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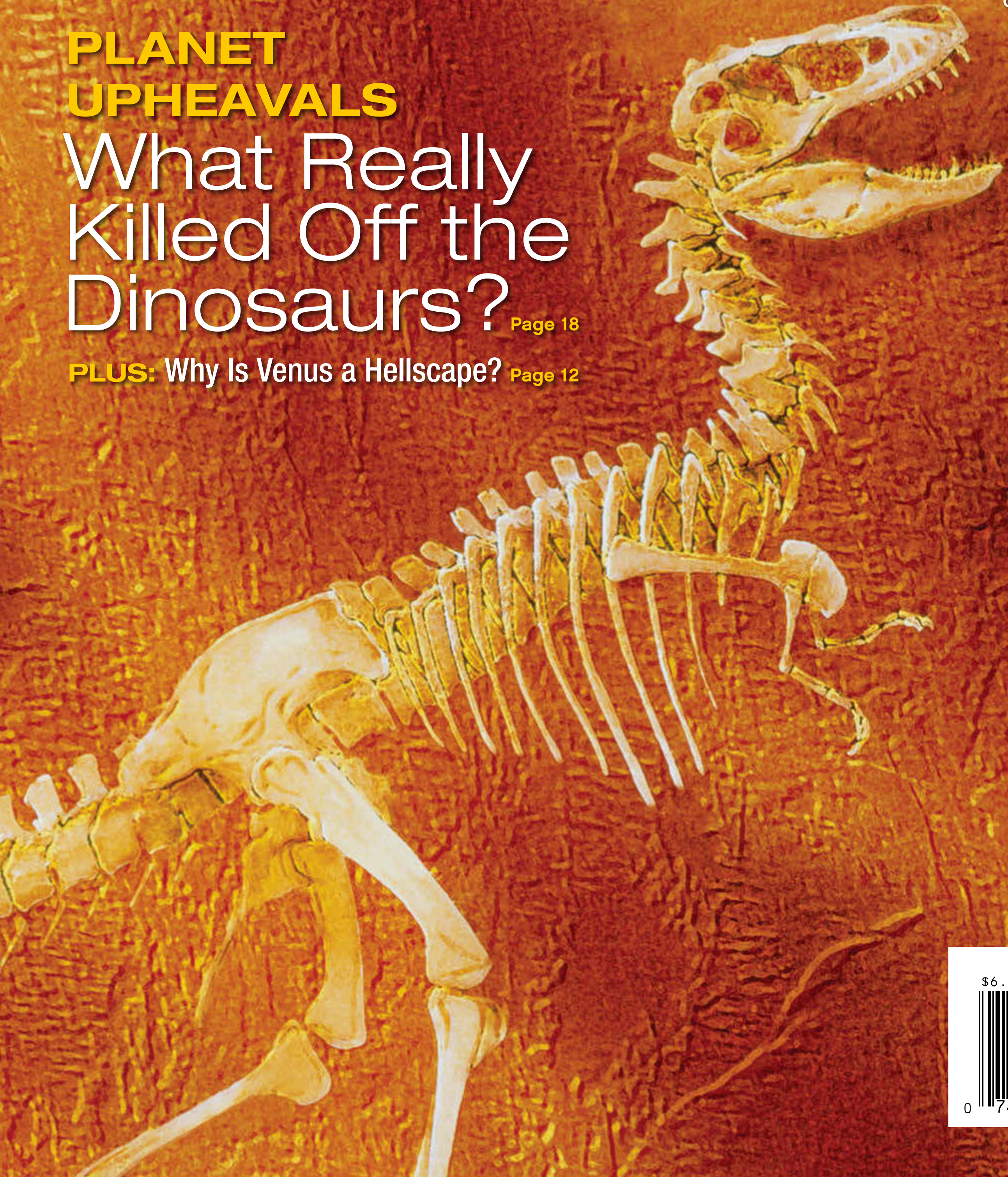

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PLANETARY CALAMITY, PART I by Paul Byrne

VENUS: INEVITABILITY OR CATASTROPHE?

Studying Venus can help us understand how large, rocky worlds evolve — and whether the hellish surface conditions on the second planet forebode a similar fate for Earth.

Venus is a study in contrasts. From far away — say, another planetary system — Venus and Earth are essentially indistinguishable. The second planet is 82% the mass, and 95% the radius, of our own world, and orbits the Sun not very much closer: about 108 million km, versus 150 million km for Earth. By most measures, Venus is an Earth-size world (or Earth a Venus-size world).

But when it comes to details, the two couldn't be more different. Early radio observations of Venus found that the planet rotates on its axis backwards relative to Earth, Mars, and nearly every other planet in the solar system. In 1962 NASA's Mariner 2 spacecraft, as it carried out the first successful interplanetary flyby, found no intrinsic magnetic field and very high surface temperatures. These measurements in particular dispelled previous notions of a lush, warm, tropical planet imagined by scientists and science-fiction writers alike, who had proposed such scenes based on Venus's proximity to the Sun.

Subsequent Venus missions sampled the atmosphere, either on the way to the surface or, in the case of the Soviet Union's 1985 Vega missions, as balloons that floated through the middle atmosphere. These missions found an atmosphere that is 97% carbon dioxide, with a global layer of sulfuric acid clouds and an unusually high ratio of deuterium to hydrogen — more than 100 times that of Earth. (More on this finding later.)

From those landed missions that managed to return data from the surface — and many did not — a picture of hell made real came into focus (*S&T:* Sept. 2018, p. 14). The planet's surface has an average pressure of 90 bars, almost as much as 1 km underwater on Earth, and the temperature is around 460°C (860°F, or about that of a self-cleaning oven). Lush, tropical forests indeed. Those missions also found a surface of basalt, the volcanic rock that constitutes Earth's seafloors.

▼ **DESOLATE WASTELAND** Artistic depiction of one of the Venera landers on the surface of Venus. The landers' data revealed flat, angular rocks of basalt, which is volcanic in origin.

COMPOSITION: THE AUTHOR, GROUND: MATTIAS MALMER

NASA's Magellan orbiter, which operated around Venus for four years from 1990, used a powerful radar instrument to peer through the global cloud layer and acquire images of virtually the entire surface. It also took remote geophysical measurements of the interior. Of its many important findings, Magellan determined that Venus has high-standing plateaus, giant rift zones, and extensive, low-lying plains. The spacecraft's gravity data indicate that some of those high-standing regions are likely supported from below by huge upwellings of warmer material from deep in the planet's interior, akin to deep-seated conduits on Earth called mantle plumes — and thus implying a geologically active interior. Venus very likely shares the same broad interior structure as Earth, then, with a basaltic crust, an iron- and magnesium-rich mantle, and an iron core. (The physical state of the core remains an open question.)

But perhaps the most unusual finding from Magellan's global imaging of Venus was what it didn't find: many craters.

A Surprisingly Young Surface

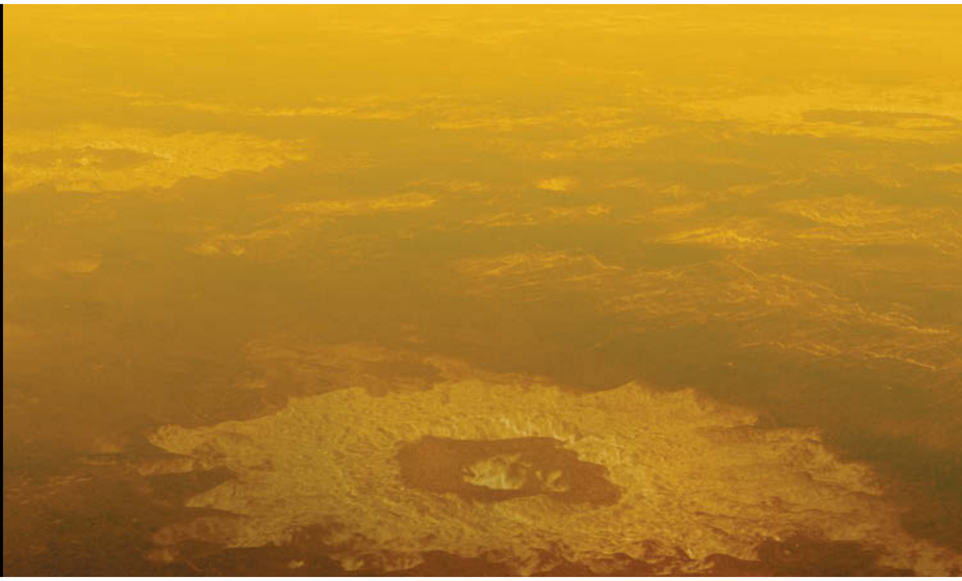
Venus hosts fewer than 1,000 craters across its surface. This discovery alone — made by scouring through the enormous amount of radar image data returned by Magellan — was surprising: Normalized by surface area, Venus doesn't have many more impact craters than Earth does, and far less than the ancient surfaces of Mercury, Mars, or the Moon. Statistical modeling suggested that the average age for the planet's surface was about 750 million years, much less than scientists had expected.

But what was *really* strange was the distribution of those craters: There are no regions on Venus that are noticeably more cratered, and thus older, than any other — again unlike other rocky inner solar system worlds. In fact, statistical analyses carried out with Magellan data showed the craters' placement is indistinguishable from random. And what's more, there are no giant impact basins, again a type of feature common to Venus's planetary neighbors (with the notable exception of Earth).

THERE ARE NO REGIONS OF VENUS THAT ARE NOTICEABLY MORE CRATERED, AND THUS OLDER, THAN ANY OTHER.

These remarkable observations quickly led scientists to develop several hypotheses. One was that the planet experienced a global-scale resurfacing event by voluminous lava, burying older craters (including any gigantic basins) and essentially "resetting" the recorded age of the surface. Another hypothesis held that, although volcanic resurfacing had operated globally, it may have done so piecemeal and perhaps in a steady-state fashion, with some areas having recently been buried and others being (relatively) older. In this picture, volcanic activity takes place at some level on the planet constantly.

Indeed, there is circumstantial evidence for ongoing volcanism on Venus. The global sulfuric acid cloud layer is not chemically stable over extended periods of time, and thus presumably requires replenishment. Water and sulfur dioxide can combine to form sulfuric acid droplets, and both are volatiles released by volcanic eruptions on Earth. In addition, the European Space Agency's Venus Express spacecraft, orbiting the planet from 2006 until 2014, found that some of the most recent lavas on the planet appear to have undergone very little weathering, suggestive of their being *very* geologically young. And that same mission detected short-lived, localized increases in surface temperature in a region known



VENUSIAN CRATERS Venus boasts fewer than 1,000 craters, three of which appear here in this simulated 3D view of Magellan radar data. Venusian craters generally look pristine and uneroded, suggesting they're very young. From left to right the craters are Danilova (48 km wide), Saskia (37 km wide), and Aglaonice (63 km wide).

CRATERS: NASA / JPL, MODIFIED BY THE AUTHOR; GLOBE: NASA / USGS, PROJECTED BY PLANETUSER / WIKIMEDIA COMMONS / CC BY-SA 4.0 INTERNATIONAL

to feature abundant volcanic landforms — again consistent with, if not proof of, the presence of actively erupting volcanoes on Venus.

A Major Mystery

If widespread resurfacing by volcanism, whether episodic or sustained, regional or global in scale, was responsible for Venus's present cratering record, what did the planet look like *before* that resurfacing?

One place we might learn the answer to this question is the planet's enigmatic *tesserae* — highly faulted and folded rocks that cover about 7% of the surface. In every instance, the rocks that form tesserae are covered by later lavas, indicating that these rocks, which show the greatest amount of tectonic squashing and squeezing of any on Venus, are among the oldest preserved portions of the planet.

Recent findings using decades-old Magellan images raise new questions about the nature of these rocks. Those radar images show distinct layering in some tesserae that resembles a deck of cards. On the one hand, such layering is characteristic of thick stacks of lavas laid down extremely quickly, and there is no shortage of other volcanic evidence on Venus. On the other hand, layering is also a hallmark of sedimentary rocks — those built up by sediment deposits, often in water.

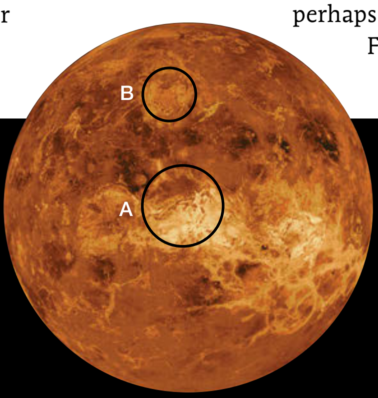
Sedimentary rock types cannot form under today's surface conditions. If some of the tesserae are in fact ancient, deformed sediments, did they form under different climatic conditions, perhaps ones that supported liquid water at the surface?

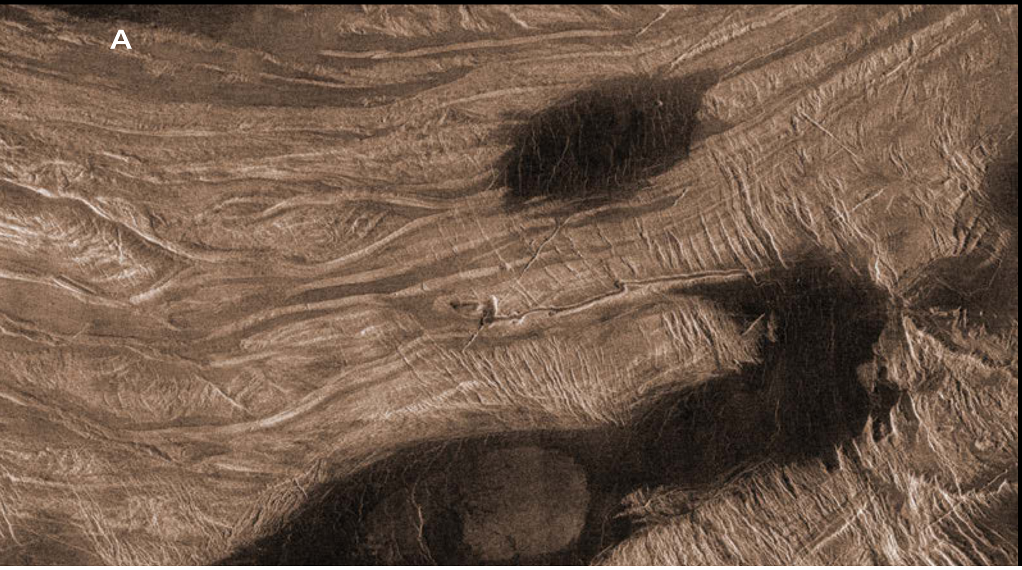
DID THE SOLAR SYSTEM HAVE TWO BLUE, EARTH-SIZE WORLDS IN THE DISTANT PAST?

Another tantalizing hint of a former climatic regime lies in the planet's elevated deuterium-to-hydrogen (D/H) ratio, which is more than 100 times that of Earth. Deuterium, an isotope of hydrogen with a neutron in the nucleus as well as a proton, is slightly heavier than regular hydrogen and, on Earth at least, much rarer.

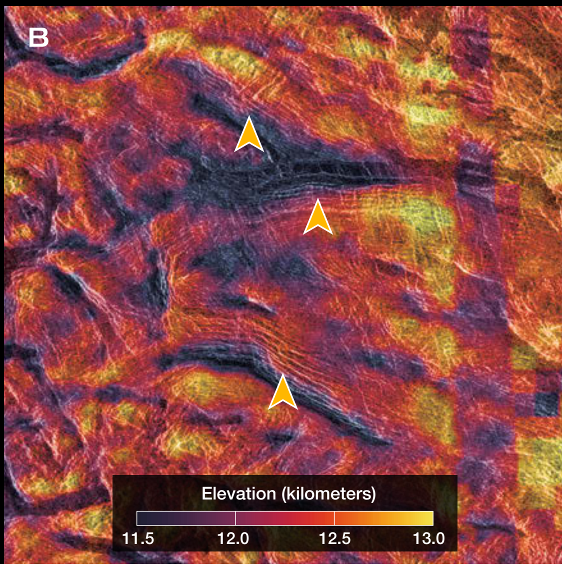
When water molecules in a planet's atmosphere reach sufficient altitudes, solar ultraviolet rays can *photodissociate* the molecules, splitting the water into its component atoms of oxygen and hydrogen — or, sometimes, deuterium. The solar wind then streams by and strips atoms from the top of the atmosphere, preferentially carrying the lighter hydrogen away into space and leaving the heavier deuterium behind. Thus, the best explanation for Venus's high D/H ratio is that the planet once had *substantially* more water than it does today — perhaps even as much as an ocean's worth.

Features including the tesserae and the elevated





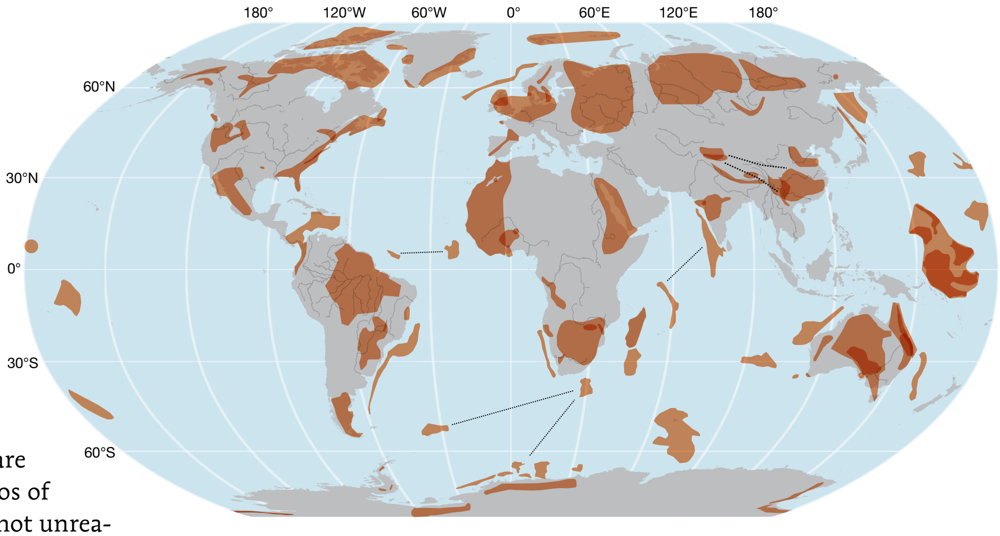
▼ **TESSERA** The northern boundary of Ovda Regio, shown here, is one of several examples of old, crunched-looking highland terrain. Tesserae appear bright in radar images because their surfaces are so rough. Darker patches are thought to be lava that filled in later. The image spans a few hundred kilometers.



▼ **LAYERS** Magellan data reveal sets of curved, parallel lines within some tesserae (arrows) that follow the ridges and troughs of the local topography (color coded by elevation relative to Venus's average radius). These lines might be ancient layers of lava or even sediment, exposed by erosion.

GLOBE: NASA / USGS, PROJECTED BY PLANETUSER / WIKIMEDIA COMMONS / CC BY-SA 4.0 INTERNATIONAL; OVDA TESSERA: THE AUTHOR, DATA FROM NASA / JPL; LAYERS: THE AUTHOR, TOPOGRAPHIC DATA FROM HERRICK ET AL. / *EOS* 2012

▶ **VOLCANIC PLANET** Earth's geologic record contains dozens of voluminous volcanic flows, called *large igneous provinces*. Shown here are those from the last billion years. On average, such eruptions occur every few tens of millions of years, and scientists have linked some to extinction events in the fossil record (see page 18).



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D/H ratio raise a fascinating question: Did Venus once have liquid water on its surface? The long-standing presumption of planetary scientists is that the inner solar system worlds are largely made of about the same ratios of the same materials, so perhaps it's not unreasonable to expect a planet almost as large as Earth to have almost as much water. Did the solar system have *two* blue, Earth-size worlds in the distant past? And, if so, what happened to leave Venus the hellscape it is today?

Old Models and New Insights

One hypothesis proposed early in the exploration of Venus holds that, at some point in the past, the planet suffered a runaway greenhouse effect. The surface temperature slowly but inexorably rose, increasing the rate of evaporation of whatever liquid water was on the surface — lakes, seas, or even oceans. The moisture content of the atmosphere increased, which served to trap more and more of the outgoing radiation that would otherwise make it to space and help keep the planet's surface cool. With a warmer atmosphere came more evaporation, and ever more steam in the atmosphere. Trapped in a feedback loop, Venus ultimately reached the point of no return: The temperature continued to increase until virtually all its water was lost first to the atmosphere and then to space, and the surface became the desiccated, nightmarish place we know today.

But what drove the initial increase in temperature? The obvious suspect is the Sun. We know that stars naturally become brighter and emit more radiation as they age, a consequence of the fusion that takes place in their cores. Early models of Venus's climate therefore included a steady increase in surface temperature from the brightening of the young, nearby Sun — a scenario under which Venus's descent from clement, ocean world to its present state was simply a function of time. Such a scenario also implies something else: Since we orbit that same brightening, aging Sun, so too will Earth one day undergo the same fate that befell Venus.

But recent climate models suggest a different story. Research published in 2020 by Michael Way and Anthony Del Genio of NASA's Goddard Institute for Space Studies found that, for certain combinations of ancient planetary spin rate, surface conditions, and atmospheric compositions, Venus may have easily weathered the effects of a steadily brightening Sun. Indeed, although it remains entirely possible that Venus was always hellish — that it started that way, was never like Earth, and the two planets never diverged — if at any point Venus did possess liquid water oceans, then it would have continued to do so, regardless of what the early Sun did. That's because, per Way and Del Genio's models, once Venus made it to the point at which its climate was stable enough to support the presence of liquid water on the surface, that stability would be hardwired into the planet: Venus would remain continuously able to regulate its temperature just as Earth does today.

Our planet manages this feat via plate tectonics, in which subducting tectonic plates drag volatiles — among them, carbon compounds — into the deep interior from whence they originally came via volcanic eruptions. In doing so, Earth balances its budget of greenhouse-causing compounds, allowing the planet to radiate into space about the same amount of heat as it receives (notwithstanding human activities over the past several centuries that have upset this natural balance, see page 25). So long as Venus had its own self-regulating mechanism — whether plate tectonics or something else — then oceans would remain. We have no evidence for Earth-like tectonic plates on Venus, but since much of the surface is geologically young, absence of proof may not necessarily mean proof of absence.

So, these new models tell us that one of two things happened: Either Venus really was always different from Earth, for reasons we don't yet understand, or it was the same as

TESSERAE

These regions of crumpled highland terrain occur on Venus both as isolated fragments embayed by lava plains and as major plateaus. Venus has six major crustal plateaus, the highest points of which tower some 4 km above the surrounding terrain.

▲ **STILL ERUPTING?** This artist's impression shows an active volcano on Venus today. Data from the Venus Express orbiter found a spike in sulfur dioxide in the planet's upper atmosphere in the mid-2000s, which might have come from volcanic activity. Alternatively, it could be part of decades-scale variations — the earlier Pioneer Venus orbiter saw a range of levels, the highest of which was comparable to the Venus Express spike.

> **EARTH HAS BEEN LUCKY: MULTIPLE SUCH MAJOR ERUPTIONS DO NOT SEEM TO HAVE TAKEN PLACE AT THE SAME TIME.**

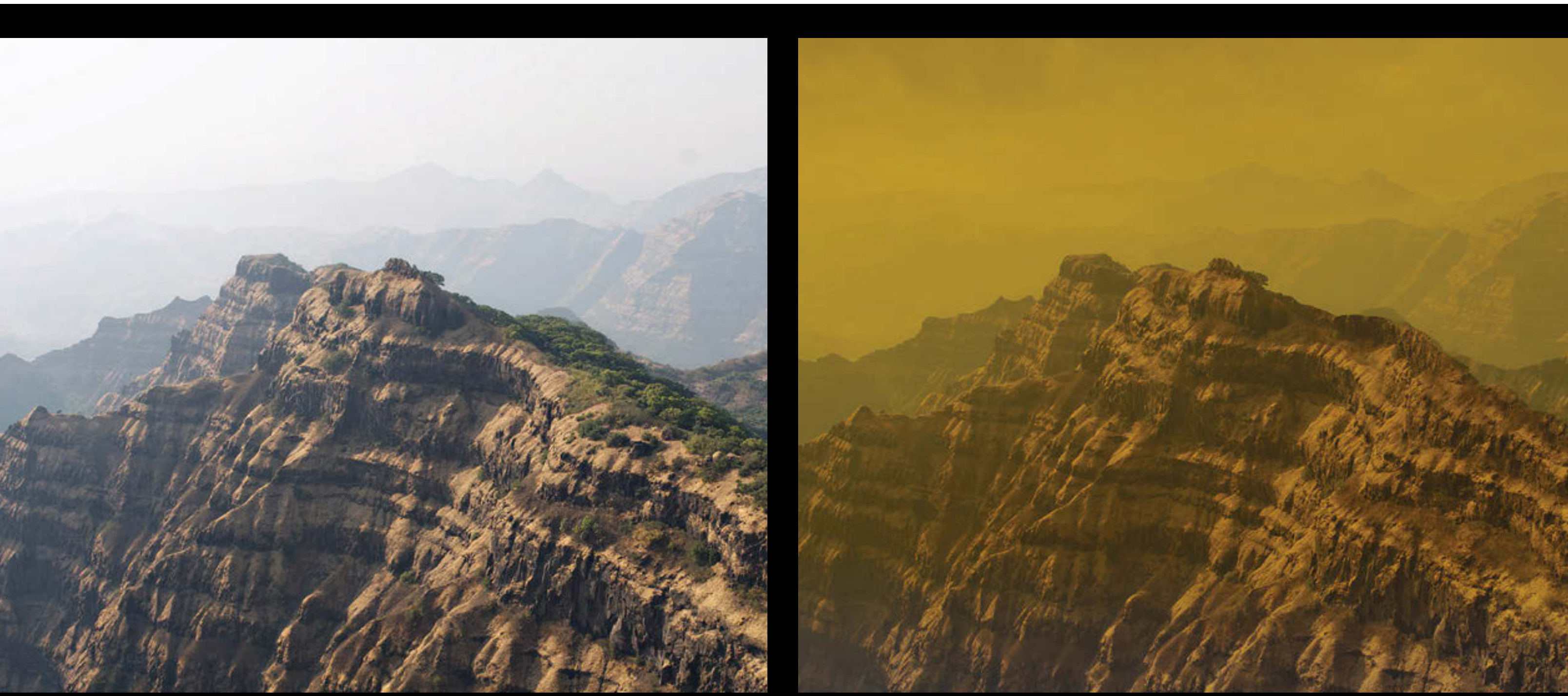
Earth — for a while. If that second scenario is correct, then we must ask an important question: What happened to that once climatically stable, blue Venus?

Way and Del Genio suggest an intriguing cause for a catastrophic change in Venus's climate, one rooted in the planet's rich history of volcanic resurfacing. A major component of terrestrial volcanic gas, in addition to water and sulfur dioxide, is carbon dioxide. Volcanoes on Earth pump out more than 200 million tons of this gas every year. Normally it would be recycled away, but volcanically sourced carbon dioxide can have a profound climatic impact *if enough of it is released quickly.*

That's what might have killed Venus.

Imagine a scenario under which a major volcanic eruption starts — the voluminous kind that produced the vast volcanic plains in India called the Deccan Traps (see page 18), or the expansive Siberian basalts emplaced some 252 million years ago. Then another such eruption takes off, and perhaps even another, all releasing gigatons of CO_2 into the atmosphere, over a geological instant. Even if Venus had plate tectonics or

VOLCANIC ILLUSTRATION: DON DAVIS; DECCAN: MARK RICHARDS; VENUSIAN DECCAN: MARK RICHARDS, MODIFIED BY THE AUTHOR



COULD TESSERAE LOOK LIKE THIS? *Left:* The Deccan Traps in India are vast, kilometers-thick stacks of lava, their layers exposed by erosion. *Right:* The same photo, with vegetation removed and edited to appear under a Venusian sky. It's possible that the ancient, layered highlands called tesserae are similar volcanic formations. Or perhaps they're instead stacks of sedimentary rock.

some other efficient means of drawing carbon out of the atmosphere and returning it to the interior, a sudden, massive influx of this greenhouse gas would overwhelm that system and quickly start to raise the surface temperature. Increasing temperatures would then lead to more evaporation of liquid water on the surface, which would trap more radiation, which would cause more evaporation . . . you get the picture.

A Matter of Luck?

The implication of this line of thinking is that as the Sun ages, it does not have as quick an inimical effect on its nearby planets as we might have feared. Sure, *eventually* a swelling red giant Sun will roast Earth (*S&T:* Oct. 2017, p. 22), but what was once seen as perhaps a climatic inevitability — that, on geological time scales, Earth would soon endure the same climate catastrophe as Venus — is now a more distant destiny.

That's the good news.

The bad news is that enormous volcanic eruptions are geologically common on our planet. In addition to the flows in India and Russia, scientists know of about 200 other examples of vast expanses of basaltic rock, both on land and under the sea. Termed *large igneous provinces* by geologists, these are regions that within only a few million years erupted enough lava to either cover an area of 100,000 km^2 — equivalent to a region the size of Iceland — or that occupy a volume of 100,000 km^3 (about four times the volume of Lake Baikal, the largest freshwater lake on Earth). The potential climate impact such events can have is profound: The Siberian eruptions may have been responsible for the Permian extinction event, the largest die-off of living creatures in Earth's history.

We don't fully understand what controls when or where a large igneous province will form; these phenomena are likely linked to the mantle plumes deep in the planet's interior. But it seems Earth has been lucky: Multiple such major eruptions do not seem to have taken place at the same time. Is that because two cannot form at the same time? Or are these events essentially random in space and time and it is *simply a coincidence* that Earth has not — yet — suffered the same fate as Venus? This is one of the biggest questions in planetary science we have yet to answer.

And answer it we can. Measurements of noble gas abundances in the middle Venusian atmosphere, for example, would give us a much better handle on how much gas has erupted from the planet's interior. Such measurements could also tell us whether the planet started off with enough water to host oceans or if, indeed, it was always a barren world. And what of those strange layers within some tessera exposures? Determining what these ancient rocks are made of, and how they formed, will help us piece together a more complete picture of Venus's geological history — at least, for that history still accessible on the surface. Recently selected missions will take us a long way toward answering the question of what happened (see sidebar at left).

If we one day establish whether Venus really ever was like Earth, and then why, and when, the paths of the two planets diverged, we will know if the relatively stable climate of our own planet has been either a foregone conclusion or simply good luck. We may also better know whether to expect Earth-like, or Venus-like, surface conditions on similarly sized worlds in orbit about other stars — even if we might not be able to say whether we're alone in the universe for quite some time.

And, whatever the reason for Venus's demise, it will give us a new appreciation for living on a world that has largely remained habitable for billions of years.

■ **PAUL BYRNE** is a planetary scientist at Washington University in St. Louis. With a combination of spacecraft data, computer and numerical modeling, and fieldwork at analog sites on Earth, he seeks to understand why planets look the way they do.

U.S. AND EUROPE RETURN TO VENUS

In June, NASA announced that it would send *two* Discovery-class missions to Venus at the end of this decade. These are the Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy orbiter (VERITAS) and the Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging (DAVINCI+) probe and spacecraft.

The VERITAS orbiter will map Venus's surface in 3D, distinguishing global features as small as 30 meters across and, for a quarter of the surface, down to 15 m — about five times better than Magellan's radar maps. Height accuracy for topographic features will be 5 m. With instruments to probe the planet's gravity and surface composition, the mission will explore the planet's geologic history, including the nature of the mysterious tesserae.

DAVINCI+ will essentially be a chemistry lab dropped into the Venusian clouds. On its plunge to a (hopefully survivable) landing in the rugged tessera region Alpha Regio, it will take images and sample the surrounding gases, providing clues about how the planet has evolved and whether it lost an early ocean. The team is also considering modifying their instrument payload to enable them to check for phosphine, a potential biosignature that might exist in Venus's cloud deck (*S&T:* Mar. 2021, p. 9). The probe's relay spacecraft will later enter orbit.

About a week after NASA's announcement, the European Space Agency declared it, too, is Venus-bound: The EnVision orbiter will launch no sooner than 2031 to study the planet's landscape, surface composition, and internal structure. It will also look for hotspots from active volcanism.

—CAMILLE M. CARLISLE