleic acid, or RNA, is common to all life on Earth and is thought to have formed first, around four billion years ago. RNA organized other molecules into groups and structures, including DNA, or deoxyribonucleic acid; these molecules eventually took on the characteristics of life: the ability to replicate and evolve.

WHY WATER?

Liquid water was necessary because it could bring together all the chemical components needed for life. Single-cell life-forms in the oceans dominated Earth for more than a billion years. Then multicelled organisms evolved, with land plants appearing about 470 million years ago, and early humans about four million years ago. So while life emerged rapidly on an early, stabilizing Earth, complex forms took an extremely long time to evolve.

What causes species to evolve and eventually become extinct? Mutations in the DNA of living organisms enable adaptations to changing conditions, and natural selection promotes the spread of those mutations that benefit a species—Darwinian evolution. A familiar recent example is bacteria developing resistance to antibiotics. Species go extinct when the ecological niche or environment they inhabit changes and they cannot adapt rapidly enough.

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LIFE IN THE EXTREME

In boiling heat or frigid cold, in nuclear waste or deep inside mines—no matter where on Earth we go, we find life. Organisms that live in these extreme conditions are called extremophiles and belong to the domain archaea in the tree of life. Extremophiles make us more confident that life could evolve in places like Europa's subsurface oceans or survive underground on Mars. Scientists estimate there are 5×10^{30} bacteria on Earth, making the seven billion of us seem insignificant. When we go beyond Earth, single-cell life-forms are likely to be the most common.

On comet Churyumov-Gerasimenko, Rosetta’s Philae lander detected organic molecules, precursors to life on Earth, which include seafloor methane ice worms (opposite)**.**

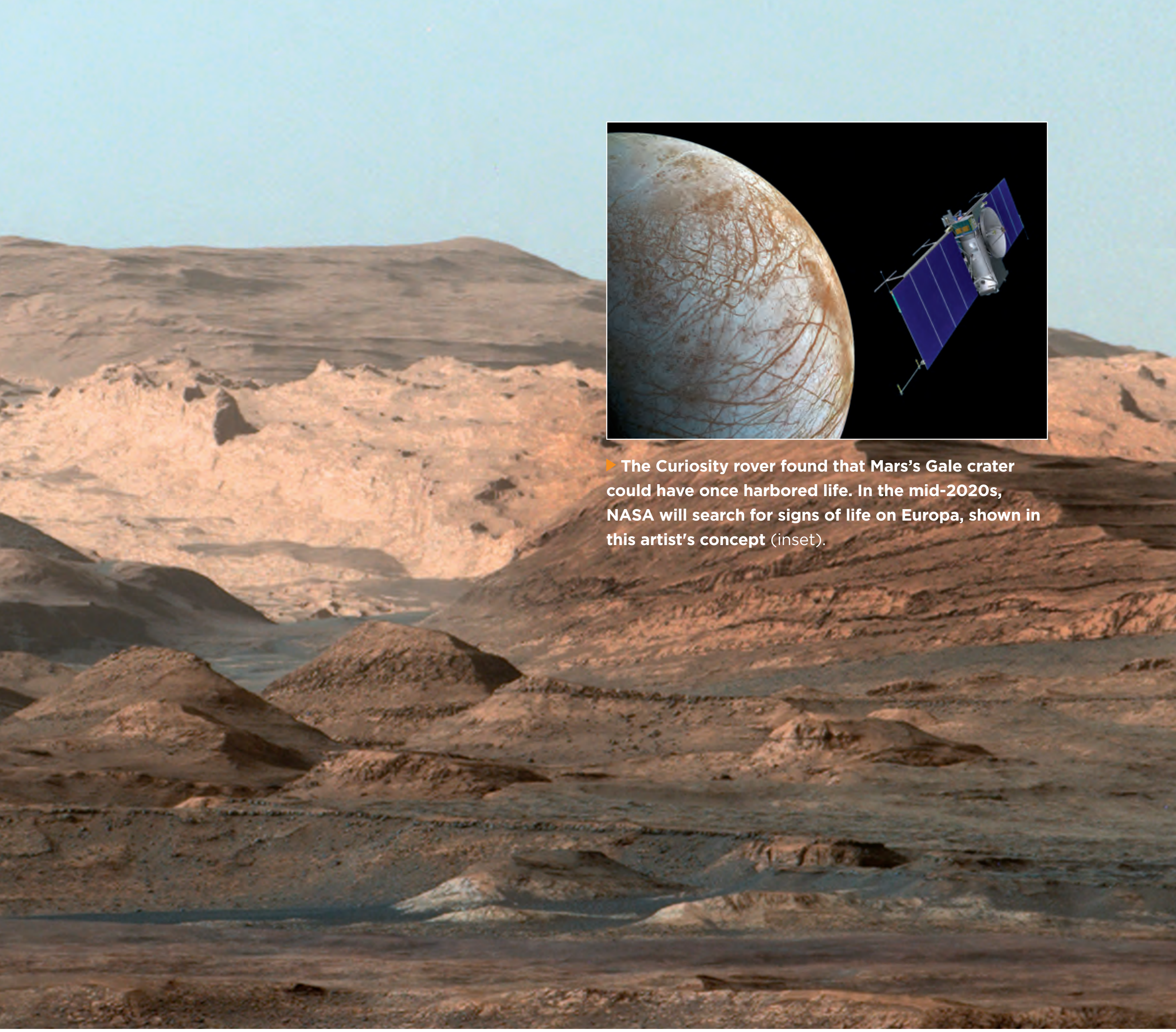
THE SEARCH FOR LIFE

FOLLOW THE WATER

Our search for life begins as a search for water—life's essential (we think!) ingredient. Many chemical compounds dissolve in water, allowing it to carry nutrients to a cell, and water's unique molecular structure also enables it to transport material such as waste products out of a cell. But the chemical reactions that lead life to develop and gain complexity require access to liquid water for millions of years. To find life, we follow the water. So first we look in what is called the habitable zone, the region around a star in which liquid water could be stable on the surface of a planet.

A TIME AND PLACE

In our solar system, the habitable zone is not just a place but also a period of time. Very early on, when the sun was cooler, Venus had a liquid water ocean, but we do not know how long it lasted or if life evolved before the planet became the hot, dry world it is today. On Mars, we know liquid water persisted on the surface for hundreds of millions of years



The Curiosity rover found that Mars's Gale crater could have once harbored life. In the mid-2020s, NASA will search for signs of life on Europa, shown in this artist's concept (inset).

amid conditions conducive to the evolution of life. Luckily for us, Earth has remained habitable, with our stable liquid oceans, for billions of years.

But the concept of the habitable zone does not apply to outer solar system satellites like Jupiter's Europa and Saturn's Enceladus, where tidal heat has created liquid water oceans beneath icy crusts, keeping them stable for hundreds of millions, or even billions, of years. At the base of these oceans is likely volcanic activity, providing the heat and chemistry that could lead to life. Whether worlds are in the habitable zone or not, we have plenty of candidate worlds for life in our solar system that can help us understand the limits of life around other stars.

TINY EUROPA HAS MORE WATER THAN ALL OF EARTH'S OCEANS COMBINED.

INTRIGUING INDICATIONS

LIFE ON MARS?

Crackling voices on the radio in 1938 warned of an invasion by Martians—but luckily *The War of the Worlds* was only science fiction. Mars has long been regarded as the prime candidate for life beyond Earth because its dry riverbeds and giant volcanoes indicate environments conducive to life. NASA's Curiosity rover has identified surface minerals that indicate persistent surface water about four billion years ago, in a not-too-acidic environment perfect for life. The evolution that we think happened early on Earth would actually be more likely in a desert world with occasional water, such as Mars.

But the conditions for life on Mars lasted only about a billion years. As the planet cooled, it lost its magnetic field and its unprotected atmosphere was thinned by the solar wind, leading to a cold, dry planet. Most of Mars's water was lost to space or migrated below the surface. Any primitive life-forms either went extinct or retreated underground. So we are left to search for subsurface life or fossil microbes.

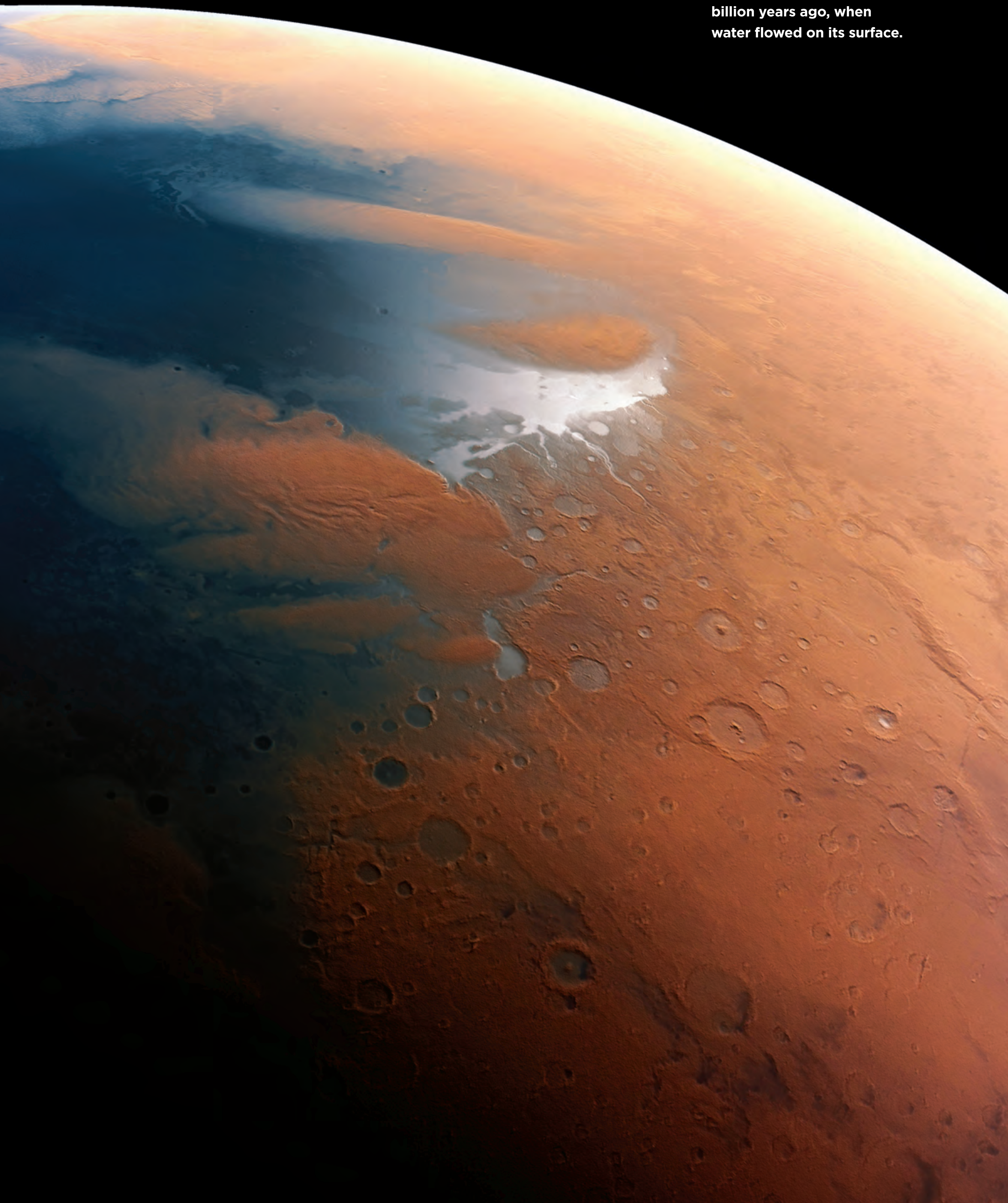
WE ARE THE MARTIANS: NASA HAS LANDED ON THE SURFACE OF MARS SEVEN TIMES.

> **»Explore More**
>
> **TECHNOLOGY FOR LIFE DETECTION**
>
> NASA and submarines might seem like an unlikely pairing, but how else can we explore the oceans of Europa and the seas of Titan? On Europa, this "cryobot" would have to melt through ice up to hundreds of feet deep to explore the ocean below. Chemical sensors could search for life, while cameras could image the unknown depths. On Titan, methane seas are hundreds of feet deep, and a useful exploration vehicle might be a submarine that could resurface to relay its findings—though Titan's minus 294°F (-181°C) temperatures would make operating any machine a challenge.

SEEKING THE SOURCE

Curiosity's instruments have measured fragments of organic molecules on the surface. But are they remnants of past life or just pieces of molecules brought by asteroids or comets? Organic molecules to a depth of at least six feet (~2 m) on Mars are broken up over time by radiation from both the sun and galactic cosmic rays. Future Mars missions will drill down past this level to search for intact evidence of past life.

Who could be better suited for the task of going to multiple locations and searching through lots of rocks than future Mars astronauts? NASA plans to send humans to Mars in the 2030s, not just to identify existing or past life but also to study what Mars biology teaches us about life here on Earth and the likelihood of life in the universe.



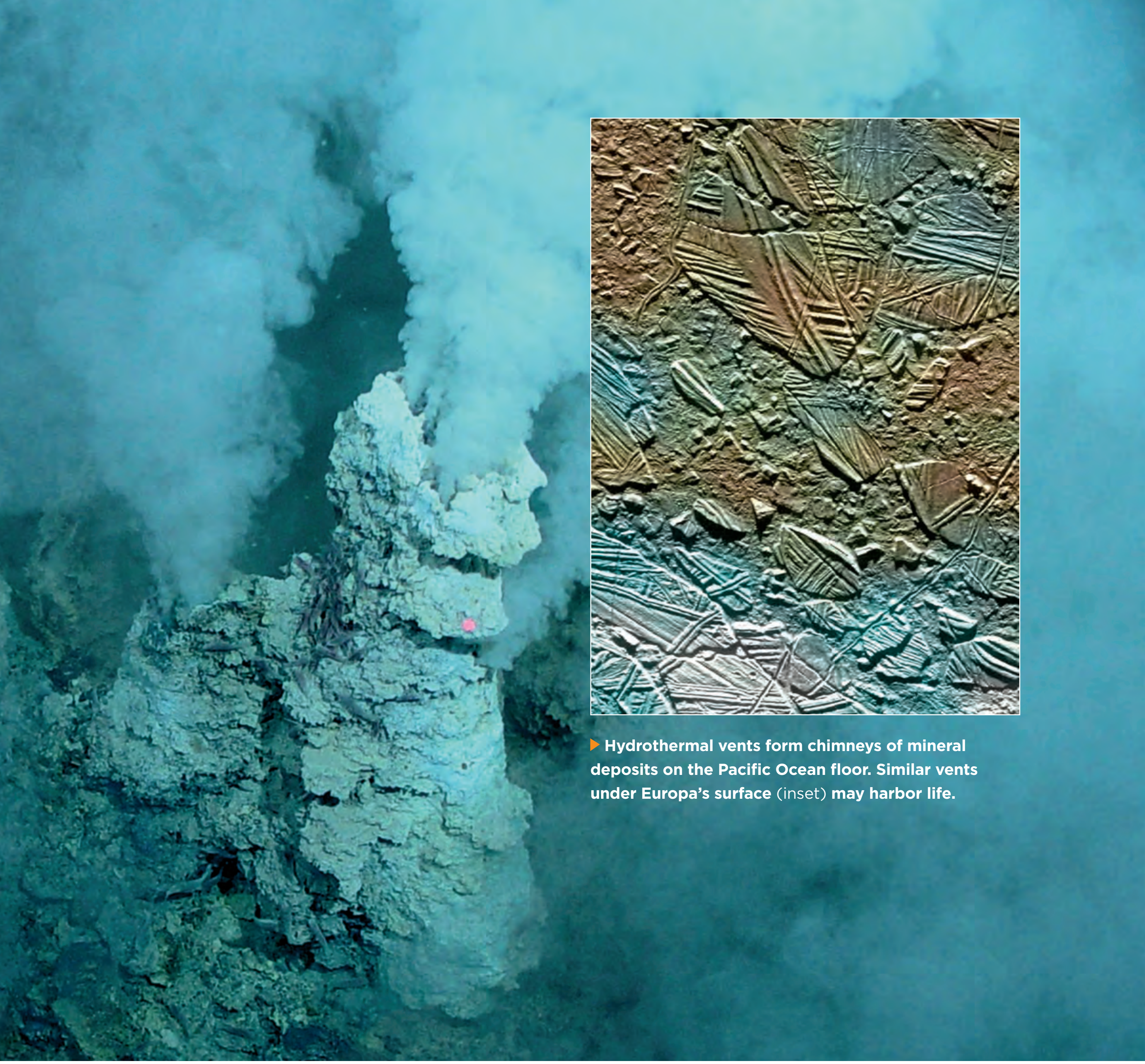
This artist's concept shows how Mars might have looked about 3.8 billion years ago, when water flowed on its surface.

JUPITER'S MOON

EUROPA'S WATERY DEPTHS

The Hubble Space Telescope has not only revealed how stars and galaxies form but also peered at Jupiter's moon Europa and detected erupting plumes of water. After the discovery of watery eruptions on Saturn's moon Enceladus, similar plumes from large cracks on Europa might have been expected. Sure enough, they were there, although they erupt less frequently than Enceladus's geysers.

What drives them? The tidal pull of Jupiter on Europa heats up its rocky core, creating a water ocean beneath an ice crust. The base of the ocean is in contact with the rocky core, where volcanic vents may have provided a warm, chemical-rich environment in which life could evolve. We can imagine parallels to volcanic vents on Earth's ocean floor, where such mineral-rich smokers are home to abundant life. The long stability of Europa's oceans



Hydrothermal vents form chimneys of mineral deposits on the Pacific Ocean floor. Similar vents under Europa's surface (inset) **may harbor life.**

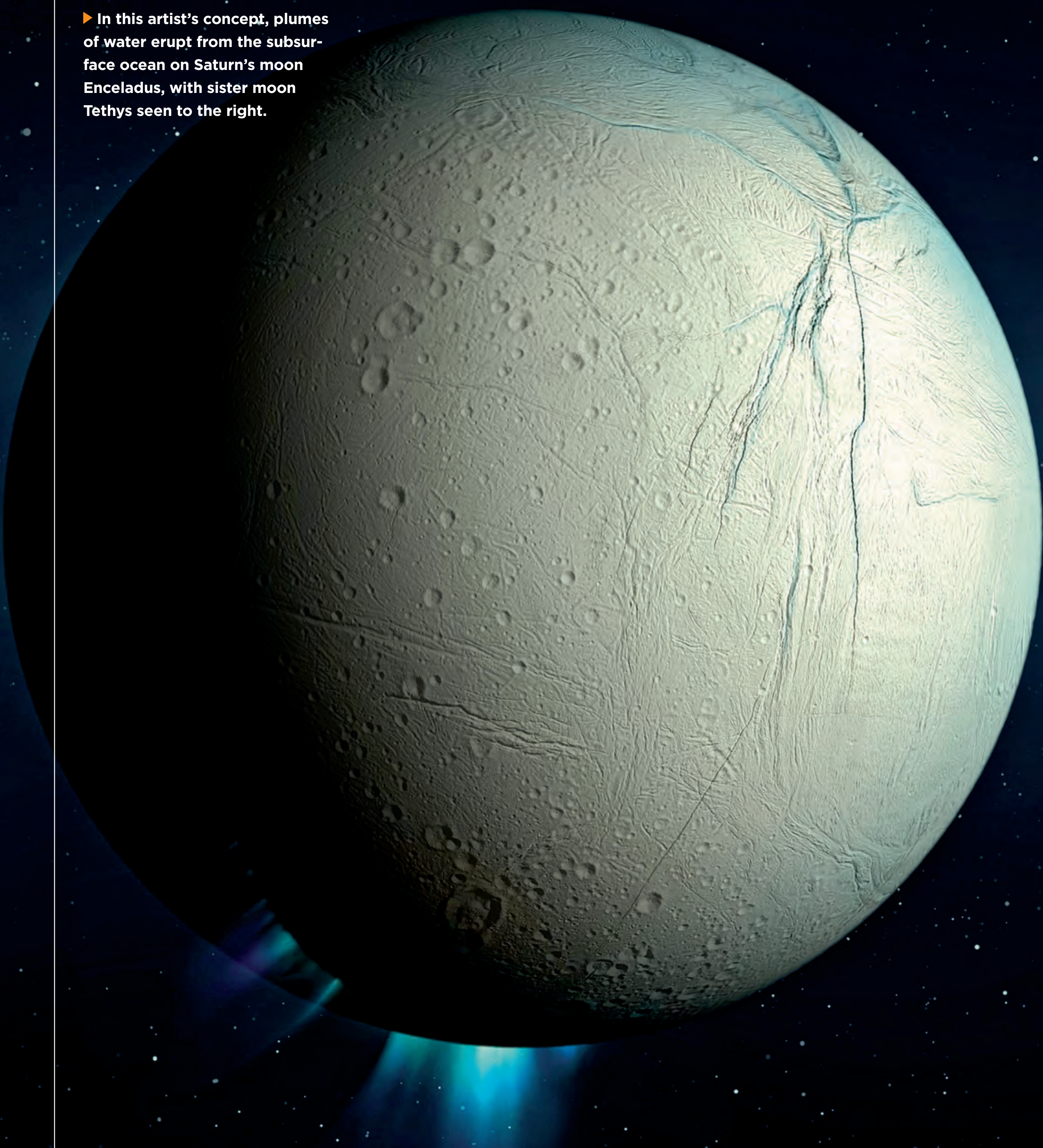
might have allowed life to become more complex than single-celled organisms.

OCEANS AND MICROBES

Europa is subjected to Jupiter's intense radiation, so any organism that made it onto the surface would soon be destroyed. But if we could land close to one of the erupting plumes, fresh ice deposits from the oceans might allow us to identify microbes that evolved under Europa's crust. Life in the Europan ocean is of particular interest to astrobiologists because it is isolated from any potential contamination from life on Earth. The theory of panspermia suggests that life could have originated on Earth or Mars and then transferred from one planet to another by rocks ejected after a giant impact. But any life that formed deep in Europa's ocean would be unrelated to us, a sign of the variety of life we might expect in other solar systems.

LUNAR LIFE

TITAN AND ENCELADUS



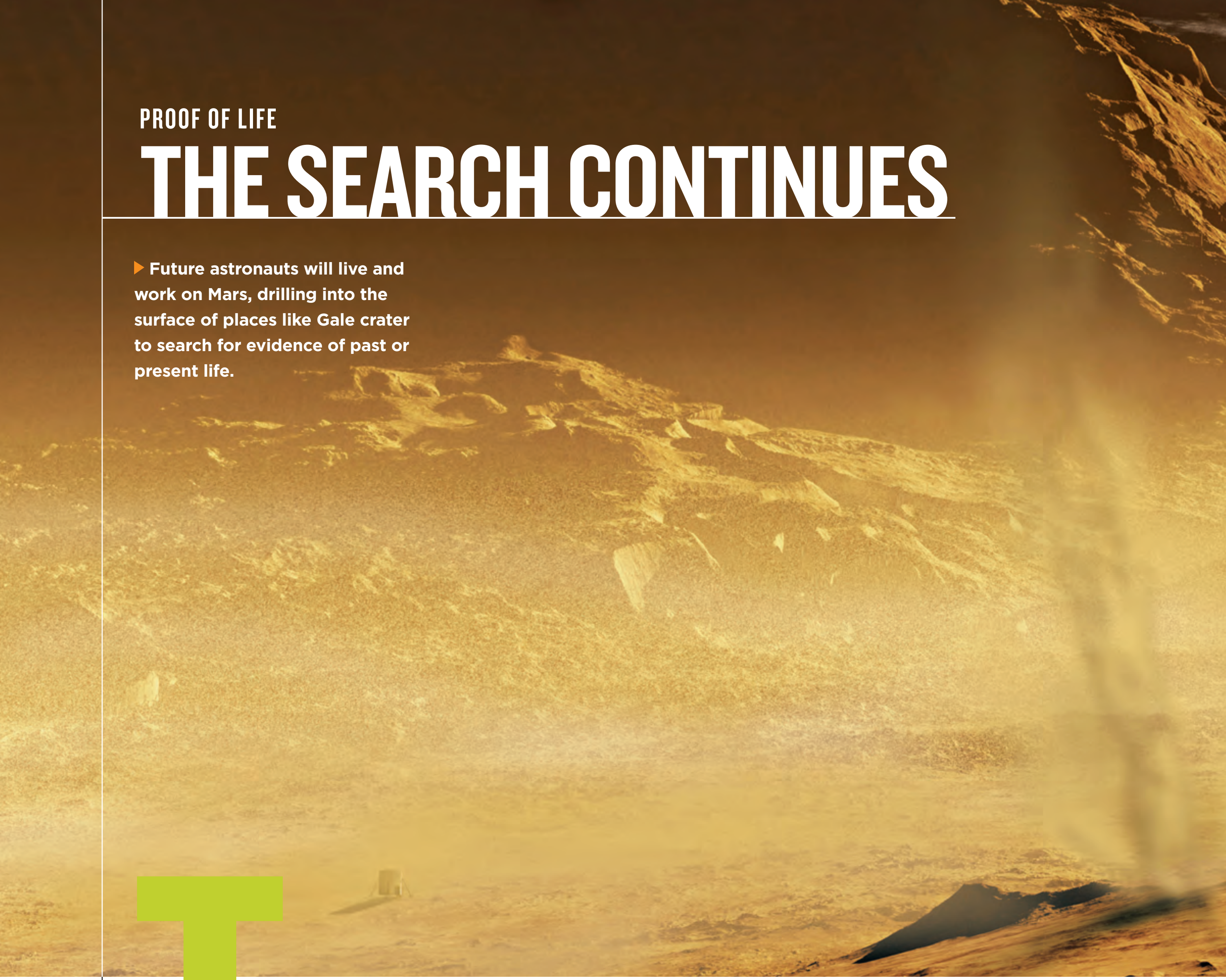
In this artist's concept, plumes of water erupt from the subsurface ocean on Saturn's moon Enceladus, with sister moon Tethys seen to the right.

At the end of the Cassini mission to Saturn in 2017, the spacecraft will swan-dive into the atmosphere of Saturn to keep it from possibly contaminating the tiny moon Enceladus. Cassini's dramatic discovery of erupting plumes of water from Enceladus made the moon a prime candidate for extraterrestrial life. The spacecraft flew right through the plumes to measure their composition, skimming less than 30 miles (48 km) above the surface of Enceladus. Cassini detected water, complex organic molecules, salts, and silica, all pointing toward an ocean in contact with rocky eruptions, organic nutrients, and the potential for life. But Cassini's instruments were not designed to search for life and could not identify what the organic molecules were—a prime task for a future mission.

Titan, Saturn's largest moon, is quite a different story, one that might help us understand the limits of life. Titan is the only moon in the solar system with a substantial atmosphere, composed mostly of nitrogen like our own. As we saw in Chapter Five, Titan has lakes and seas of methane and ethane, a rich organic soup that also contains exotic organic particles called tholins, which form in the atmosphere and rain down into the lakes and seas. So how important is water to life? Some research suggests that liquids may be the most important factor, with cell membranes able to use organic liquids as well as water to thrive. But Titan's extremely cold temperatures—minus 294°F (-181°C)—would result in very slow chemical reactions, making life more unlikely. Still, as we search for life beyond Earth, relying on our own planet as the lone reference point for life's origins could give us too narrow a perspective.

PROOF OF LIFE

THE SEARCH CONTINUES



Future astronauts will live and work on Mars, drilling into the surface of places like Gale crater to search for evidence of past or present life.

The search for life in our solar system takes many forms, from telescopes that search for plumes on Europa to orbiters and landers at Mars and the outer planets of our solar system. To date, the search for extraterrestrial life focuses on indirect rather than direct evidence. Spacecraft search for evidence of past or present liquid water by studying surface landforms, rock chemistry, and atmospheric chemistry. Gravity data and rotational information are used to detect subsurface oceans. On Mars, rovers are becoming equipped with increasingly sophisticated instruments that search for evidence of fossil life or biosignatures. But astrobiologists continue to struggle with the question of whether or not we can easily identify extraterrestrial life if it looks or behaves very differently from life on Earth.

FAMILIAR AND EXOTIC

We are on the verge of finding out if we are alone in our solar system. The most likely type of life we find may resemble the most common we find on Earth: single-celled organisms. On Mars, after the planet became cold and dry, life could have migrated underground or died out, its traces awaiting discovery by visiting astronauts. Farther out, landers and orbiters will probe the ocean worlds of

Europa, Enceladus, and Titan to search for life in these exotic environments.

On Earth, species "normally" go extinct at a rate of one to five per year. However, some scientists have suggested that we are in the midst of a mass extinction, losing many more species per year, although the exact rate is in dispute. It is clear that loss of habitat and climate change are the biggest threats. Previous mass extinctions were caused by giant impacts or massive volcanic eruptions; this one is primarily caused by humans.

»Explore More PROXIMA B

A mere 4.2 light-years from the sun is the red dwarf star Proxima Centauri, companion to the binary star Alpha Centauri. Astronomers in 2016 discovered Proxima b, a rocky, Earth-size planet orbiting in the habitable zone around Proxima Centauri. Proxima b's discovery energized the Breakthrough Starshot project, which plans to send a tiny, laser-propelled probe there. Current rockets would take 165,000 years to get to Proxima b; Starshot hopes to reduce the flight time to 20 years.

Planets are born within the Pillars of Creation, columns of gas and dust in the Eagle Nebula, 6,500 light-years from Earth.

• CHAPTER NINE •

NEW WORLDS

Astronomers had long suspected that there must be planets around other stars in our galaxy, but telescopes were not capable of detecting worlds light-years away. In 1995 astronomers announced the discovery of a planet circling the star 51 Pegasi, 50 light-years from Earth (1 light-year = 5.9 trillion miles, or 9.5 trillion km). 51 Pegasi b, 150 times the mass of Earth, orbits just 5 million miles (8 million km) from its parent star, just one-sixth Mercury's distance from our sun. This "hot Jupiter" is cloaked by an atmosphere heated to 1800°F (982°C).

But this uninhabitable world is nevertheless a planet, and its discovery proved that other worlds were out there waiting to be found. Other extrasolar planet discoveries followed swiftly. Astronomers have identified more than 3,400 "exoplanets." Our Milky Way harbors an estimated 100 billion planets or more, and at least 1,500 should exist within 50 light-years of Earth. The search is on for Earthlike worlds that may harbor life.

WORLDS BEYOND OUR SIGHT

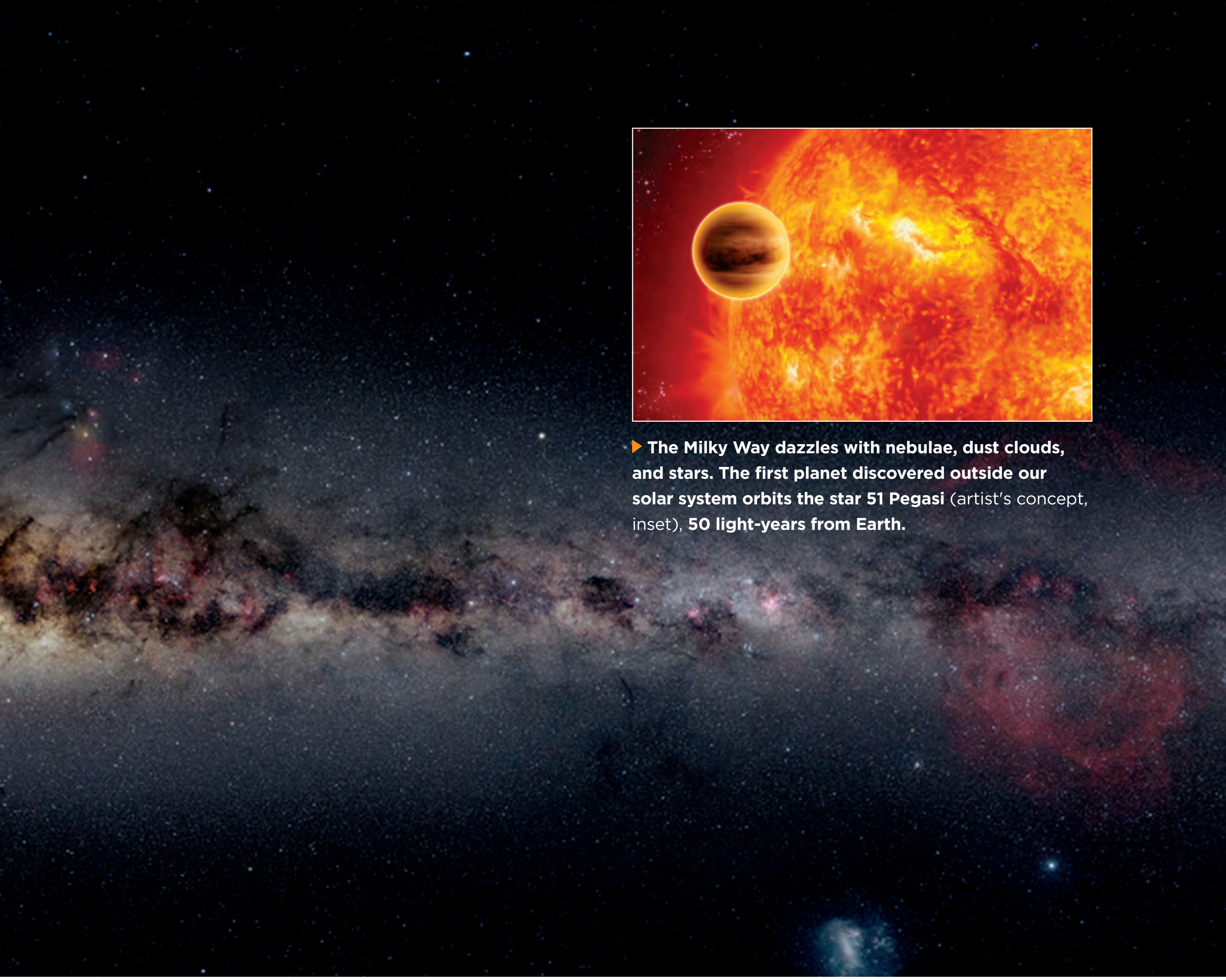
EXPANDING THE NEIGHBORHOOD

Detecting the reflected light of an exoplanet is a seemingly impossible task for Earth-based telescopes. Across many light-years of empty space, our telescopes could not distinguish the tiny apparent separation between an orbiting planet and its parent star, nor block out the star's billion-times-brighter glare. Seeing an extrasolar planet is like trying to discern the glow of a firefly in the beam of a high-intensity searchlight.

GRAVITY AND STARLIGHT

The first detection of an exoplanet, 51 Pegasi b, was made indirectly by measuring the tiny gravitational tug it exerts on its parent star. (Jupiter's gravity, for example, pulls the sun back and forth every six years by about 461,000 miles.) A spectrometer can detect this wobble using the Doppler effect. The star's motion toward or away from us causes a tiny shift in the starlight's wavelength: toward us, a blue shift; away from us, a shift to redder wavelengths. By measuring the star's oscillation relative to us, we can deduce the mass of the unseen planet, how long it takes to orbit the parent star, and its corresponding distance. Astronomers call this technique the radial velocity method.

It works best for massive exoplanets that exert a significant tug on their star. To find



The Milky Way dazzles with nebulae, dust clouds, and stars. The first planet discovered outside our solar system orbits the star 51 Pegasi (artist's concept, inset), 50 light-years from Earth.

smaller planets, astronomers look for the tiny "wink" seen as an exoplanet passes in front of its parent star, dimming its light. This method has been used very successfully by the Kepler space observatory; its photometer can spot the dimming one might see if a flea were to crawl across a car's headlight several miles away. Kepler has monitored hundreds of thousands of stars for these mini-eclipses—the repeat eclipse interval tells us a planet's orbital period.

»Explore More SO CLOSE, SO FAR

At night, co-author Tom Jones and his shuttle crewmates would marvel at the clouds of stars visible from Earth's orbit. Tom and crew were only 220 miles (354 km) up but wanted to know what else was out there among the thousands of glowing stars in the black-velvet sky.

From Tom's flight diary: *"Sweeping across the Indian Ocean … I saw more stars than I've ever seen from the ground. The Southern Cross … The spangled cloth of the Milky Way stretching toward the Magellanic Clouds … An occasional meteor below. Part of a marvelous night scene from the orbiter* Columbia."

KEPLER SPACE OBSERVATORY

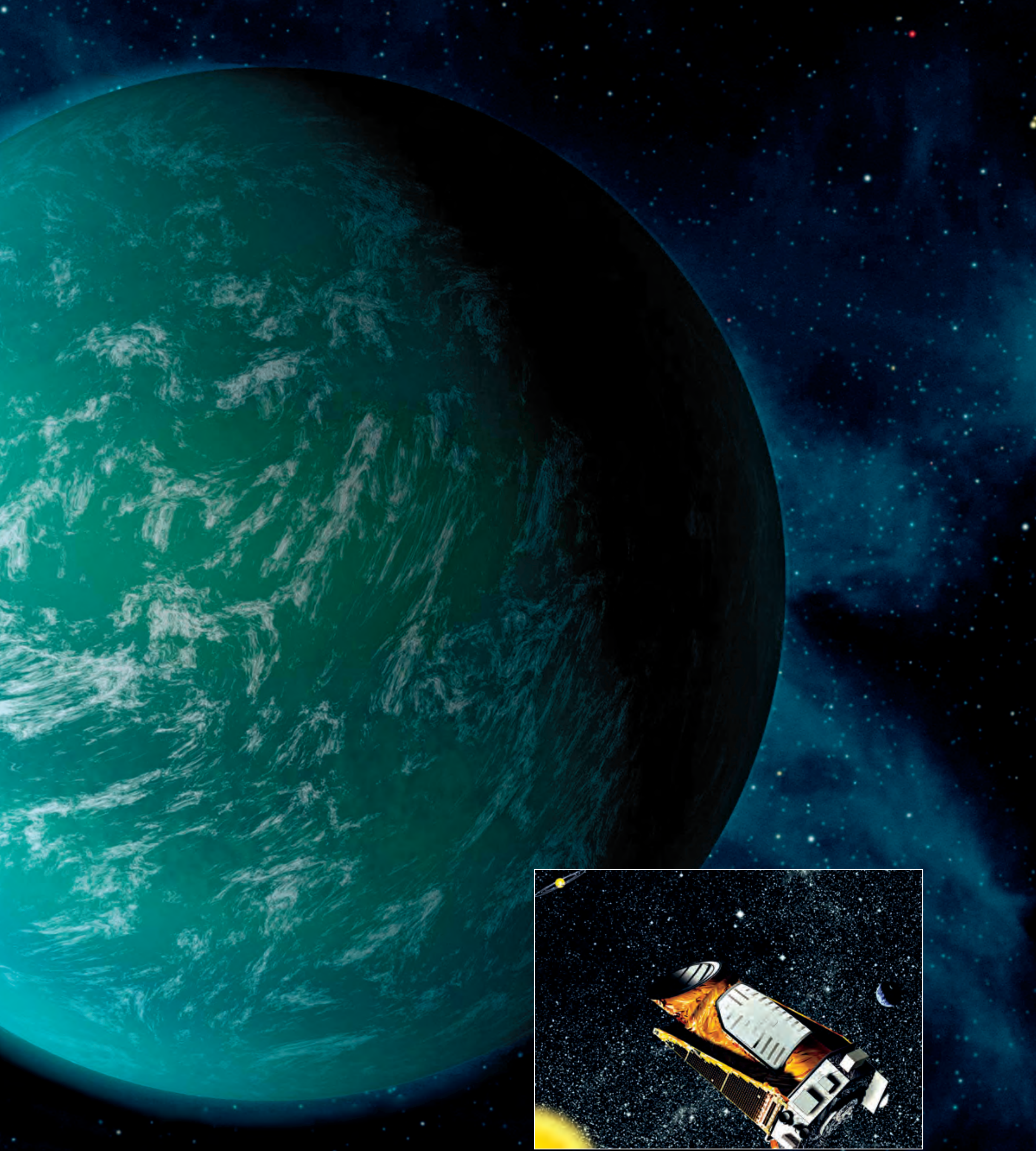
SEEING THE INVISIBLE

The radial velocity method has discovered about 18 percent of known exoplanets, including the first one located, 51 Pegasi b. The Kepler telescope, launched in 2009, uses the transit photometry technique to detect the decrease in a star's brightness caused when an exoplanet passes in front of it. By observing the repeated eclipses of hundreds of thousands of stars, Kepler has discovered thousands of extrasolar planets. More than 75 percent of exoplanets have been found by using this transit method.

The Kepler observatory is in its final two years of operation, searching for exoplanets in the plane of Earth's orbit around the sun. As of February 2017, Kepler had detected 4,696 candidate exoplanets, of which 2,331 have been confirmed.

Astronomers have now managed to discover a few exoplanets by imaging them directly, using telescopes that eliminate the brilliant glare from the parent star so the dim planet can be seen. One approach is to precisely mask the star's incoming light while allowing the planet's weak, reflected glow to pass into the telescope. In the interferometry method, light from the parent star is collected in two telescopes, one of which shifts the phase of the starlight just enough to interfere with, or cut out, the light from the parent star.

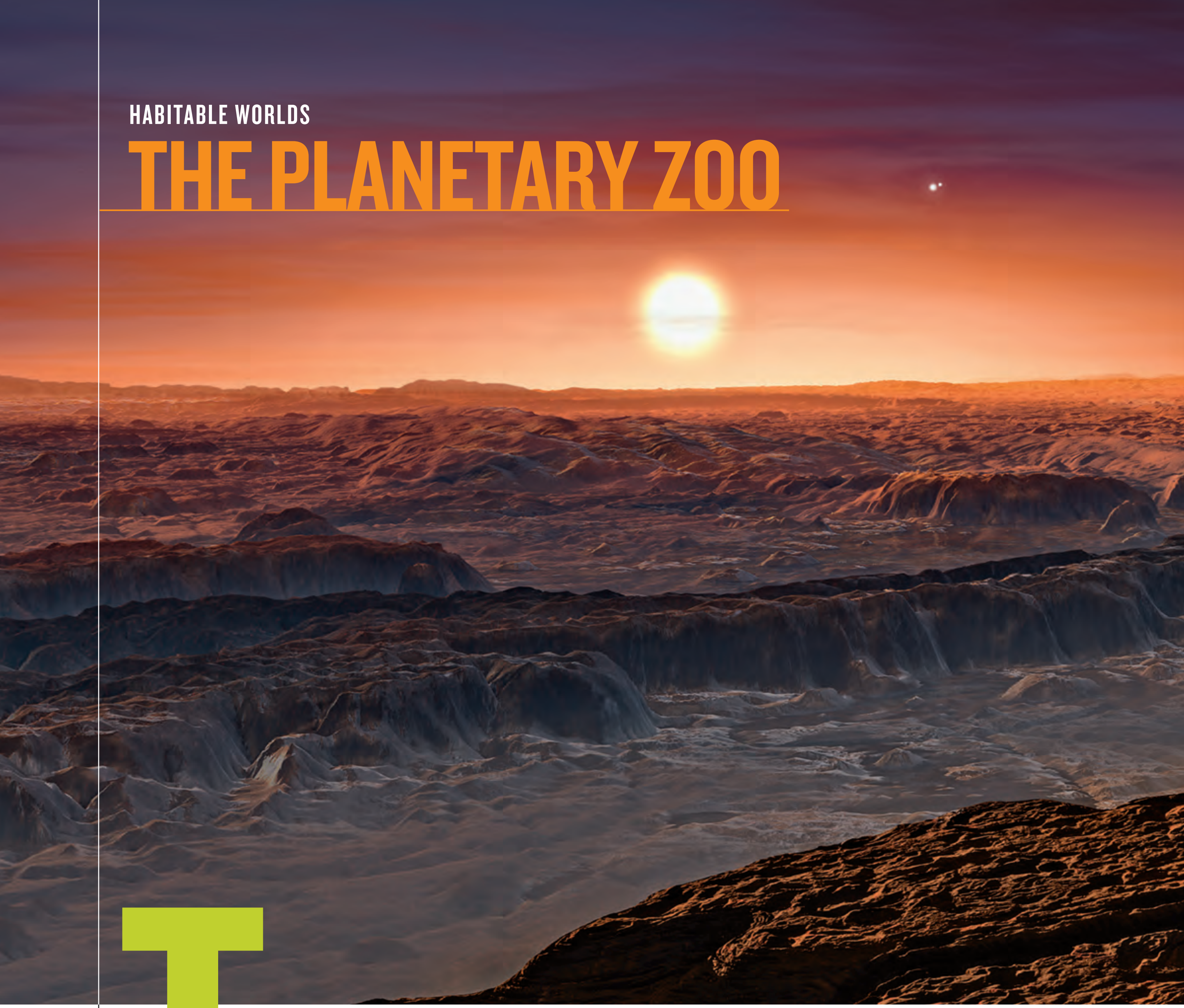
The microlensing technique uses the gravity of a random star passing between a planet and Earth to magnify, in a sense, the exoplanet's light. The nearer star's gravity bends and focuses the more distant star's light; a planet is seen as a tiny irregularity in that pattern of starlight. Because an alignment of an intervening star occurs so rarely, microlensing has yielded only a few planet discoveries.



An artist's rendering of Kepler-22b, a planet 2.4 times larger than Earth and 600 light-years away. It is one of thousands of exoplanets discovered by NASA's Kepler space observatory (inset)**.**

HABITABLE WORLDS

THE PLANETARY ZOO



The planets of our own solar system exhibit plenty of individuality, but those found elsewhere in the Milky Way are truly exotic. The exoplanets discovered so far fall into two main categories: terrestrial planets, similar in size and composition to Earth, and gas giants—large, low-density worlds with thick, gaseous atmospheres and no solid surfaces, similar to Jupiter, Saturn, or Neptune.

The majority of the gas giants are "hot Jupiters," which orbit so close to their star that they complete a revolution around it in just a few days, seared by intense heat and light.

Others are long-period gas giants, similar in size and stellar distance to Jupiter or Uranus. Because they take a dozen years or more to orbit (and create a noticeable wobble), they were hard to find at first. Orbiting far from their parent stars, these "ice giants" are easier to detect directly, because it's easier for instruments to block the glare of their more distant parent.

OTHER EARTHS

We are most curious, of course, about finding much smaller worlds resembling our own

▶ An artist imagines the view from Proxima Centauri b, an exoplanet orbiting within the habitable zone of its red dwarf parent star, the closest to our sun.

Earth. These terrestrial exoplanets, anywhere from 0.1 to 10 times the mass of our Earth, are tough to detect: too small to make their parent star wobble much, and at the limit of the dimming that we can detect when they cross in front of their parent star.

About 30 percent of all confirmed exoplanet discoveries are either Super Earths—roughly 5 to 10 times as massive as our planet—or smaller, rocky worlds 0.1 to 5 times the mass of Earth. The Kepler space observatory has discovered a large number of rocky, terrestrial planets. Most interesting are those closest in size to Earth and orbiting within a star's habitable zone, where the temperature is right for liquid water to exist on the surface. That's where life might be.

THE MILKY WAY HARBORS 40 BILLION EARTH-SIZE PLANETS CAPABLE OF SUPPORTING LIFE.

BILLIONS OF POSSIBILITIES

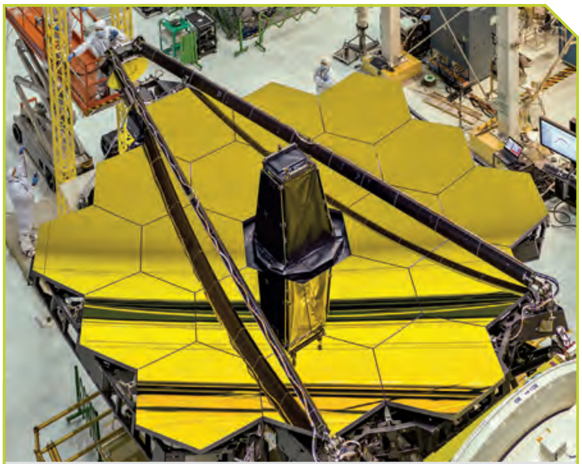
FINDING OTHER EARTHS

In our Milky Way, planets are the rule rather than the exception: A Kepler study of cool, M-class dwarf stars, which make up 75 percent of our galaxy's stars, showed each is likely to harbor one or more planets. That means at least 100 billion planets in the Milky Way. Of these, about 10 billion should be potentially habitable, Earth-size worlds. Adding in K- and G-class stars, closer in temperature to our sun, brings the estimate of Earth-size planets in the habitable zones around their stars—where liquid water can exist on the surface—into the tens of billions.

Astronomers have so far detected about a half dozen potential Earths around other stars, each slightly larger than our planet and in the habitable zone around its parent star. In 2016 a team used the radial velocity method to discover Proxima Centauri b, an Earth-size planet in the habitable zone around the nearest star, 4.2 light-years from our sun.

The habitable zone for cooler, red dwarf stars like Proxima Centauri is 25 times more compact—closer to the star—than our sun's. Proxima Centauri b lies well within that sweet spot. But it's so close to its parent—closer than Mercury is to our sun—that solar flares, x-ray radiation, and temperature extremes make life's existence problematic.

Finding better candidates will be the job of NASA's planned Transiting Exoplanet Survey Satellite and the James Webb Space Telescope, which will team up to discover the nearest rocky exoplanets and determine their composition and atmospheric makeup. Gases like free oxygen or methane are strong indicators that life may be present, and their detection will further spur the search for planetary oases around other stars.



»Explore More

THE JAMES WEBB TELESCOPE

The James Webb Space Telescope (JWST) is NASA's successor to the Hubble Space Telescope. The JWST has a 21-foot-4-inch (6.5-m) mirror that will capture infrared light from across the universe. To be launched in October 2018, the JWST will orbit near an Earth-sun Lagrange point a million miles beyond our planet. A large sunshield will chill the telescope's mirror and instruments to below minus 370°F (-223°C). Among its many astronomical missions, the JWST will observe the atmospheres of Earthlike exoplanets, looking for the chemical signatures of life.

The James Webb Space Telescope's 19-segment mirror (opposite) **will measure the makeup of exoplanet atmospheres, while looking for the chemical fingerprints of life.**

CLOSING THOUGHTS

As planetary explorers, we have learned much about our solar system by examining Earth's many geologic features; in turn, observing geologic processes at work on other worlds has deepened our understanding of those forces reshaping this planet. As we expand our "planet lab" to worlds around other stars, our quest to understand their surfaces and suitability for life will start with what we've learned about Earth and its solar system neighbors. Whether exploring with our own eyes and hands or sending robot probes to extend our senses, our discoveries will always bring us back to this island Earth, our textbook for knowing other worlds.

– TOM JONES AND ELLEN STOFAN

Tom Jones is a planetary scientist, pilot, author, speaker, and veteran NASA astronaut. An expert on asteroids, he helped build the International Space Station and spent 53 days in space. **Ellen Stofan** is a planetary geologist who studies Venus, Earth, Mars, and Titan, and is the former chief scientist of NASA. She has worked on NASA and European Space Agency missions.

The authors thank our spouses and children for their support of our love of planetary science, despite the countless field geology trips, planetary science conferences, shuttle training expeditions, mission simulations, NASA-related travel, and many weeks spent off this planet. Their selflessness truly made this special issue possible. We thank our literary agent, Deborah C. Grosvenor, of Grosvenor Literary Agency, for her encouragement and ready advice. Thanks to our editors, Rose Ellen D'Angelo and Bridget Hamilton, and our graphics team of Linda Makarov, Elisa Gibson, Kate Napier, and Susan Blair at National Geographic. Any errors of fact, interpretation, or explanation are wholly the responsibility of the authors.

Exploring is a high calling; we salute those who dedicate themselves to pioneering our understanding of Earth and the planets. And we honor the courage of the explorers of Apollo 1, Soyuz 1, Soyuz 11, *Challenger,* and *Columbia.*

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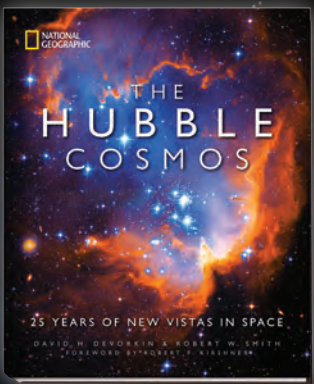

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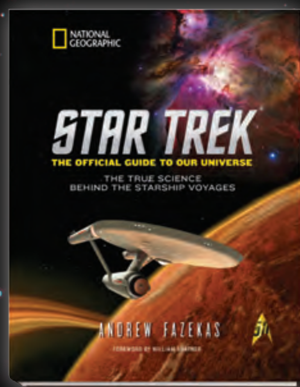

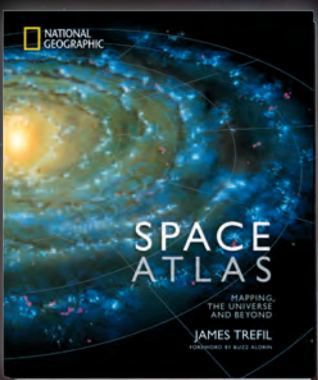

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