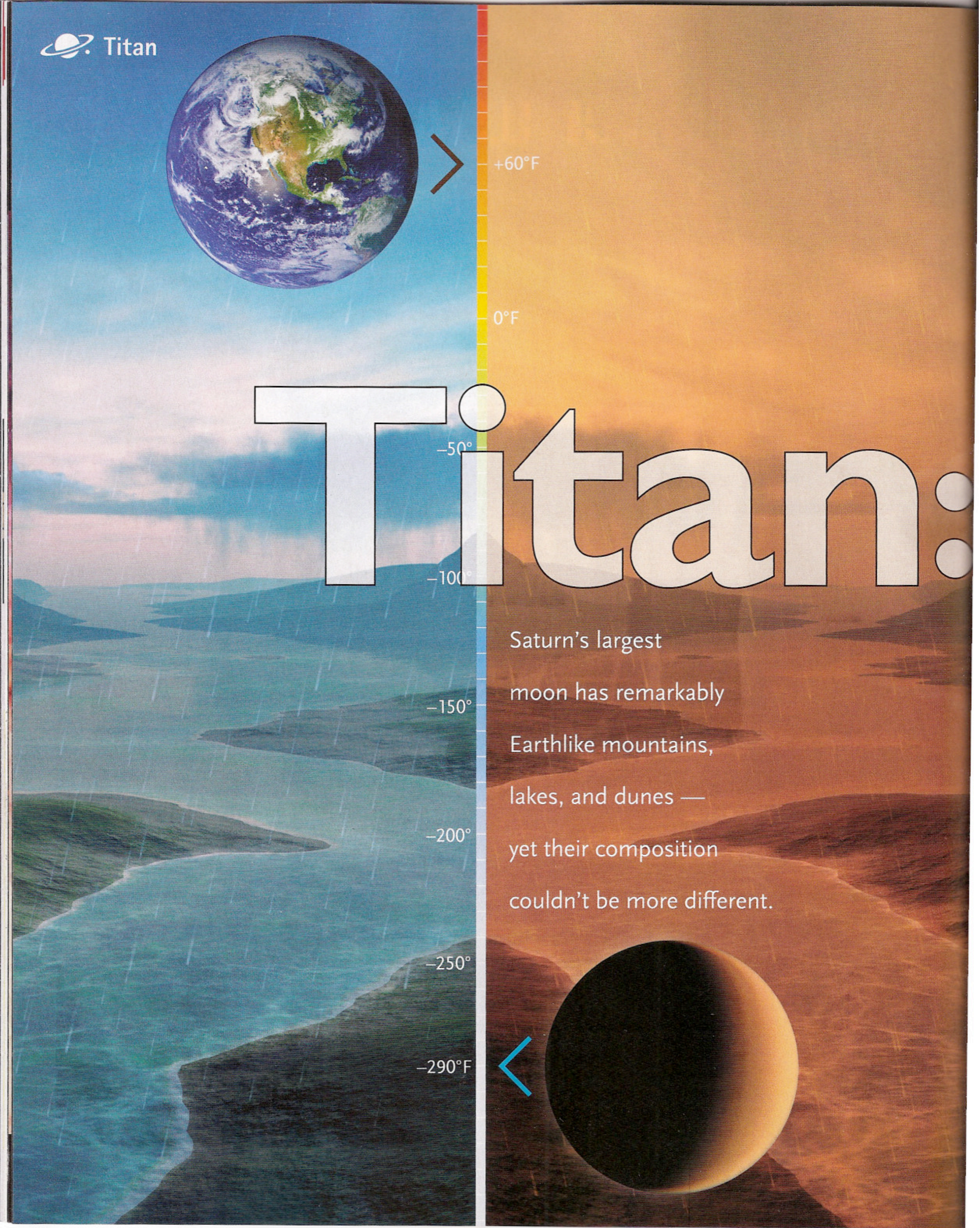
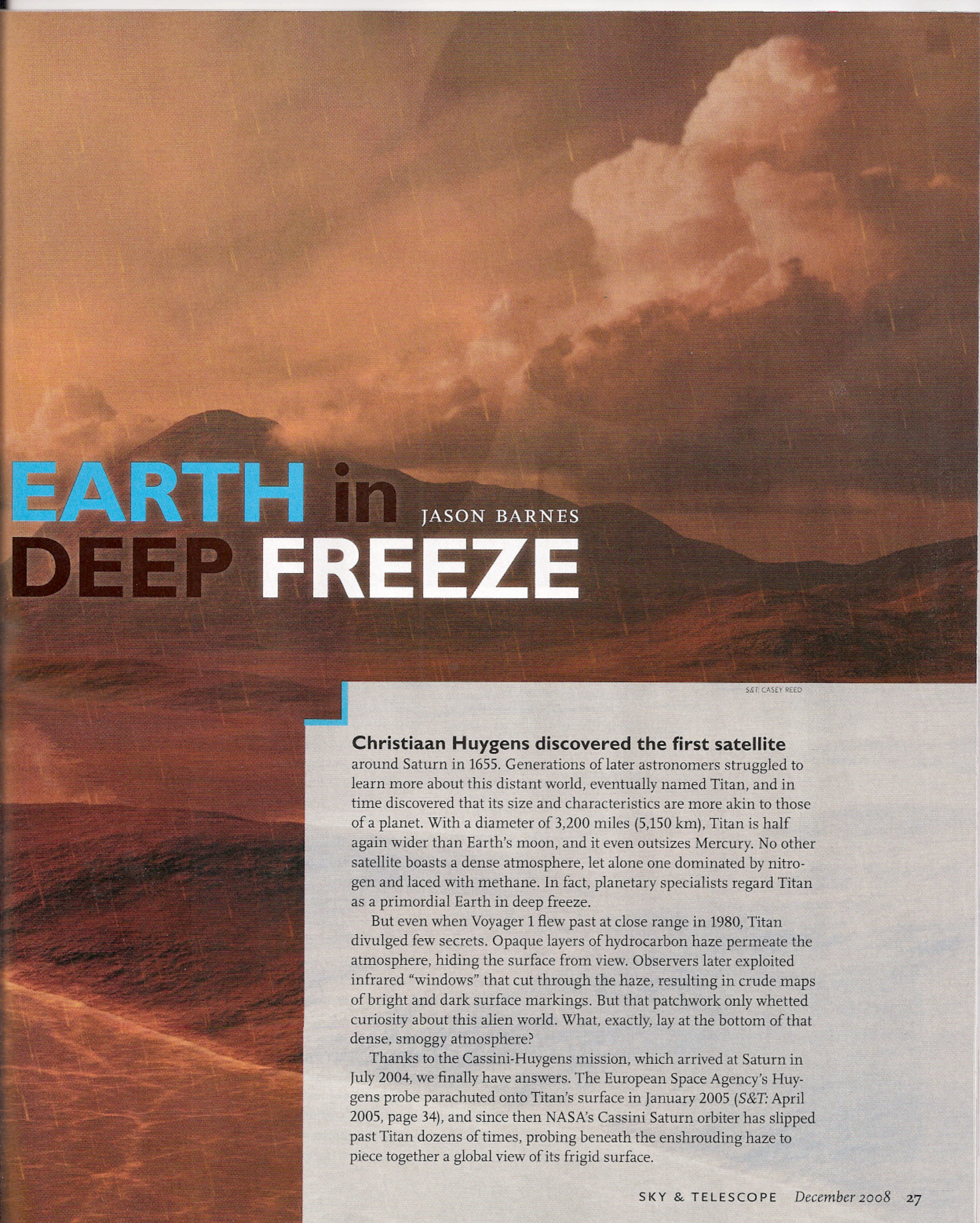


Titan:

Saturn's largest moon has remarkably Earthlike mountains, lakes, and dunes — yet their composition couldn't be more different.



S&T: CASEY REED

EARTH in DEEP FREEZE

JASON BARNES

Christiaan Huygens discovered the first satellite around Saturn in 1655. Generations of later astronomers struggled to learn more about this distant world, eventually named Titan, and in time discovered that its size and characteristics are more akin to those of a planet. With a diameter of 3,200 miles (5,150 km), Titan is half again wider than Earth's moon, and it even outsizes Mercury. No other satellite boasts a dense atmosphere, let alone one dominated by nitrogen and laced with methane. In fact, planetary specialists regard Titan as a primordial Earth in deep freeze.

But even when Voyager 1 flew past at close range in 1980, Titan divulged few secrets. Opaque layers of hydrocarbon haze permeate the atmosphere, hiding the surface from view. Observers later exploited infrared "windows" that cut through the haze, resulting in crude maps of bright and dark surface markings. But that patchwork only whetted curiosity about this alien world. What, exactly, lay at the bottom of that dense, smoggy atmosphere?

Thanks to the Cassini-Huygens mission, which arrived at Saturn in July 2004, we finally have answers. The European Space Agency's Huygens probe parachuted onto Titan's surface in January 2005 (*S&T:* April 2005, page 34), and since then NASA's Cassini Saturn orbiter has slipped past Titan dozens of times, probing beneath the enshrouding haze to piece together a global view of its frigid surface.

LIFTING THE VEIL
Cassini's VIMS instrument recorded these images of Titan's surface at near-infrared wavelengths. The dark patches are not the seas revealed by radar, but are instead dunefields.

NASA / JPL / UNIVERSITY OF ARIZONA

Planetary scientists expected to find much of Titan covered with an ocean of liquid ethane (C_2H_6) and other hydrocarbons that have rained out of the smoggy sky. Solar ultraviolet light and charged-particle bombardment from Saturn's magnetosphere shatter atmospheric methane (CH_4) molecules, which recombine to form droplets of more complex hydrocarbons, along with hydrogen gas that escapes to space. Over 4½ billion years this conversion should have produced enough ethane for a global ocean 1,000 feet (300 meters) deep.

But there is no ocean. What we've found instead has paradoxically advanced our knowledge leaps and bounds while sending us back to the drawing board.

Titan is a world where water ice acts like "rock," and a cryogenic brew of liquid ethane and methane plays the role of "water." Yet Titan abounds with mountains, plains, dunes, and riverbeds that eerily mimic their terrestrial counterparts. Mars may have its vast deserts and Venus its pervasive volcanism, but of all worlds in our solar system, Titan is the place where field geologists would feel most at home, except for the –290°F (–179°C) temperature.

TITAN'S ATMOSPHERE

Of all the bodies in the solar system, Titan's atmosphere is by far and away the most similar to Earth's in both composition and pressure. Both atmospheres are dominated by nitrogen (78% Earth, about 95% Titan). The atmospheric pressure on Titan's surface is about 50% greater than the pressure at sea level on Earth. That's a paltry difference when compared to Venus's pressure (90 times that at sea level), and Mars's pressure (about 1% that at sea level).

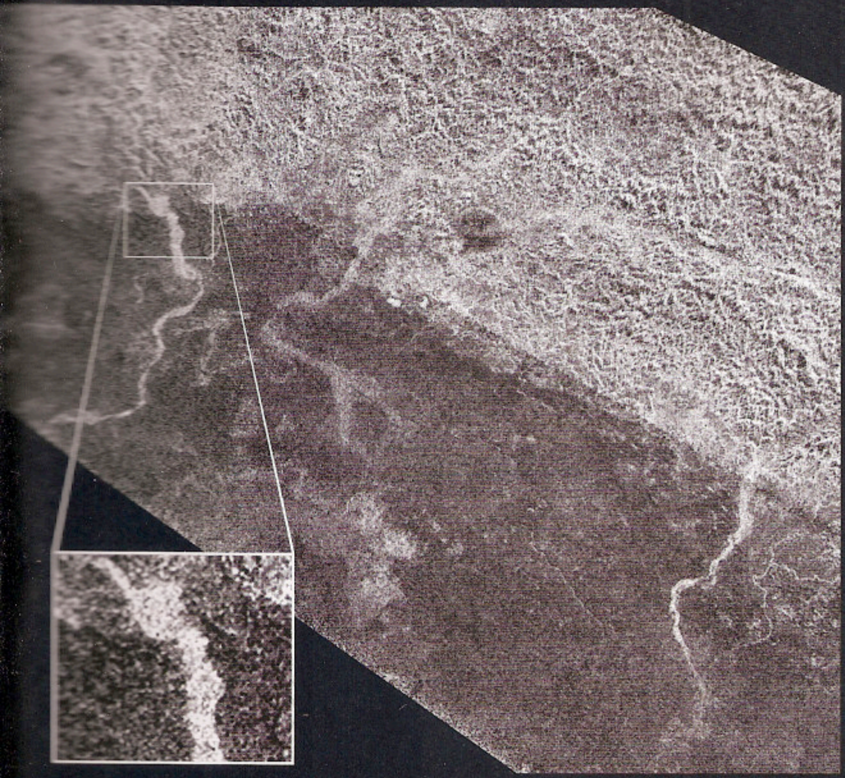
Rivers Run Through It

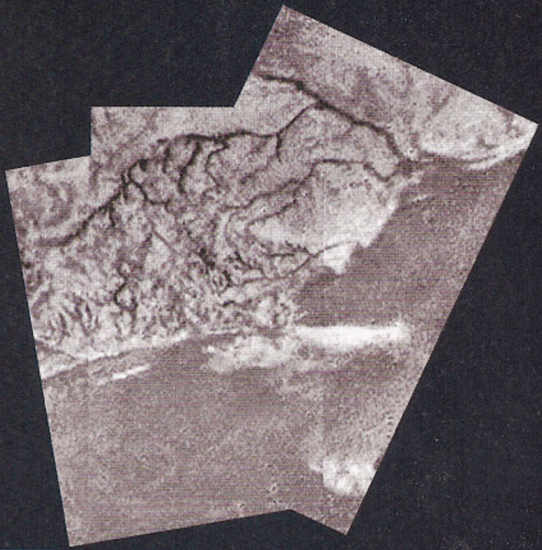
Perhaps the most striking results from Huygens's descent were snapshots that showed intricate, branching patterns of dark lines cascading down hilly slopes. Liquid has unquestionably flowed on Titan's surface in recent times, and the nature of the branching shows that the channels were formed by rainfall — not from the floods or underground processes that we have probably occurred on Mars.

Cassini has spotted similar drainage systems at the equatorial latitudes where Huygens touched down, at mid-latitudes, and at the poles. None of these channels appear to be flowing now, but they presumably fill with runoff whenever it rains. As liquid flows downhill from nearby hills and mountains, it gathers speed and drives the kinds of erosion so common here on Earth.

Titan's channels exhibit considerable variety, and we don't yet understand why. The big ones seen by Cassini, between ½ and 1 mile across, could be dried-up riverbeds, or they might include adjacent valleys or floodplains.

A few of the wandering channels course through canyons, a testament to the erosive power of the flows that created them. Some stretch for hundreds of miles. Others, like those near the Huygens landing site, originate and disappear within only a few miles. Some have bottoms that appear dark in radar scans, meaning that they are smooth on scales of a few inches, while others are bright, meaning they are rough.





RIVERBEDS *Left:* Cassini's radar instrument has found dry riverbeds all over Titan. The channels come in all sizes and in both smooth and rough textures. They were presumably carved by liquid hydrocarbons running downhill. *Right:* As Huygens parachuted to Titan's surface, its descent camera imaged dark channels flowing into what appears to be a dry lakebed. The channels are currently dry, but they indicate recent fluvial activity fed by rainfall.

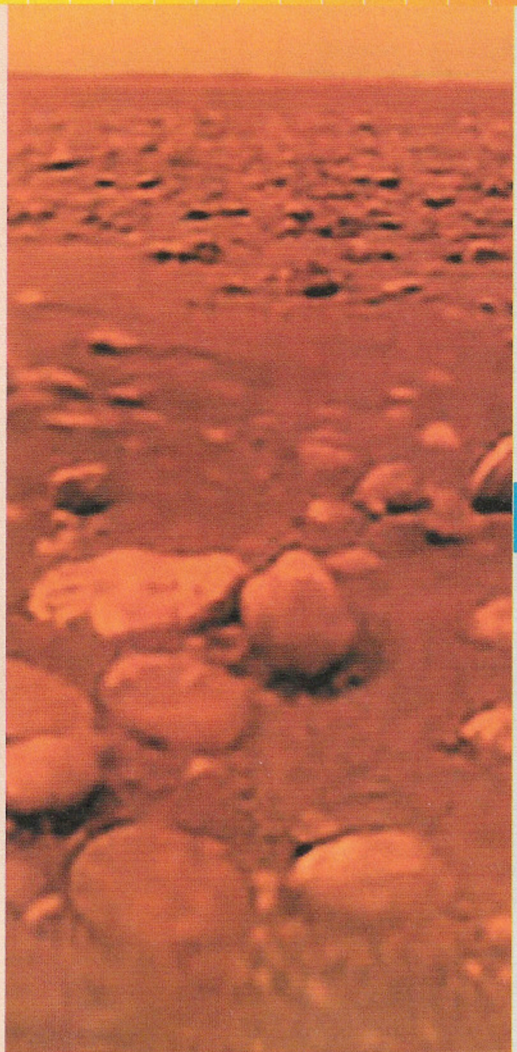
NASA / JPL

NASA / JPL / ESA / UNIVERSITY OF ARIZONA

We suspect that methane rainfall drives the channel flows. But how does this rainfall vary by season and latitude? And does it simply rain on Titan, or do its clouds unleash torrential downpours? Although we haven't seen any lightning yet, Titan's storms evolve much as thunderstorms do on Earth. Low cumulus clouds rapidly grow in vertical extent until they reach the tropopause and then shrink — presumably as they dump a methane-ethane rain onto Titan's surface.

As on Earth, thunderstorms are localized in a few preferred spots. One hovers over Titan's south pole, which is now experiencing late-summer's constant sunlight. Another is a thin band centered at 40° south, where solar heating pushes air upward in much the same way that the Intertropical Convergence Zone drives water to Earth's tropical rain forests.

But why was the ground beneath Huygens moist, when Cassini doesn't see clouds anywhere near the equator? Perhaps we don't yet know how to predict where rain will fall. Huygens found lots of turbulence 15 to 20 miles up, conditions that could produce precipitation despite the absence of clouds. Confirmation of this "ghost rain" came from Hawaii's Keck Observatory, which found liquid methane to be more concentrated in this same atmospheric layer. Still, it's not yet clear what drives this drizzle, or whether it occurs all over Titan or just at equatorial latitudes.



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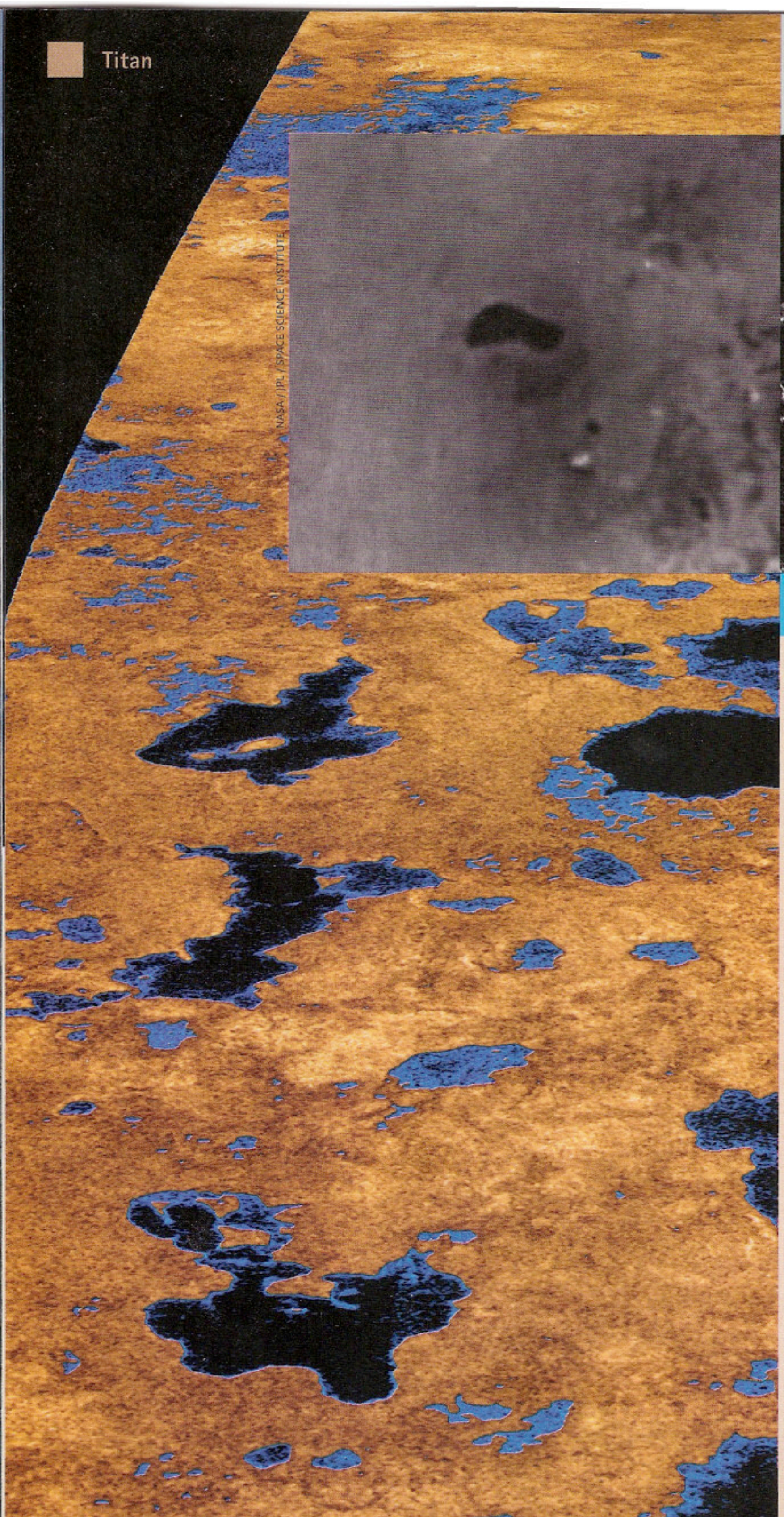
SOLID GROUND
Huygens landed on a dry plain, but the smooth, rounded rocks and moist "soil" suggest this area was recently wet. Not knowing what awaited Huygens, ESA planners equipped the probe to land safely in liquid or on solid ground. The foreground rocks are made of water ice and are about the size of a fist.



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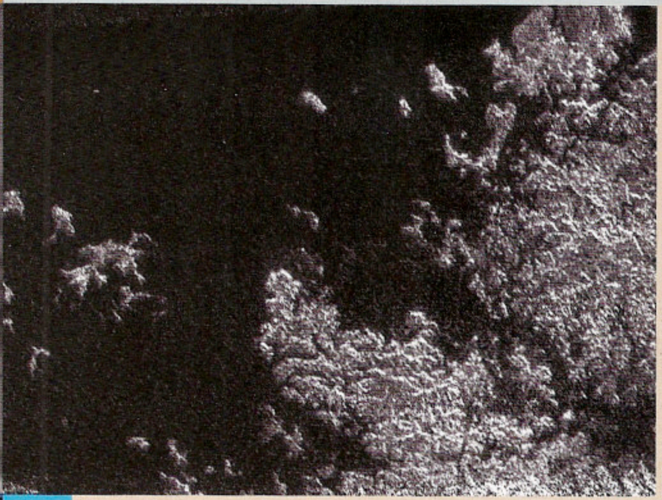


NASA / JPL

LAND OF LAKES ***Left and above:*** **Cassini's radar has revealed numerous flat, smooth features, mainly at high northern latitudes, which scientists have interpreted as lakes. This view has been confirmed by recent spectral analysis. Titan and Earth are the only bodies in the solar system to have liquid bodies on their surface. The colors in the left image represent radar reflectivity, not what you'd see.** ***Above left:*** **Cassini imaged Ontario Lacus in near-infrared light. This feature is similar in size and shape to Lake Ontario, and is located near Titan's south pole. Recent spectral observations have confirmed the presence of liquid ethane.**

NASA / JPL

Splish, Splash

Huygens didn't see any surface puddles because, we now realize, it landed in Titan's equivalent of a vast desert. There are big pools of liquid on the surface — but they're in the polar regions. Cassini first spotted clusters of dark polar patches in 2005, and they've tantalized our science team ever since.

Initially the evidence for true hydrocarbon lakes was circumstantial. They appear really dark in both radar scans and infrared images. The radar result is consistent with nearly mirror-smooth surfaces that reflect Cassini's radar emissions away from the spacecraft and out into space. The infrared darkness implies that clear liquid extends so far down that photons of light are absorbed before they can scatter off suspended particulates.

The lake hypothesis reached its splash point last December, when Cassini's Visual and Infrared Mapping Spectrometer (VIMS) got a good look at a conspicuous dark region near the south pole known as Ontario Lacus. VIMS analyzed the feature's reflectivity between 2 and 5 microns, infrared wavelengths at which the atmosphere is transparent. A handful of absorption lines match the ones expected for liquid ethane — finally, we had our long-sought "smoking gun" for fluid-filled reservoirs (November issue, page 19).

Close-ups of Ontario Lacus from that flyby also reveal what may be mudflats and a surrounding bathtub ring.

These concentric shoreline features tell us that the lake has evaporated from its greatest extent, and its level ebbs and flows over time. Recent work has shown that the northern lakes drive clouds and rain downwind of them, like lake-effect snow from the Great Lakes.

Sailing the Sandy Sea

Rain isn't the only thing falling out of Titan's sky. Much of the precipitation comes as little clots of hydrocarbon smog that slowly fall out of the atmosphere and onto the surface. Each smog particle is just 1% the width of a human hair, but mammoth drifts of this stuff has piled up over billions of years. Through a process not yet understood, these particles agglomerate into grains 250 times larger in diameter, at which point they get blown around the surface like sand on Earth.

In 2005, after Cassini's second radar pass over Titan, team scientists were immediately struck by large expanses of thin, dark streaks dubbed "cat scratches." The streaks' distinctive patterns, 1- to 2-mile separations, and 100- to 500-foot heights make them dead-ringers for the most common sand dunes on Earth.

Found abundantly in Africa's Sahara and Namib Deserts, the Arabian Desert, and in Australia, these *longitudinal dunes* form with their crests oriented parallel to the average wind direction. Winds don't blow particles up or down a dune, but rather sideways along it. On Earth, some longitudinal dunes are maintained by strong primary winds that move great volumes of sand parallel to the dune, supplemented by off-axis winds that help keep the sand piled up. In other cases, the winds come from two different directions that change seasonally.

We don't yet know which wind regime is shaping Titan's vast dune fields, but we can tell that all that hydrocarbon fluff is on the move (or has been recently). The strips of surface between the dunes are amazingly free of sand, despite their proximity to giant mountains around them. That's the signature of ongoing dune formation.

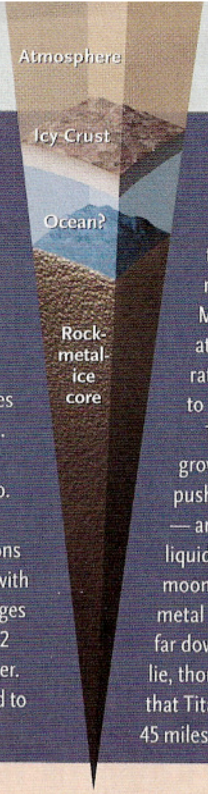
Cassini can't deduce the range of particle sizes from orbit. But given Titan's surface gravity (about one-seventh that on Earth) and atmospheric pressure (nearly 50% greater than Earth's), the particles would need to be only just a little bit larger than those found in our dunes.

We don't yet have a good handle on the particles' composition. Most sand dunes on Earth consist of silica (SiO_2), but Titan's sands must be another beast altogether. VIMS

The Spin on Titan

Last year, Titan threw Cassini's radar scientists a real curve. They were unable to match up surface features wherever one of the instrument's long image swaths overlapped another. The coordinates of a given surface feature could be off by up to 25 miles (40 km) from one swath to the next.

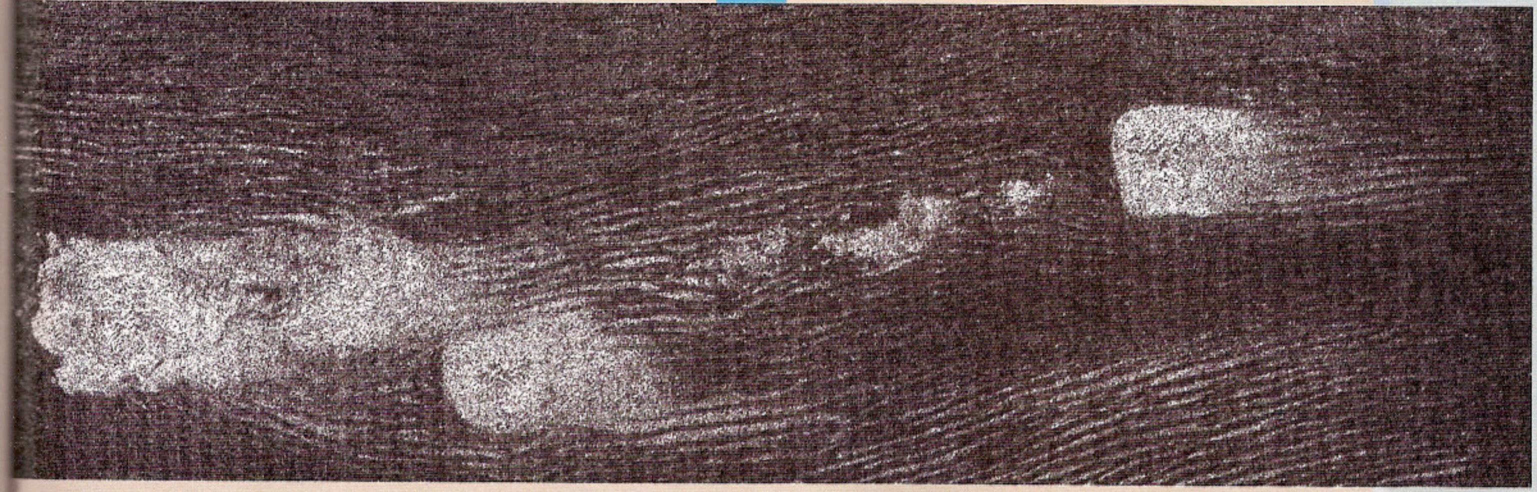
The team had assumed that Titan's obliquity (axial tilt) was zero. If instead the pole could drift by nearly a half degree, the observations fit together much better. Yet even with the revised polar tilt, the radar images continued to show offsets of up to 2 miles — and they were getting larger. Incredibly, the moon's spin seemed to be speeding up!



Tides from Saturn should force Titan to keep one hemisphere constantly facing the planet, just as the Moon's near side always faces Earth. Motions within Titan's dense atmosphere can affect the spin rate slightly, but not if they have to tug the moon's entire mass.

The only way to explain the growing mismatch is if the winds push only on Titan's icy crust — and that's only possible if a liquid-water mantle separates the moon's crust from its rock-and-metal core. We're not yet sure how far down this lubricating layer might lie, though the radar team estimates that Titan's ice crust might be about 45 miles thick.

DUNE PLANET **This radar image reveals longitudinal dunes on Titan that have similar structures to those found in terrestrial deserts. Titan's dunes are found mostly near the equator, and, unlike Earth's sand dunes, are made of solid organic particles or ice coated with organics.**



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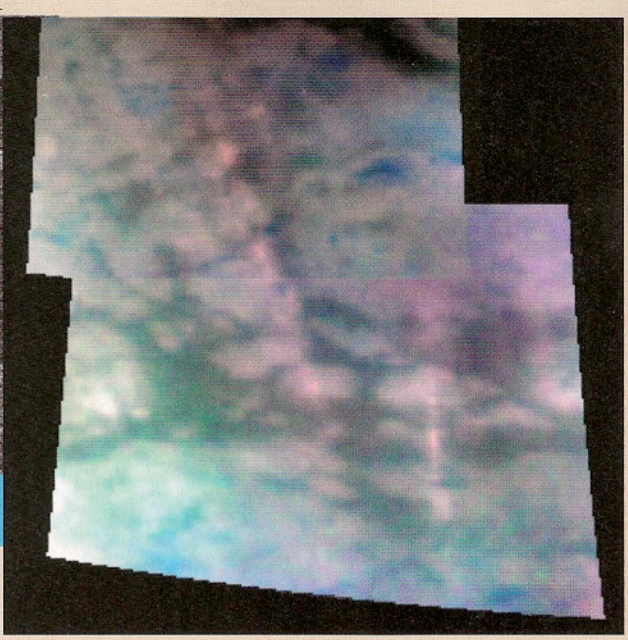

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MOUNTAIN RANGES ***Above:*** **Cassini's radar has found numerous mountain ranges that are similar in scale to the Appalachians in eastern North America.** ***Right:*** **This composite VIMS image from Cassini reveals a 100-mile-long range just south of the equator. The origin of these structures remains unknown.**

spectra suggest some kind of organic composition. Imagine mountains of coffee grounds hundreds of feet high!

The global maps built from Cassini's dozens of close Titan flybys reveal that these sand "seas" straddle the equator and cover about 20% of Titan's surface. By comparison, dunes cover only 1% of the "desert world" Mars and only 6% of Earth's dry land.

Much Ado About Mountains

If you had taken a poll of planetary scientists before Cassini reached Saturn, few would have bet that the orbiter would discover mountains on Titan. But the orbiter has found not just isolated peaks, but entire ranges. Most are between 2,000 and 7,000 feet high, similar to the elevations of the Appalachians in the eastern U.S.

Given that the mountains consist of ice, these somewhat modest peaks are rather substantial, and their heights help us to constrain the nature of Titan's crust. Some ranges might be large blocks ejected by large impacts. Others form true ranges, tens of miles wide and hundreds long. Mountain chains are ubiquitous on Earth, thanks to plate tectonism, but they're rare elsewhere in the solar system. Some kind of crustal upheaval within Titan must have created these mountain chains — and may still be building them — though the cause remains unknown.

The set of mountains at 40° south, near a dark region called Senkyo, may be large enough to influence Titan's weather. As winds blow over these peaks, the rising moist air cools and generates clouds, and ground-based observers have noticed that thunderstorms preferentially gather at this latitude. Nearer the equator, winds deviate around mountains and fashion dune crests that resemble streamlines around a raindrop.

With all of this churning, blowing, and precipitating, geologists wouldn't expect to see many impact craters on Titan — and, in fact, they're surprisingly rare. The few that we can identify are being eroded away, covered up, or both. In reality, Titan has probably experienced just as many large impacts as have its sister moons, such as heavily cratered Rhea. But geologic activity has erased all the old scars over the intervening eons and has nearly removed more recent ones.

Despite these leaps in knowledge, our exploration of Titan remains in its infancy, roughly matching what we knew about Mars following Mariner 9's pioneering flight more than 35 years ago. Cassini remains in excellent health, and we're hoping the mission continues to fill the gaps in our understanding until it runs out of propellant or funding, whichever comes first.

After that, the future exploration of Titan is an open book. Scientists are looking to bundle an orbiter, lander, and hot-air balloon on a single mission that could be mounted a couple of decades from now. But given Titan's many similarities to Earth, it's not hard to imagine future astronauts — ice picks in hand — chipping away at an icy outcrop and scooping up samples of Titanian coffee grounds for analysis. ✦

AN ABODE FOR LIFE?

Titan's surface abounds with organic molecules and water ice, but its frigid temperatures offer bleak prospects for life. At Titan's –290°F (–179°C) surface temperatures, chemical reactions slow to a crawl, limiting the ability of complex molecules to form. But Titan's interior is warm enough to sustain liquid water. Given the plethora of life's building blocks on Titan, scientists cannot rule out the possibility that the moon harbors biological activity deep underground.

Now an assistant professor of physics at the University of Idaho, ***Jason Barnes*** *has worked with Cassini's VIMS team for three years.*