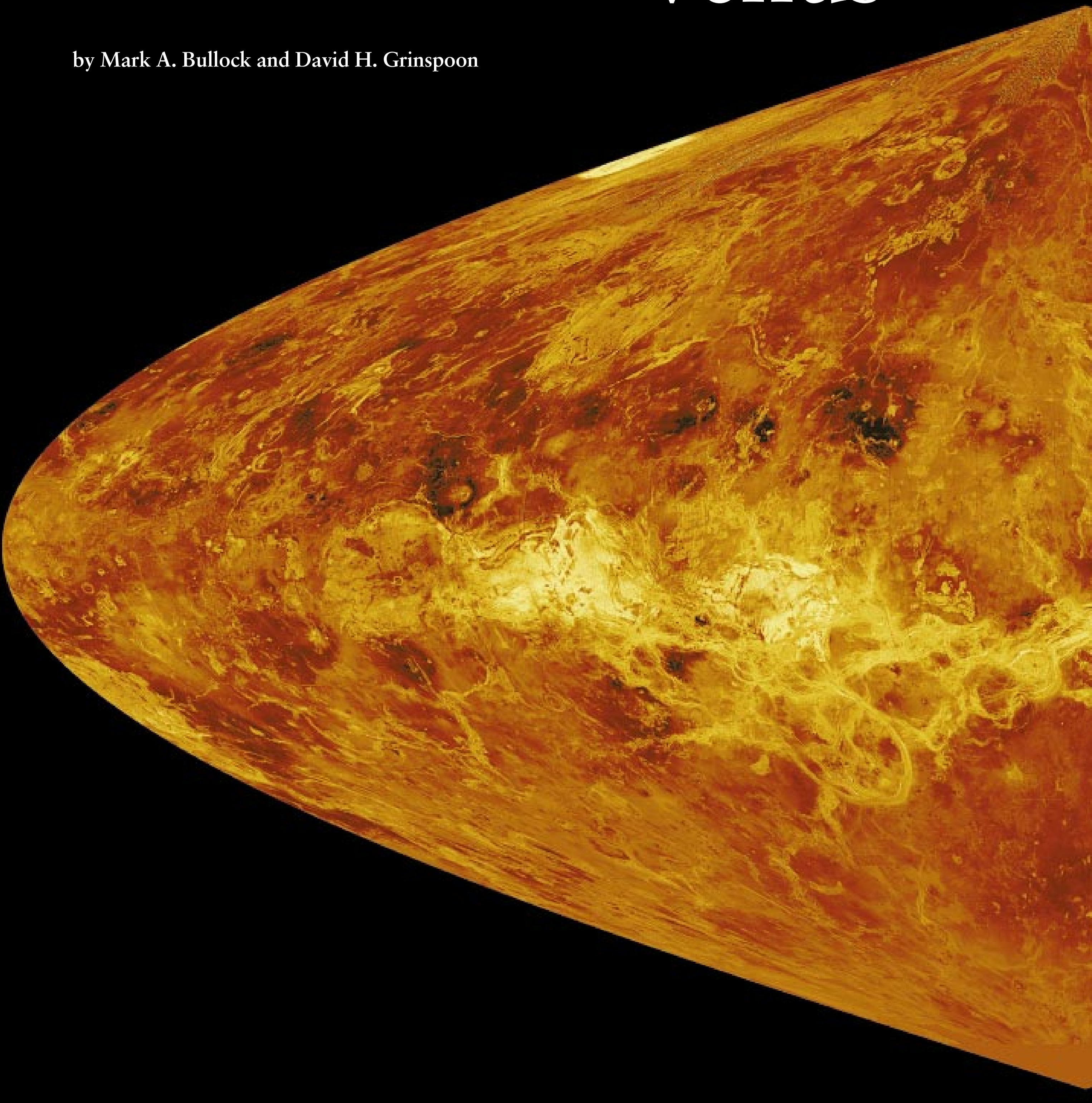
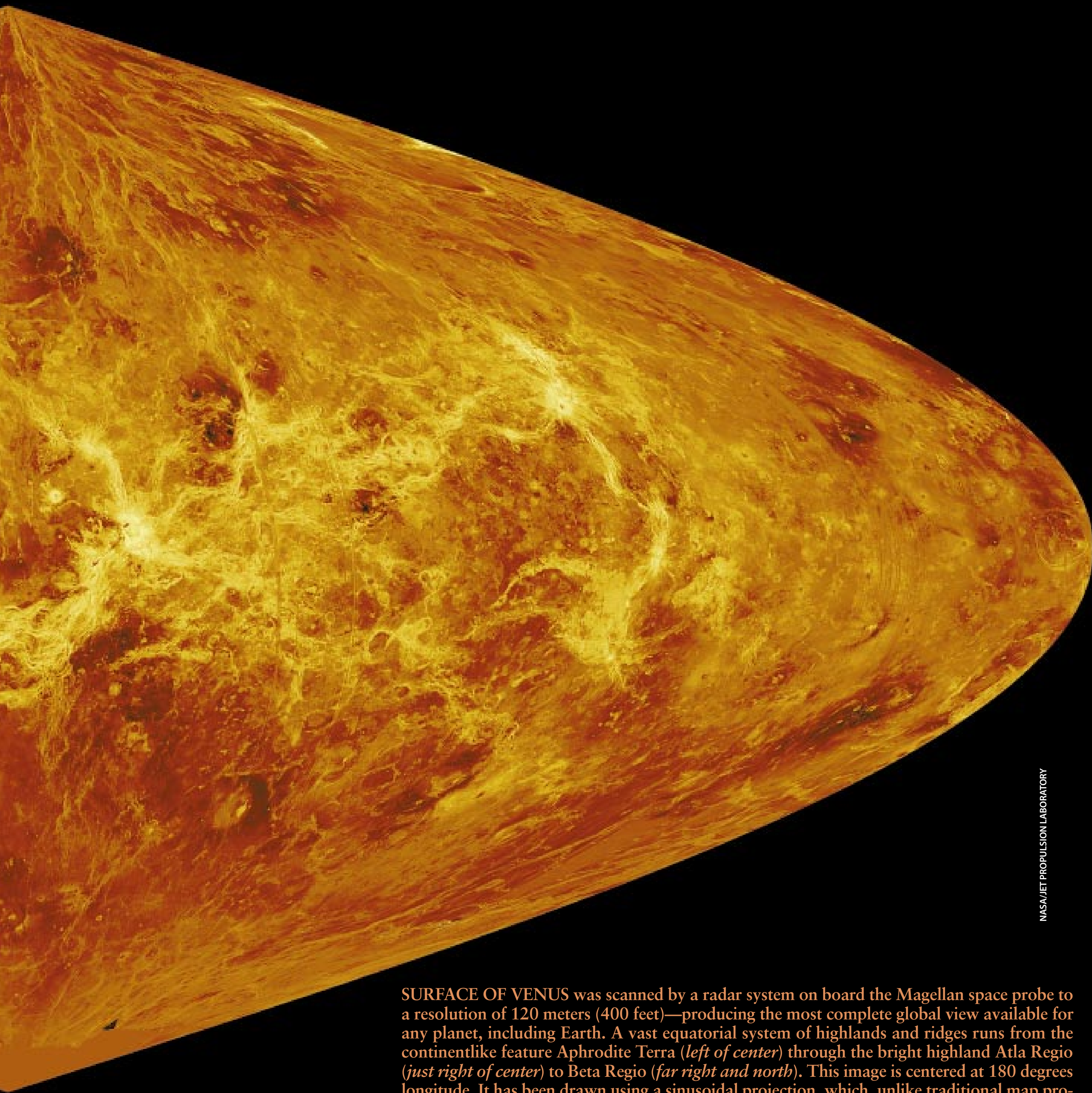
Global Climate Change on Venus

by Mark A. Bullock and David H. Grinspoon

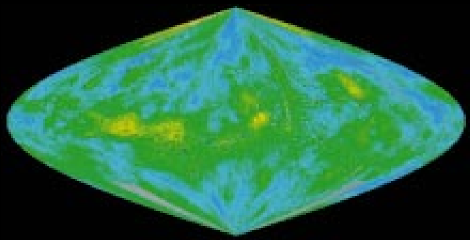


Venus's climate, like Earth's, has varied over time—the result of newly appreciated connections between geologic activity and atmospheric change



SURFACE OF VENUS was scanned by a radar system on board the Magellan space probe to a resolution of 120 meters (400 feet)—producing the most complete global view available for any planet, including Earth. A vast equatorial system of highlands and ridges runs from the continentlike feature Aphrodite Terra (*left of center*) through the bright highland Atla Regio (*just right of center*) to Beta Regio (*far right and north*). This image is centered at 180 degrees longitude. It has been drawn using a sinusoidal projection, which, unlike traditional map projections such as the Mercator, does not distort the area at different latitudes. Dark areas correspond to terrain that is smooth at the scale of the radar wavelength (13 centimeters); bright areas are rough. The meridional striations are image artifacts.

TOPOGRAPHY



The topography of Venus spans a wide range of elevations, about 13 kilometers from low (*blue*) to high (*yellow*). But three fifths of the surface lies within 500 meters of the average elevation, a planetary radius of 6,051.9 kilometers. In contrast, topography on Earth clusters around two distinct elevations, which correspond to continents and ocean floors.

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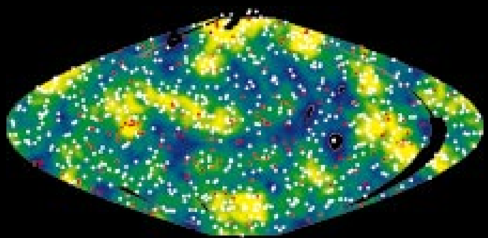
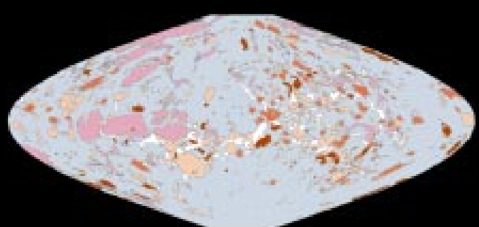
IMPACT CRATERS



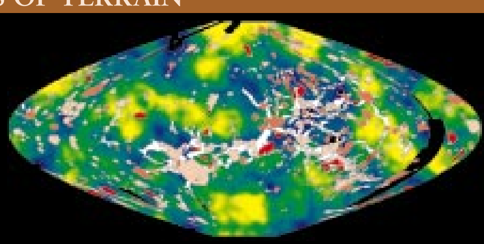
Impact craters are randomly scattered all over Venus. Most are pristine (*white dots*). Those modified by lava (*red dots*) or by faults (*triangles*) are concentrated in places such as Aphrodite Terra. Areas with a low density of craters (*blue background*) are often located in highlands. Higher crater densities (*yellow background*) are usually found in the lowland plains.

TYPES OF TERRAIN



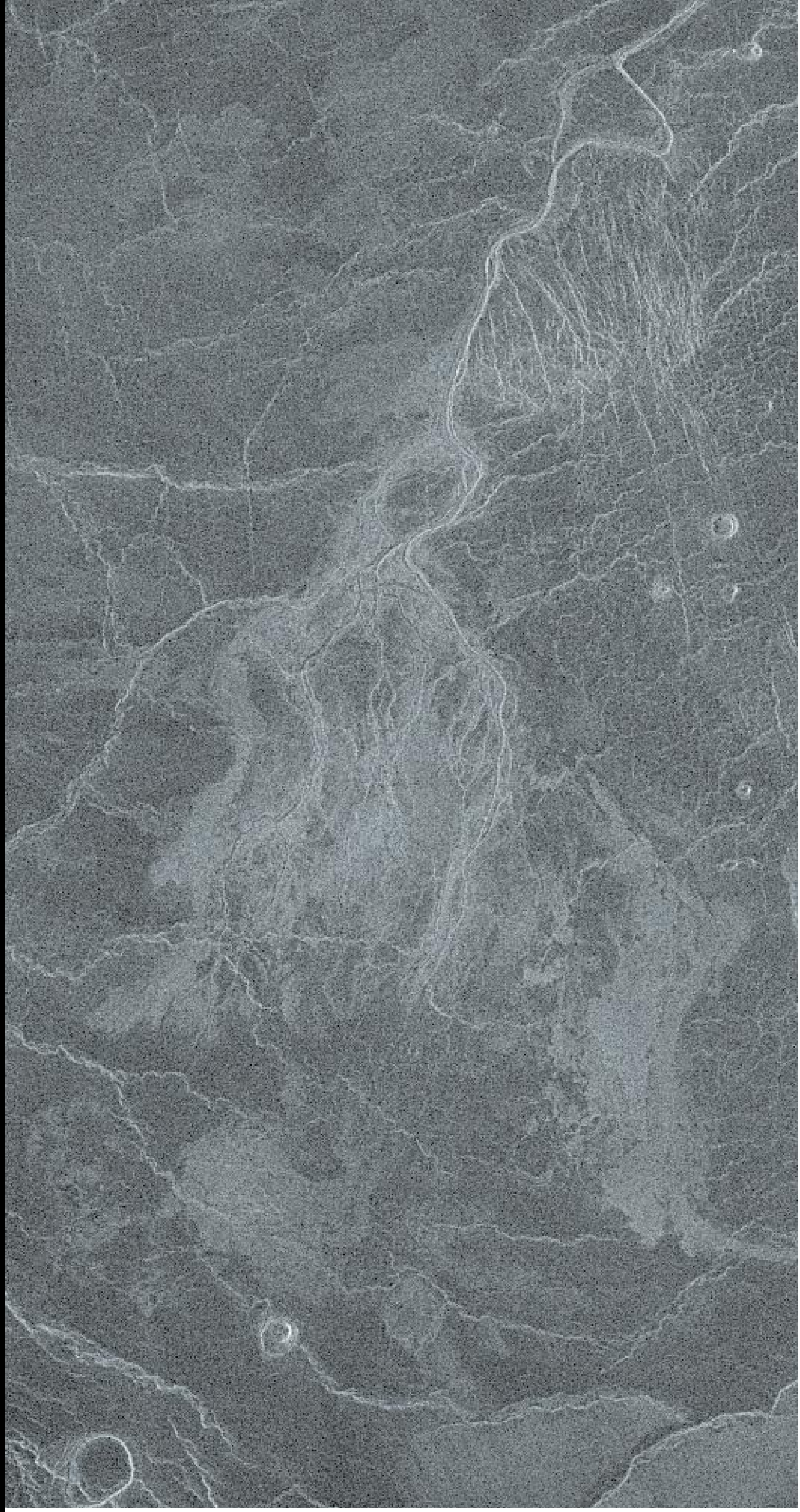
The terrain of Venus consists predominately of volcanic plains (*blue*). Within the plains are deformed areas such as tesserae (*pink*) and rift zones (*white*), as well as volcanic features such as coronae (*peach*), lava floods (*red*) and volcanoes of various sizes (*orange*). Volcanoes are not concentrated in chains as they are on Earth, indicating that plate tectonics does not operate.

AGES OF TERRAIN



This geologic map shows the different terrains and their relative ages, as inferred from the crater density. Volcanoes and coronae tend to clump along equatorial rift zones, which are younger (*blue*) than the rest of the Venusian surface. The tesserae, ridges and plains are older (*yellow*). In general, however, the surface lacks the extreme variation in age that is found on Earth and Mars.

MARIBETH PRICE *South Dakota School of Mines and Technology (bottom three images)*



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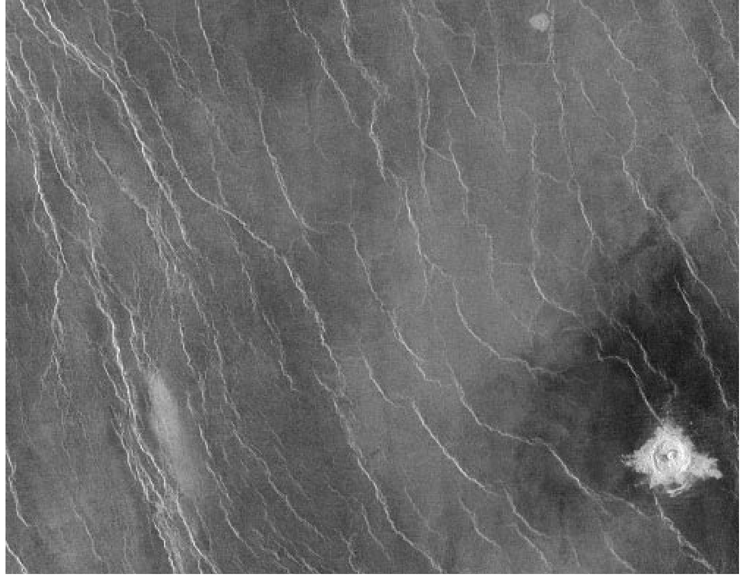
RIVER ON VENUS? This delta exists at the terminus of a narrow channel that runs for 800 kilometers through the northern volcanic plains. Water could not have carved it; Venus is too hot and dry. Instead it was probably the work of lavas rich in carbonate and sulfate salts—which implies that the average temperature used to be several tens of degrees higher than it is today. The region shown here is approximately 40 by 90 kilometers.



WRINKLE RIDGES are the most common feature on the volcanic plains of Venus. They are parallel and evenly spaced, suggesting that they formed when the plains as a whole were subjected to stress—perhaps induced by a dramatic, rapid change in surface temperature. This region, which is part of the equatorial plains known as Rusalka Planitia, is approximately 300 kilometers across.

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Emerging together from the presolar cauldron, Earth and Venus were endowed with nearly the same size and composition. Yet they have developed into radically different worlds. The surface temperature of Earth's sister planet is about 460 degrees Celsius—hot enough for rocks to glow visibly to any unfortunate carbon-based visitors. A deadly efficient greenhouse effect prevails, sustained by an atmosphere whose major constituent, carbon dioxide, is a powerful insulator. Liquid water is nonexistent. The air pressure at the surface is almost 100 times that on Earth; in many ways it is more an ocean than an atmosphere. A mélange of gaseous sulfur compounds, along with what little water vapor there is, provides chemical fodder for the globally encircling clouds of sulfuric acid.

This depiction of hell has been brought to us by an armada of 22 robotic spacecraft that have photographed, scanned, analyzed and landed on Venus over the past 37 years. Throughout most of that time, however, Venus's obscuring clouds hindered a full reconnaissance of its surface. Scientists' view of the planet remained static because they knew little of any dynamic processes, such as volcanism or tectonism, that might have occurred there. The Magellan spacecraft changed that perspective. From 1990 to 1994 it mapped the entire surface of the planet at high resolution by peering through the clouds with radar [see "The Surface of Venus," by R. Stephen Saunders; Scientific American, December 1990]. It revealed a planet that has experienced massive volcanic eruptions in the past and is almost surely active today. Coupled with this probing of Venusian geologic history, detailed computer simulations have attempted to reconstruct the past billion years of the planet's climate history. The intense volcanism, researchers are realizing, has driven large-scale climate change. Like Earth but unlike any other planet astronomers know, Venus has a complex, evolving climate.

Earth's other neighbor, Mars, has also undergone dramatic changes in climate [see "Global Climate Change on Mars," by Jeffrey S. Kargel and Robert G. Strom; Scientific American, November 1996]. Its atmosphere today, however, is a relic of its geologic past. The interior of Mars is too cool now for volcanism to be active, and the surface rests in a deep freeze. Although variations in Mars's orbital and rotational motions can induce climate change there, volcanism will never again participate. Earth and Venus, on the other hand, have climates that are driven by the dynamic interplay between geologic and atmospheric processes.

From our human vantage point next door in the solar system, it is sobering to ponder how forces similar to those on Earth have had such a dissimilar outcome on Venus. Studying that planet has broadened research on climate evolution beyond the single example of Earth and given scientists new approaches for answering pressing questions: How unique is Earth's climate? How stable is it? Humankind is engaged in a massive, uncontrolled experiment on the terrestrial climate brought on by the growing effluent from a technological society. Discerning the factors that affect the evolution of climate on other planets is crucial to understanding how natural and anthropogenic forces alter the climate on Earth.

To cite one example, long before the ozone hole became a topic of household discussion, researchers were trying to come to grips with the exotic photochemistry of Venus's upper atmosphere. They found that chlorine reduced the levels of free oxygen above the planet's clouds. The elucidation of this process for Venus eventually shed light on an analogous one for Earth, whereby chlorine from artificial sources destroys ozone in the stratosphere.

Climate and Geology

The climate of Earth is variable partly because its atmosphere is a product of the ongoing shuffling of gases among the crust, the mantle, the oceans, the polar caps and outer space. The ultimate driver of geologic processes, geothermal energy, is also an impetus for the evolution of the atmosphere. Geothermal energy is a product primarily of the decay of radioactive elements in the interior, and a central problem in studying solid planets is understanding how they lose their heat. Two mechanisms are chiefly responsible: volcanism and plate tectonics.

The interior of Earth cools mainly by means of its plate tectonic conveyor-belt system, whose steady recycling of gases has exerted a stabilizing force on Earth's climate [*see box on page 56*]. Whereas volcanoes pump gases into the atmosphere, the subduction of lithospheric plates returns them to the interior. Most volcanoes are associated with plate tectonic activity, but some of the largest volcanic edifices on Earth (such as the Hawaiian Islands) have developed as "hot spots" independent of plate boundaries. Historically, the formation of immense volcanic provinces—regions of intense eruptions possibly caused by enormous buoyant plumes of magma within the underlying mantle—may have spewed large amounts of gases and led to periods of global warming [see "Large Igneous Provinces," by Millard F. Coffin and Olav Eldholm; SCIENTIFIC AMERICAN, October 1993].

What about Venus? Before the Magellan mission, much of the planet's geologic history remained speculative, relegated to comparisons with Earth and to extrapolations based on presumed similarities in composition and geothermal heat production. Now a global picture of the history of Venus's surface is emerging. Plate tectonics is not in evidence, except possibly on a limited scale. It appears that heat was transferred, at least in the relatively recent past, by the eruption of vast plains of basaltic lava and later by the volcanoes that grew on top of them. Understanding the effects of volcanoes is the starting point for any discussion of climate.

A striking feature of Magellan's global survey is the paucity of impact craters. Although Venus's thick atmosphere can shield the planet's surface from small impactors—it stops most meteoroids smaller than a kilometer in diameter, which would otherwise gouge craters up to 15 kilometers (nine miles) across—there is a shortage of larger craters as well. Observations of the number of asteroids and comets in the inner solar system, as well as crater counts on the moon, give a rough idea of how quickly Venus should have collected impact scars: about 1.2 craters per million years. Magellan saw only, by the latest count, 963 craters spread randomly over its surface. Somehow impacts from the first 3.7 billion years of the planet's history have been eradicated.

A sparsity of craters is also evident on Earth, where old craters are eroded by wind and water. Terrestrial impact sites are found in a wide range of altered states, from the nearly pristine bowl of Meteor Crater in Arizona to the barely discernible outlines of buried Precambrian impacts in the oldest continental crust. Yet the surface of Venus is far too hot for liquid water to exist, and surface winds are mild. In the absence of erosion, the chief processes altering and ultimately erasing impact craters should be volcanic and tectonic activity. That is the paradox. Most of the Venusian craters look fresh: only 6 percent of them have lava lapping their rims, and only 12 percent have been disrupted by folding and cracking of the crust. So where did all the old ones go, if most of those that remain are unaltered? If they have been covered up by lava, why do we not see more craters that are partially covered? And how have they been removed so that their initial random placement has been preserved?

To some researchers, the random distribution of the observed craters and the small number of partially modified ones imply that a geologic event of global proportions abruptly wiped out all the old craters some 800 million years ago. In this scenario, proposed in 1992 by Gerald G. Schaber of the U.S. Geological Survey (USGS) and Robert G. Strom of the University of Arizona, impacts have peppered the newly formed surface ever since.

But the idea of paving over an entire planet is unpalatable to many geologists. It has no real analogue on Earth. Roger J. Phillips of Washington University proposed an alternative model the same year, known as equilibrium resurfacing, which hypothesized that steady geologic processes continually eradicate craters in small patches, preserving an overall global distribution that appears random. A problem with this idea is that some geologic features on Venus are immense, suggesting that geologic activity would not wipe craters out cleanly and randomly everywhere.

These two views grew into a classic scientific debate as the analysis of Magellan data became more sophisticated. The truth is probably somewhere in the middle. Elements of both models have been incorporated into the prevailing interpretation of the past billion years of Venus's geologic history: globally extensive volcanism wiped out most impact craters and created the vast volcanic plains 800 million years ago, and it has been followed by a reduced level of continued volcanic activity up to the present.

Chocolate-Covered Caramel Crust

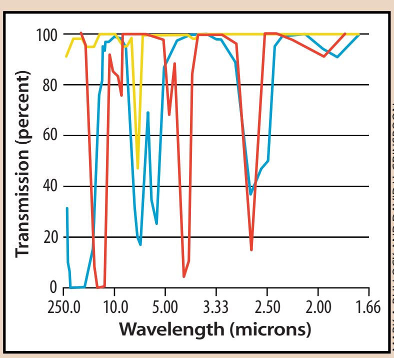
Although there is no doubt that volcanism has been a major force in shaping Venus's surface, the interpretation of some enigmatic geologic features has until recently resisted integration into a coherent picture of the planet's evolution. Some of these features hint that the planet's climate may have changed drastically.

First, several striking lineaments resemble water-carved landforms. Up to 7,000 kilometers long, they are similar to meandering rivers and floodplains on Earth. Many end in outflow channels that look like river deltas. The extreme dryness of the environment makes it highly unlikely that water carved these features. So what did? Perhaps calcium carbonate, calcium sulfate and other salts are the culprit. The surface, which is in equilibrium with a hefty carbon dioxide atmosphere laced with sulfur gases, should be replete with these substances. Indeed, the Soviet Venera landers found that surface rocks are about 7 to 10 percent calcium minerals (almost certainly carbonates) and 1 to 5 percent sulfates.

Lavas laden with these salts melt at temperatures of a few tens to hundreds of degrees higher than Venusian surface temperatures today. Jeffrey S. Kargel of the USGS and his co-workers have hypothesized that vast reservoirs of molten carbonatite (salt-rich) magma, analogous to water

GREENHOUSE EFFECT

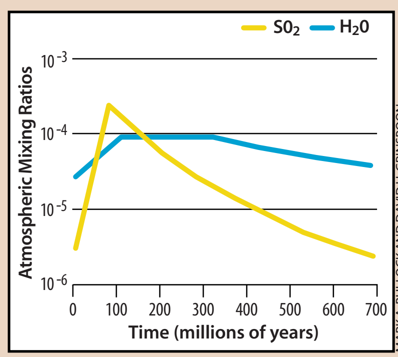
Greenhouse gases let sunlight reach the Venusian surface but block outgoing infrared light. Carbon dioxide (*red*), water (*blue*) and sulfur dioxide (*yellow*) each absorb a particular set of wavelengths. Were it not for these gases, the sunlight and infrared light would balance each other at a surface temperature of about –20 degrees Celsius (–4 degrees Fahrenheit).



MARK A. BULLOCK AND DAVID H. GRINSPOON

GAS CONCENTRATIONS

Water and sulfur dioxide are removed from the atmosphere after they are belched out by volcanoes. Sulfur dioxide (*yellow*) reacts relatively quickly with carbonates at the surface, whereas water (*blue*) is slowly broken apart by solar ultraviolet radiation.



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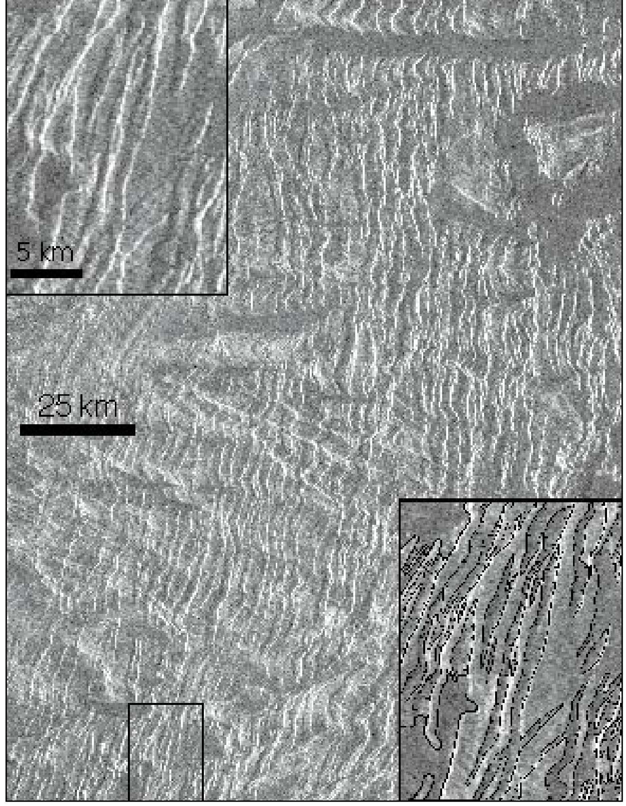
aquifers on Earth, may exist a few hundred meters to several kilometers under the surface. Moderately higher surface temperatures in the past could have spilled salt-rich fluid lavas onto the surface, where they were stable enough to carve the features we see today.

Second, the mysterious tesserae—the oldest terrain on Venus—also hint at higher temperatures in the past. These intensely crinkled landscapes are located on continentlike crustal plateaus that rise several kilometers above the lowland lava plains. Analyses by Phillips and by Vicki L. Hansen of Southern Methodist University indicate that the plateaus were formed by extension of the lithosphere (the rigid exoskeleton of the planet, consisting of the crust and upper mantle). The process was something like stretching apart a chocolate-covered caramel that is gooey on the inside with a thin, brittle shell. Today the outer, brittle part of the lithosphere is too thick to behave this way. At the time of tessera formation, it must have been thinner, which implies that the surface was significantly hotter.

Finally, cracks and folds crisscross the planet. At least some of these patterns, particularly the so-called wrinkle ridges, may be related to temporal variations in climate. We and Sean C. Solomon of the Carnegie Institution of Washington have argued that the plains preserve globally coherent episodes of deformation that may have occurred over short intervals of geologic history. That is, the entire lithosphere seems to have been stretched or compressed all at the same time. It is hard to imagine a mechanism internal to the solid planet that could do that. But what about global climate change? Solomon calculated that stresses induced in the lithosphere by fluctuations in surface temperature of about 100 degrees C (210 degrees Fahrenheit) would have been as high as 1,000 bars—comparable to those that form mountain belts on Earth and sufficient to deform Venus's surface in the observed way.

Around the time that the debate over Venus's recent geologic history was raging, we were working on a detailed model of its atmosphere. Theory reveals that the alien and hostile conditions are maintained by the complementary properties of Venus's atmospheric constituents. Water vapor, even in trace amounts, absorbs infrared radiation at wavelengths that carbon dioxide does not. Sulfur dioxide and other sulfur gases block still other infrared wavelengths [*see illustration below left*]. Together these greenhouse gases conspire to make the atmosphere of Venus partially transparent to incoming solar radiation but nearly completely opaque to outgoing thermal radiation. Consequently, the surface temperature (measured in kelvins) is three times what it would be without an atmosphere. On Earth, by comparison, the greenhouse effect currently



VICKI L. HANSEN *Southern Methodist University* AND ROGER J. PHILLIPS *Washington University*

RIBBON TERRAIN consists of steep-sided, flat-bottomed, shallow (400-meter) troughs. These features may have resulted from fracturing of a thin, brittle layer of rock above a weaker, ductile substrate. The insets show an enlargement of the region in the box, with the troughs marked on the bottom right.

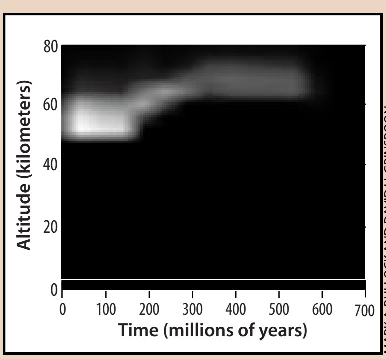
boosts the surface temperature by only about 15 percent.

If volcanoes really did repave the Venusian surface 800 million years ago, they should have also injected a great deal of greenhouse gases into the atmosphere in a relatively short time. A reasonable estimate is that enough lava erupted to cover the planet with a layer one to 10 kilometers thick. In that case, the amount of carbon dioxide in the atmosphere would have hardly changed—there is already so much of it. But the abundances of water vapor and sulfur dioxide would have increased 10- and 100-fold, respectively. Fascinated by the possible implications, we modeled the planet's climate as an interconnected system of processes, including volcanic outgassing, cloud formation, the loss of hydrogen from the top of the atmosphere, and reactions of atmospheric gases with surface minerals.

The interaction of these processes can be subtle. Although carbon dioxide, water vapor and sulfur dioxide all warm the surface, the last two also have a countervailing effect: the production of clouds. Higher concentrations of water vapor and sulfur dioxide would not only enhance the greenhouse

CLOUD COVER

The sulfuric acid clouds vary in thickness after a global series of volcanic eruptions. The clouds first thicken as water and sulfur dioxide pour into the air. Then they dissipate as these gases thin out. About 400 million years after the onset of volcanism, the acidic clouds are replaced by thin, high water clouds.



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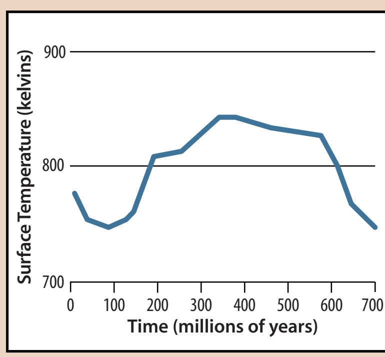
TEMPERATURE

The surface temperature depends on the relative importance of clouds and the greenhouse effect. Initially volcanism produces thick clouds that cool the surface. But because water is lost more slowly from the planet's atmosphere than sulfur dioxide is, a greenhouse effect subsequently warms the surface.



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Why Is Venus a Hellhole?

The stunning differences between the climates of Earth and Venus today are intimately linked to the history of water on these two worlds. The oceans and atmosphere of Earth currently have 100,000 times as much water as the atmosphere of Venus. Liquid water is the intermediary in reactions of carbon dioxide with surface rocks. Because of it, carbon dioxide in the air can form minerals. In addition, water mixed into the underlying mantle is probably responsible for the low-viscosity layer, or asthenosphere, on which Earth's lithospheric plates slide. The formation of carbonate minerals and their subsequent descent on tectonic plates prevent carbon dioxide from building up to the levels seen on Venus.

Yet models of planet formation predict that the two worlds should have been endowed with roughly equal amounts of water, delivered by the impact of icy bodies from the outer solar system. In fact, when the Pioneer Venus mission went into orbit in 1978, it measured the ratio of deuterium to ordinary hydrogen within the water of Venus's clouds. The ratio was an astonishing 150 times the terrestrial value [see "The Pioneer Mission to Venus," by Janet G. Luhmann, James B. Pollack and Lawrence Colin; Scientific American, April 1994]. The most likely explanation is that Venus once had far more water and lost it. Both the hydrogen and the deuterium, which are chemically equivalent, were tied up in water molecules. When water vapor drifted into the upper atmosphere, solar ultraviolet radiation decomposed it into oxygen and either hydrogen or deuterium. Because hydrogen, being lighter, escapes to space more easily than deuterium does, the relative amount of deuterium increased.

Why did this process occur on Venus but not on Earth? In 1969 Andrew P. Ingersoll of the California Institute of Technology showed that if the solar energy available to a planet were strong enough, any water at the surface would rapidly evaporate. The added water vapor would further heat the atmosphere and set up what he called the runaway greenhouse effect. The process would transport the bulk of the planet's water into the upper atmosphere, where it would ultimately be decomposed and lost. Later James F. Kasting of Pennsylvania State University and his co-workers developed a more detailed model of this effect [see "How Climate Evolved on the Terrestrial Planets," by James F. Kasting, Owen B. Toon and James B. Pollack; Scientific American, February 1988]. They estimated that the critical solar flux required to initiate a runaway greenhouse was about 40 percent larger than the present flux on Earth. This value corresponds roughly to the solar flux expected at the orbit of Venus shortly after it was formed, when the sun was 30 percent fainter. An Earth ocean's worth of water could have fled Venus in the first 30 million years of its existence.

A shortcoming of this model is that if Venus had a thick carbon dioxide atmosphere early on, as it does now, it would have retained much of its water. The amount of water that is lost depends on how much of it can rise high enough to be decomposed—which is less for a planet with a thick atmosphere. Furthermore, any clouds that developed during the process would have reflected sunlight back into space and shut off the runaway greenhouse.

So Kasting's group also considered the possibility of a solar flux slightly below the critical value. In this scenario, Venus had hot oceans and a humid stratosphere. The seas kept levels of carbon dioxide low by dissolving the gas and promoting carbonate formation. With lubrication provided by water in the asthenosphere, plate tectonics might have operated. In short, Venus possessed climate-stabilizing mechanisms similar to those on Earth today. But they were not foolproof. The atmosphere's lower density could not prevent water from diffusing to high altitudes. Over 600 million years, an ocean's worth of water vanished. Any plate tectonics shut down, leaving volcanism and heat conduction as the interior's ways to cool off. Thereafter carbon dioxide accumulated in the air.

This picture, termed the moist greenhouse, illustrates the intricate interaction of solar, climate and geologic change. Atmospheric and surface processes can reinforce one another and preserve the status quo, or they can conspire in their own destruction. If the theory is right, Venus once had oceans—perhaps even life, although it may be impossible to know for sure. *—M.A.B. and D.H.G.*

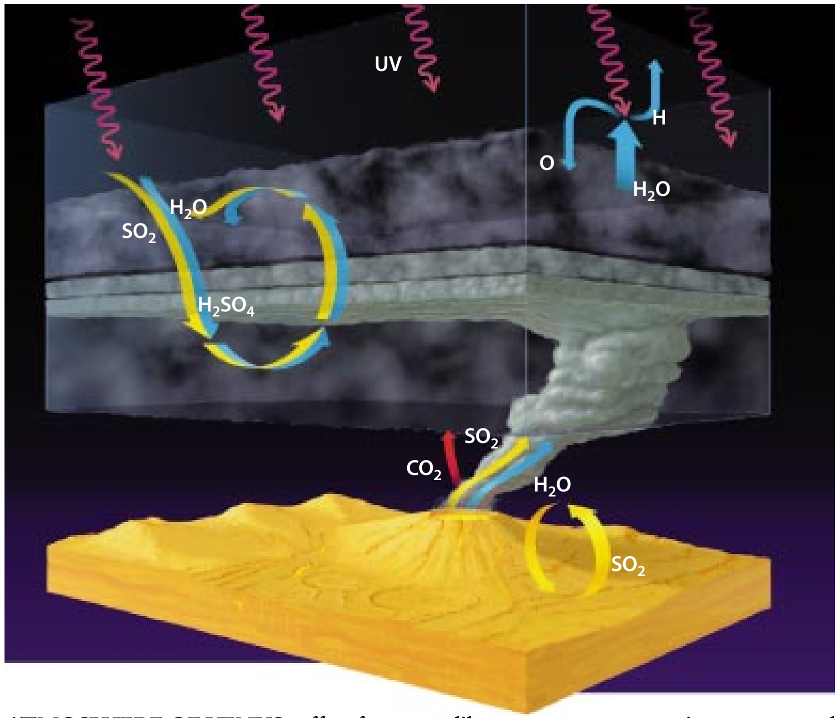
effect but also thicken the clouds, which reflect sunlight back into space and thereby cool the planet. Because of these competing effects, it is not obvious what the injection of the two gases did to the climate.

The Planetary Perspective

Our simulations suggest that the clouds initially won out, so that the surface cooled by about 100 degrees C. But then the clouds were slowly eaten away. Water diffused higher in the atmosphere, where it was dissociated by solar ultraviolet radiation. The hydrogen slowly escaped into space; half of it was lost within 200 million years. The sulfur dioxide, meanwhile, reacted with carbonate rocks. As laboratory experiments by Bruce Fegley, Jr., of Washington University and his co-workers have demonstrated, sulfur dioxide in Venus's atmosphere is taken up by carbonates much more quickly than water is lost to space.

As the clouds thinned, more solar energy reached the surface, heating it. After 200 million or so years, temperatures were high enough to start evaporating the clouds from below. A positive feedback ensued: the more the clouds eroded, the less sunlight was reflected back into space, the hotter the surface became, the more the clouds were evaporated from below, and so on. The magnificent cloud decks rapidly disappeared. For about 400 million years, all that remained of them was a wispy, high stretch of clouds composed mostly of water. Surface temperatures were 100 degrees C higher than at present, because the atmospheric abundance of water vapor was still fairly high and because the thin clouds contributed to the greenhouse effect without reflecting much solar energy. Eventually, about 600 million years after the onset of global volcanism, and in the absence of any further volcanic activity, the clouds would have dissipated completely.

Because sulfur dioxide and water vapor are continuously lost, clouds require ongoing volcanism for their maintenance. We calculated that volcanism must have been active within the past 30 million years to support the thick clouds observed today. The interior processes that generate surface volcanism occur over periods longer than tens of millions of years, so volcanoes are probably still active. This finding accords with observations of varying amounts of sulfur dioxide on Venus. In 1984 Larry W. Esposito of the University of Colorado at



TOM MOORE; SOURCE: MARK A. BULLOCK AND DAVID H. GRINSPOON; BASED ON DIAGRAM BY CARTER EMMART *Hayden Planetarium*

ATMOSPHERE OF VENUS suffers from ovenlike temperatures, oceanic pressures and sulfuric acid clouds (H_2SO_4). The reason is that Venus lacks the cycles that stabilize conditions on Earth. Its atmospheric processes are one-way. Carbon dioxide (CO_2), once injected by volcanoes, stays in the atmosphere; water (H_2O), once destroyed by ultraviolet light, is lost forever to the depths of space; sulfur dioxide (SO_2), once locked up in minerals, piles up on the surface (though a small amount does recycle).

Boulder noted that cloud-top concentrations of sulfur dioxide had declined by more than a factor of 10 in the first five years of the Pioneer Venus mission, from 1978 to 1983. He concluded that the variations in this gas and associated haze particles were a result of volcanism. Surface temperature fluctuations, precipitated by volcanism, are also a natural explanation for many of the enigmatic features found by Magellan.

Fortunately, Earth's climate has not experienced quite the same extremes in the geologically recent past. Although it is also affected by volcanism, the oxygen-rich atmosphere—provided by biota and plentiful water—readily removes sulfur gases. Therefore, water clouds are key to the planet's heat balance. The amount of water vapor available to these clouds is determined by the evaporation of the oceans, which in turn depends on surface temperature. A slightly enhanced greenhouse effect on Earth puts more water into the atmosphere and results in more cloud cover. The higher reflectivity reduces the incoming solar energy and hence the temperature. This negative feedback acts as a thermostat, keeping the surface temperature moderate over short intervals (days to years). An analogous feedback, the carbonate-silicate cycle, also stabilizes the abundance of atmospheric carbon dioxide. Governed by the slow process of plate tectonics, this mechanism operates over timescales of about half a million years.

These remarkable cycles, intertwined with water and life, have saved Earth's climate from the wild excursions its sister planet has endured. Anthropogenic influences, however, operate on intermediate timescales. The abundance of carbon dioxide in Earth's atmosphere has risen by a quarter since 1860. Although nearly all researchers agree that global warming is occurring, debate continues on how much of it is caused by the burning of fossil fuels and how much stems from natural variations. Whether there is a critical amount of carbon dioxide that overwhelms Earth's climate regulation cycles is not known. But one thing is certain: the climates of Earth-like planets can undergo abrupt transitions because of interactions among planetary-scale processes [*see box on page 56*]. In the long run, Earth's fate is sealed. As the sun ages, it brightens. In about a billion years, the oceans will begin to evaporate rapidly and the climate will succumb to a runaway greenhouse. Earth and Venus, having started as nearly identical twins and diverged, may one day look alike.

We both recall the utopian view that science and technology promised us as children of the 1960s. Earth's capacity to supply materials and absorb refuse once seemed limitless. For all the immense change that science has wrought in the past few decades, one of the most powerful is the acquired sense of Earth as a generous but finite home. That perspective has been gained from the growing awareness that by-products from a global technological society have the power to alter the planetary climate [see "Global Warming Trends," by Philip D. Jones and Tom M. L. Wigley; SCIENTIFIC AMERICAN, August 1990]. Studying Venus, however alien it may seem, is essential to the quest for the general principles of climate variation—and thus to understanding the frailty or robustness of our home world.

The Authors

MARK A. BULLOCK and DAVID H. GRINSPOON are planetary scientists at the University of Colorado at Boulder. Bullock began his career studying the destruction of organic compounds on Mars and now analyzes the destruction of clement conditions on Venus. At night he takes his young sons, Sean and Brian, outside and shows them the points of light he studies. Grinspoon, in addition to studying the evolution of planetary atmospheres and of life, is a member of the Solar System Exploration Subcommittee, which advises NASA on space policy. He has played electric guitar and percussion in a variety of world-beat and trip-hop bands and lived in Zimbabwe for two months to learn chimurenga music.

Further Reading

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