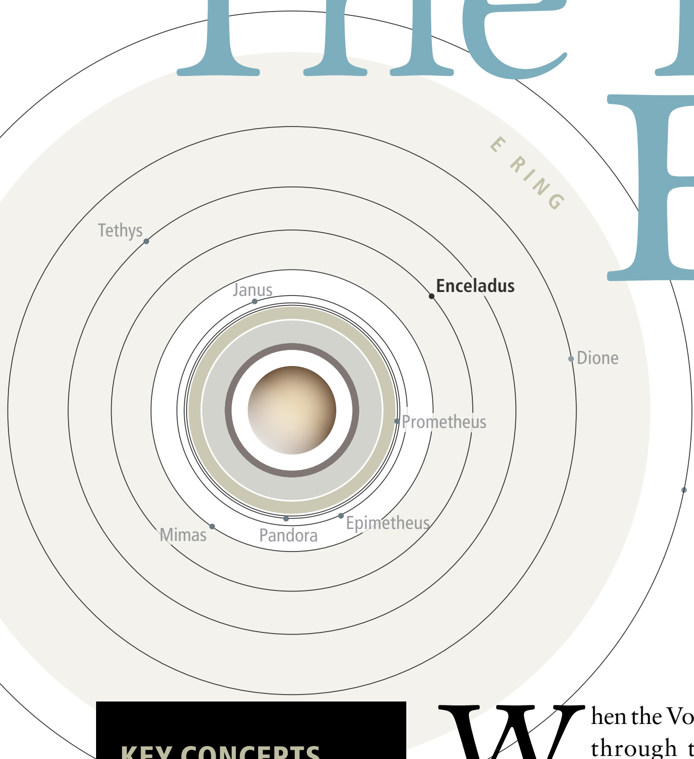
The Restless ENCEL



Wrinkled landscapes and spouting jets on Saturn's sixth-largest moon hint at underground waters

By Carolyn Porco

KEY CONCEPTS

- On the Saturnian moon Enceladus, jets of powdery snow and water vapor, laden with organic compounds, vent from the "tiger stripes," warm gashes in the surface. How can a body just over 500 kilometers across sustain such vigorous activity?
- The answer may be the presence of underground fluids, perhaps a sea, which would increase the efficiency of heating by tidal effects. Support for this idea has come from recent flybys.
- If Enceladus has liquid water, it joins Mars and Jupiter's moon Europa as one of the prime places in the solar system to look for extraterrestrial life.

—The Editors

When the Voyager 2 spacecraft sped through the Saturnian system more than a quarter of a century ago, it came within 90,000 kilometers of the moon Enceladus. Over the course of a few hours, its cameras returned a handful of images that confounded planetary scientists for years. Even by the diverse standards of Saturn's satellites, Enceladus was an outlier. Its icy surface was as white and bright as fresh snow, and whereas the other airless moons were heavily pocked with craters, Enceladus was mantled in places with extensive plains of smooth, uncratered terrain, a clear sign of past internally driven geologic activity. At just over 500 kilometers across, Enceladus seemed far too small to generate much heat on its own. Yet something unusual had clearly happened to this body to erase vast tracts of its cratering record so completely.

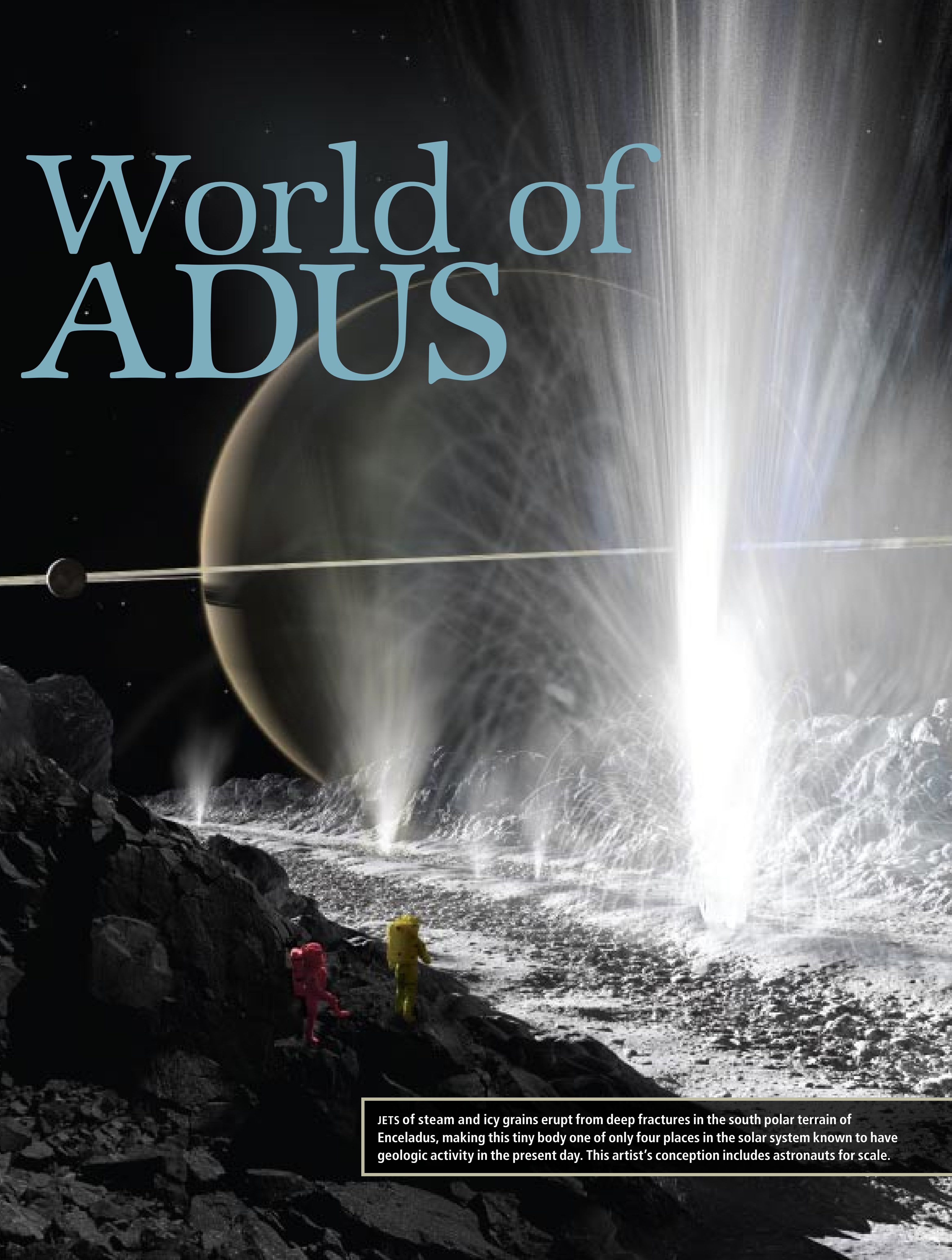
Voyager's brief encounter allowed no more than a cursory look, and, in hindsight, its imaging coverage of Enceladus was terribly unfortunate: a few medium-resolution images of the northern hemisphere, some low-resolution coverage in the south, and none of the south pole. We had no idea what we had missed.

The interest generated by Voyager's visit made a comprehensive examination of Enceladus a cardinal goal of the Cassini mission to Saturn. Launched in 1997, Cassini spent seven long years crossing interplanetary space carrying the most sophisticated suite of instruments ever taken into the outer solar system. It finally pulled into port in the summer of 2004 [see "Saturn at Last!" by Jonathan I. Lunine; Scientific American, June 2004]. In December of that year it dropped a probe into the atmosphere of Titan, Saturn's largest moon, and then commenced its tour of the rest of the Saturnian system—not least Enceladus, which it has examined more closely than ever over the past several months.

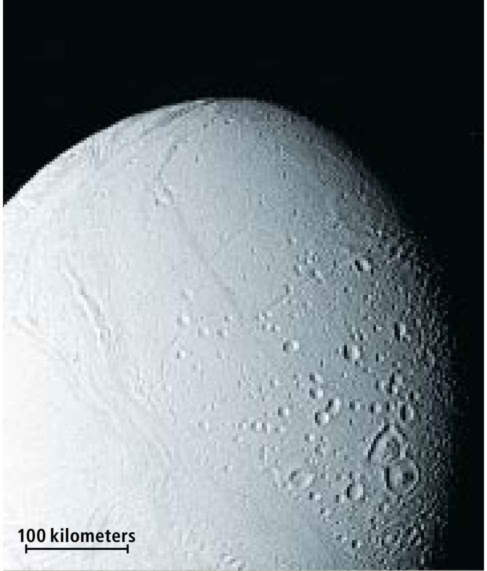
What it found on this tectonically wracked little world has been a planetary explorer's dream, and now this tiny outpost tucked deep within a magnificent planetary system clear across the solar system has taken on a significance that belies its diminutive size. Enceladus not only has enough heat to drive surface-altering geologic activity but also is endowed with organic compounds and possibly underground channels or even seas of liquid water. Energy, organics, liquid water: these are the three requisites for life as we know it. In our explorations of this alien and faraway place, we have come face to face with an environment potentially suitable for living organisms. It does not get much better than this.

RON MILLER

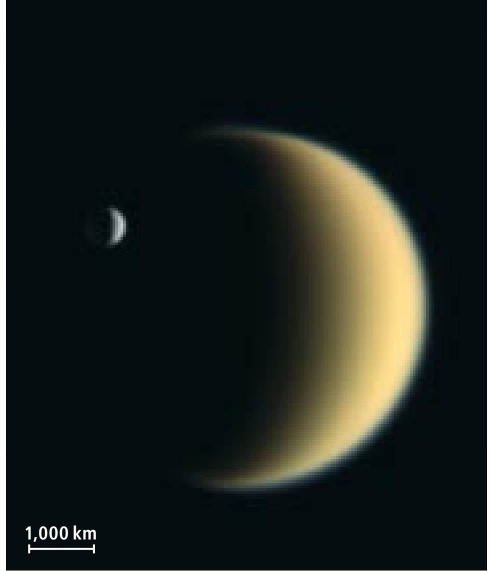
World of ADUS



JETS of steam and icy grains erupt from deep fractures in the south polar terrain of Enceladus, making this tiny body one of only four places in the solar system known to have geologic activity in the present day. This artist's conception includes astronauts for scale.



FIRST FLYBY of Enceladus, by the Voyager 2 spacecraft in 1981, produced images of limited coverage and mediocre resolution. The smooth areas indicated geologic activity in the recent past.



ENCELADUS (*left of center*) is a tenth the size of Saturn's largest moon, Titan. Bodies of its size lose their internal heat quickly; apart from Enceladus, they are all geologically dead. What keeps Enceladus active?

The Slow Reveal of Enceladus

The first hint, not unanimously appreciated at the time, that we were in for something very big emerged even before Cassini's first close encounter with Enceladus. In January 2005 our cameras took the first images of the moon backlit by the sun, a viewing geometry that planetary astronomers call high solar phase. Just as the dust that coats your car's windshield becomes dramatically more visible when you drive into the sun, so do the very fine particulates that are spread throughout the solar system when you look through them toward the sun. These viewing circumstances had proved very successful throughout the Voyager mission in revealing hard-to-see structures in rings and atmospheres of the outer planets and their moons, and they were key to the investigation of Enceladus.

The January images showed a flare protruding from the moon's south polar limb. No one needed to say it; we Voyager veterans were immediately reminded of the volcanic plumes rising above Jupiter's volcanic moon Io and the gossamer hazes in the atmosphere of Neptune's moon Triton. Some on the imaging team were convinced the flare was hard evidence that material was erupting from the south pole; others cautioned that the feature was probably one of those annoying camera artifacts that often turn up under sunward-facing conditions.

I was on the fence. Unfortunately, we were all too busy with planning future observations and writing scientific papers to undertake the kind of detailed analysis that might settle the matter. With no time for verification, I made the decision to say nothing publicly; I knew too well how embarrassing it would be to announce a discovery of a plume of material leaping off the surface of a moon that was supposed to be geologically dead, only to have to admit soon thereafter it was a smudge. Fortunately, we did not have long to wait.

The first two close flybys of Enceladus, in February and March, took the spacecraft sailing above and along the equator of Enceladus. Both returned spectacular results. The smooth plains seen by Voyager are not smooth at all. Instead they are extensively and finely fractured at subkilometer scales, in places crisscrossed by multiple generations of fractures and grooves, some linear, some curved. In other places, the surface is deeply scored with chasms half a kilometer deep. On an even finer scale, a spidery network of roughly parallel narrow cracks slices topographic forms into slabs. Enceladus has obviously seen multiple and distinct episodes of severe tectonic activity in its past—and has the scars to prove it.

The February flyby produced yet another high-solar-phase image showing a flare bigger and more dramatic than before. In addition, the magnetometer noticed that Saturn's magnetic field lines were being distorted as the planet's rotation carried them past Enceladus—a sign that the field lines were picking up heavy ions. The source of the ions appeared to be the moon's south pole. The evidence was mounting: our imaging artifacts were beginning to look like anything but.

The Cassini scientists presented the case to the project managers to get a better look—specifically, to lower the altitude of the July 2005

[THE AUTHOR]

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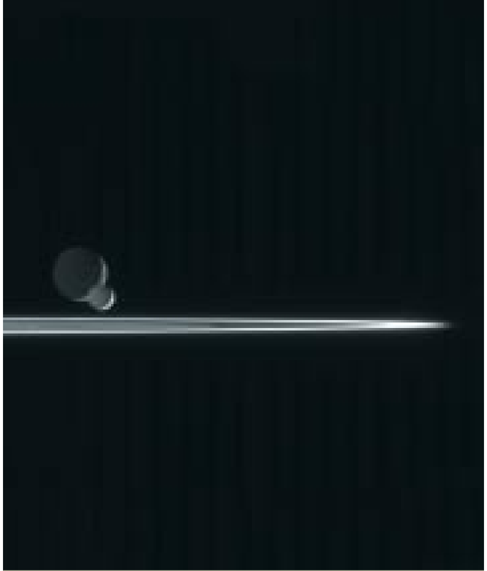
COURTESY OF CAROLYN PORCO AND ILM (*author and E.T.*); NASA/JPL/SPACE SCIENCE INSTITUTE (*Enceladus/Titan*)



AS SEEN FROM CASSINI spacecraft, Enceladus slips in front of Dione, a larger and more distant moon whose gravity indirectly helps to drive Enceladus's activity. The outer part of Saturn's rings is in the foreground.

flyby from 1,000 kilometers to 168 kilometers. They agreed. On July 14, Cassini flew under the moon and over its high southern midlatitudes, giving us for the first time a clear view of the south pole, where lies a landscape as astonishing and geologically distinct as any seen anywhere in our solar system.

The terrain capping the south pole is a roughly circular region, completely crater-free and prominently etched by a handful of deep, parallel cracks we dubbed the "tiger stripes." Nearly evenly spaced, they run for 130 kilometers and terminate in hook-shaped bends. In between the stripes are brighter than average plains of finely grooved terrain, and the entire region is sharply demarcated at 55 degrees south latitude by a contiguous and meandering circumpolar boundary of concentric mountains and valleys. The boundary's meanders are spaced roughly every 45 degrees in longitude, with long cracks extending from some toward the equator into largely uncratered provinces.

The structure and placement of the mountains and valleys suggested to imaging team associate Paul Helfenstein of Cornell University that the boundary formed when the surface buckled as it was compressed horizontally along the north-south direction, like a convergent tectonic boundary resembling the Himalaya, and that the entire enclosed region is the Enceladus equivalent of the mid-Atlantic ridge—a spreading center where new surface is formed and pushes outward.

There is obviously a tale writ on the countenance of this little moon that tells of dramatic events in its past, but its present, we were about to find out, is more stunning by far. In its excursion over the outskirts of the south polar terrain, Cassini's dust analyzer picked up tiny particles, apparently coming from the region of the tiger stripes. Two other instruments detected water vapor, and one of them delivered the signature of carbon dioxide, nitrogen and methane. Cassini had passed through a tenuous cloud.

What is more, the thermal infrared imager sensed elevated temperatures along the fractures—possibly as high as 180 kelvins, well above the 70 kelvins that would be expected from simple heating by sunlight. These locales pump out an extraordinary 60 watts per square meter, many times more than the 2.5 watts per square meter of heat arising from Yellowstone's geothermal area. And smaller patches of surface, beyond the resolving power of the infrared instrument, could be even hotter.

By now we could not believe our good fortune to have stumbled on such a fascinating place. In quick response, the imaging team planned a special series of images to be taken in four months' time—late November 2005—looking over the south pole at high resolution and very high solar phase. In the meantime, a sufficient number of images of other moons, seen at similarly high phase, had accumulated, and with the help of image analysts in my group, I proved to the skeptics on our team that these had no flares whatsoever, and what we had on Enceladus was decidedly not an

DATA BANK: ENCELADUS

Mass: **1.08** × **10^{20}** kilograms

Diameter: **504** kilometers

Density: **1.61** grams per cubic centimeter

Average orbital distance from Saturn: **238,037** km

Orbital period: **1.37** days

Eccentricity: **0.0047**

Inclination to Saturn's equator plane: **0.0083** degrees

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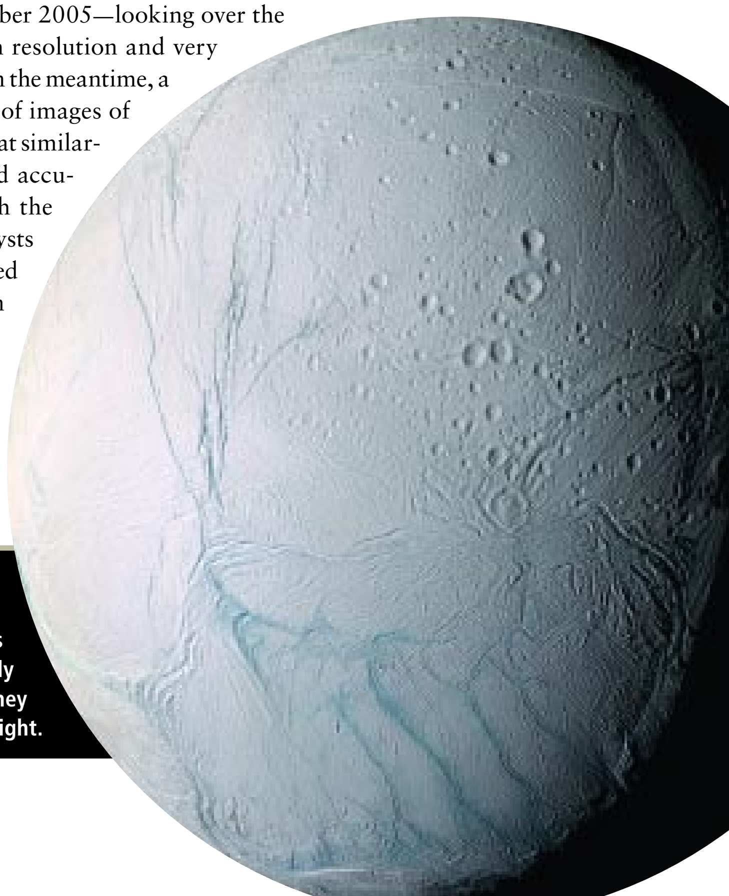
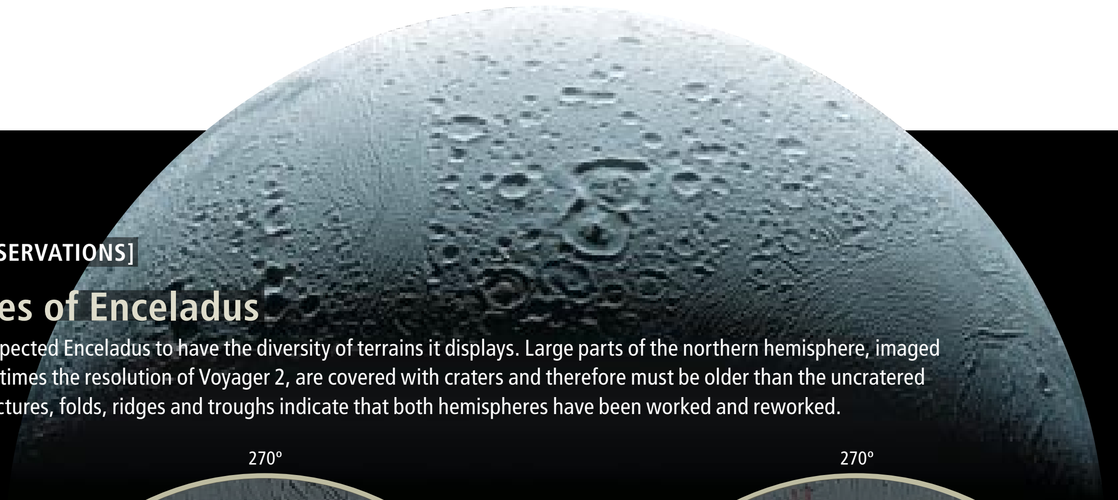


SOUTHERN HEMISPHERE of Enceladus was revealed by Cassini for the first time in 2005. This mosaic of images shows the surface as it would appear if our vision extended into the infrared and ultraviolet. (To the unaided eye, the surface looks uniformly white.) The "tiger stripes" near the bottom are warm, geologically active gashes across the south polar terrain. Their bluish colors arise because they are coated with larger than average ice grains that absorb infrared light.

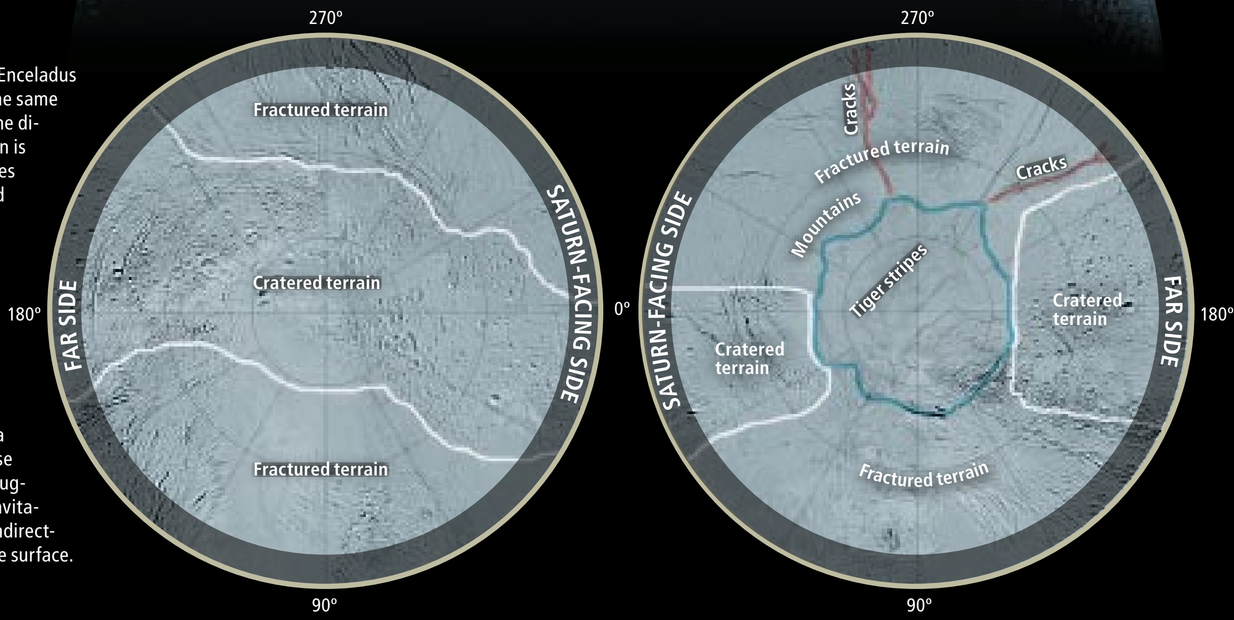
[CASSINI SURFACE OBSERVATIONS]

The Many Faces of Enceladus

Few planetary scientists expected Enceladus to have the diversity of terrains it displays. Large parts of the northern hemisphere, imaged by Cassini (*above*) with six times the resolution of Voyager 2, are covered with craters and therefore must be older than the uncratered south polar terrain. But fractures, folds, ridges and troughs indicate that both hemispheres have been worked and reworked.



Like Earth's moon, Enceladus always presents the same face to its planet; the direction toward Saturn is defined as 0 degrees longitude. Cratered regions lie along the Saturn-Enceladus axis (at 0 and 180 degrees); fractured regions are perpendicular to it (90 and 270 degrees). The tiger stripes straddle the south pole and are surrounded by a mountain chain. These special orientations suggest that Saturn's gravitational influence has indirectly helped mold the surface.



Northern hemisphere

Southern hemisphere

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artifact. Our fence-sitting days were over as we all realized we were looking at a plume of tiny particles that was absolutely gargantuan, extending at least several hundred kilometers above the moon's south pole.

On November 27 our series of striking black-and-white images of a crescent Enceladus finally arrived and showed, clear as day, a dozen or more distinct and narrow fountains of fine, icy particles jetting into space and feeding a faint but giant, flame-shaped plume towering over the south polar region. Later analysis by imaging team associate Joseph Spitale of the Space Science Institute and me showed that the jet sources coincide with the hottest locations on the tiger stripes—the first definitive evidence of a connection between warmth and active venting. Most of the particles fall back to the surface, but some have sufficient velocity to go into orbit around Saturn and are in fact responsible for creating its outermost ring, known as the E ring.

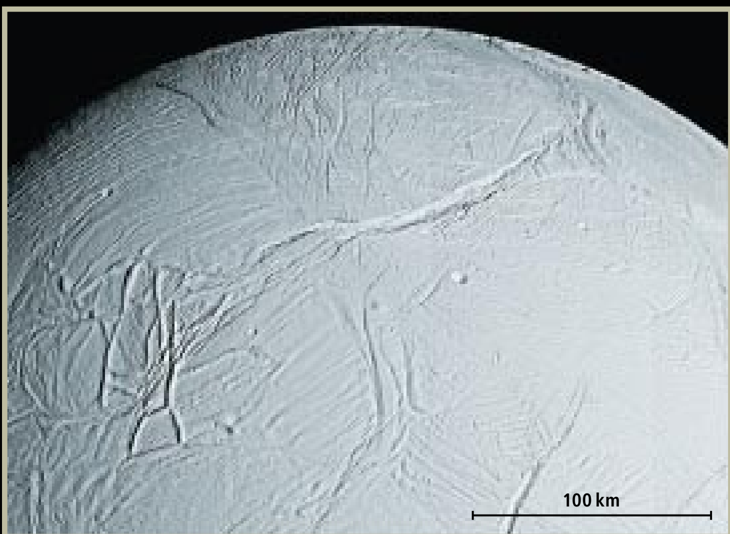
By anyone's measure, these images were a dramatic find: an incontrovertible indicium of current internal activity on an otherwise cold little moon. I could not help but feel an immediate kinship with those long ago who first set eyes on the geysering turmoil of Yellowstone.

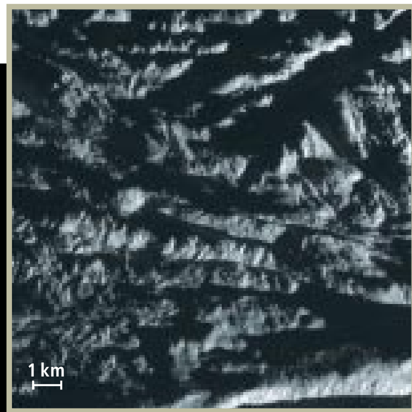
Turning Up the Heat

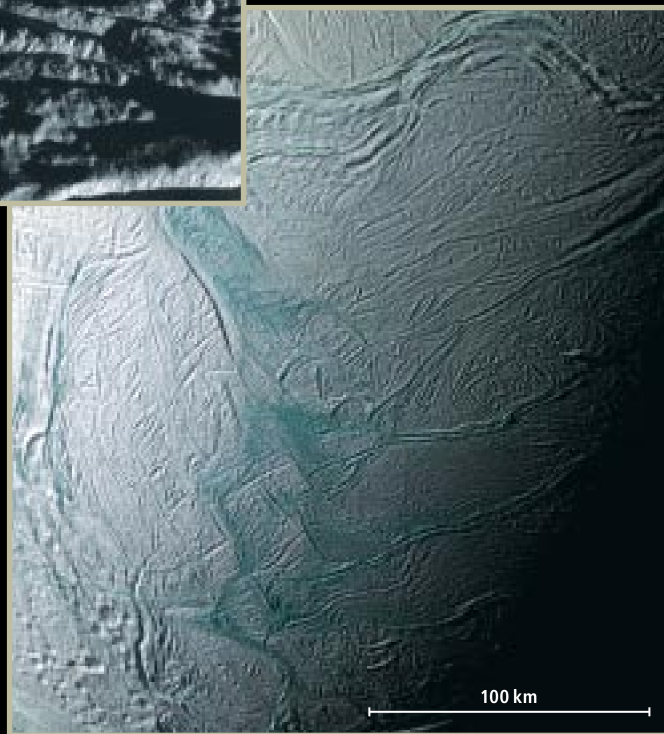
The first Cassini science papers on Enceladus were published in early March 2006, and the craze began. Everyone began talking Enceladus. Cassini has since made a number of flybys of Enceladus, penetrating deeper into denser regions of the plume, reaching as low as 25 kilometers' altitude. During one very low flyby this past March, Cassini refined its measurements of the water vapor, nitrogen, carbon dioxide and methane, and, in addition, it discovered a smattering of other carbon-bearing compounds, such as acetylene and hydrogen cyanide, as well as trace amounts of ethane, propane, benzene, formaldehyde and other organics.

During another very close flyby in August, our cameras focused on the surface sources of the jets. The spacecraft's flyover was so fast that

On close inspection by Cassini, large regions on Enceladus that looked smooth to Voyager are actually highly textured (*below*). Deep chasms extend northward into fractured terrains. Even craters are fractured, sliced and often degraded (*left*).







Close-up of the tiger-stripe region shows blocks of ice the size of houses (*top*). Surrounding the stripes is a sinuous circumpolar chain of mountains that may be the Enceladan tectonic equivalent of the Himalaya (*above*).

a special camera-panning technique, akin to skeet shooting, had to be devised to avoid motion smear. Perfectly executed, the sequence revealed the tiger stripes to be as deep as 300 meters, with V-shaped walls and blocks of ice the size of houses strewn across their flanks and beyond. Areas along the flanks appear smoother than average—probably blankets of freshly fallen snow.

Unexpectedly, the immediate vicinity of each vent is not obviously distinguishable from other places along the fractures. We preliminarily concluded that no one vent stays active very long. Ice plugs grow from condensing vapor and choke off the vent before it can significantly alter the ground around it. At that point, pressure forces open a new vent somewhere else along the fracture, it, too, becomes choked off, and on it goes. A long time-lapse movie might show migration of jets up and down long linear extents of the fracture.

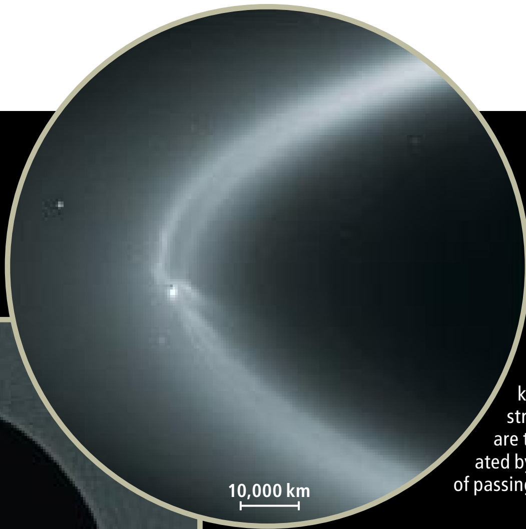
Apart from giving us a window on a breathtaking geologic phenomenon, the images have also yielded precise measurements of Enceladus's size and shape. Together with the moon's mass, derived from its gravitational perturbations to Cassini's trajectory during their close encounters, this information has revealed that Enceladus is the rockiest of Saturn's major moons. Its average density of 1.6 grams per cubic centimeter implies that rock is 60 percent of the moon's mass, and chances are good that the rock is concentrated in a rocky core surrounded by a mantle of water ice several tens of kilometers thick.

On Earth, rock contains radioactive substances that produce heat. The same is undoubtedly true on Enceladus. But even all that rock is insufficient to produce the observed heat. The only other plausible source of warmth is tidal heating. Just as the gravity exerted by the sun and Earth's moon deforms our planet slightly, creating the ocean tides, Saturn's gravity deforms Enceladus. Enceladus has a noncircular orbit; its distance from Saturn varies. The closer it gets, the more it is deformed. This daily varia-

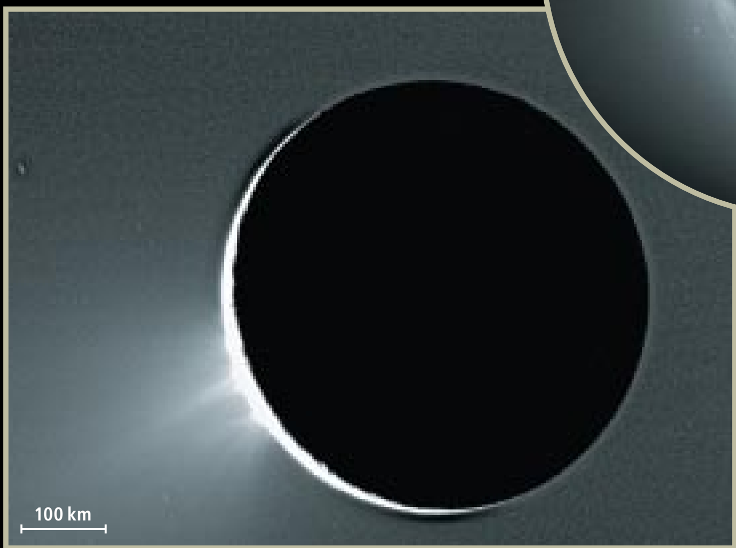
[CASSINI GEYSER OBSERVATIONS]

Hot Springs on a Cold Moon

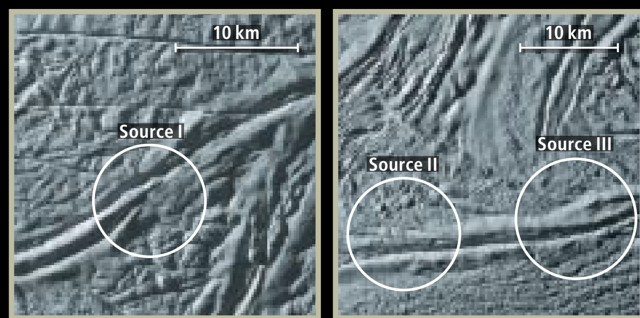
Shooting out of the south pole are jets of material, which feed a broad, towering plume.



The jets feed Saturn's E ring, as Cassini saw from a distance of about two million kilometers. Some of the long, tendril-like structures seen in the vicinity of Enceladus are the extensions of the jets. Others are created by Enceladus's gravitational perturbations of passing particles in the E ring.



The tiny, icy grains sprayed into space are easiest to see when backlit by the sun. Mountains and valleys are visible along the edge of this silhouette.



The jets can be traced to specific locations on the tiger stripes. Oddly, these locations do not obviously differ from other parts of the stripes.

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tion gives rise to flexure and internal heating. Gravity may also play a role in forming the surface features. The tiger stripes are angled 45 degrees from the direction to Saturn—an orientation that tidal forces would naturally explain.

The magnitude of heating depends not only on the orbital eccentricity—the degree to which the orbit departs from a perfectly circular shape—but also on the consistency of the moon's interior. A very rigid body would resist deformation. A perfectly elastic body would deform but not dissipate energy as heat. A pliable moon consisting of viscous material would yield and heat up, as would a moon that is partly rigid but shot through with cracks, so that slabs of ice rub against one another and generate heat by friction. The heating need not occur uniformly throughout the moon. It can be concentrated in the outer shell of ice or in limited regions within the outer shell such as cracks.

Typically tidal heating tends to shut itself off. The material in a moon takes time to deform, so the distortion is always out of alignment with the forces that produce it. The result is a gravitational torque that alters the moon's orbital motion and gradually circularizes the orbit. The tidal stresses stop varying, the moon settles into a fixed shape, and heating ceases. Enceladus, however, remains in an elliptical orbit because of an orbital resonance with its bigger sibling moon Dione. For every two orbits Enceladus makes, Dione makes one. This synchrony allows periodic gravitational kicks from Dione to act coherently over time and keep Enceladus's orbit out-of-round.

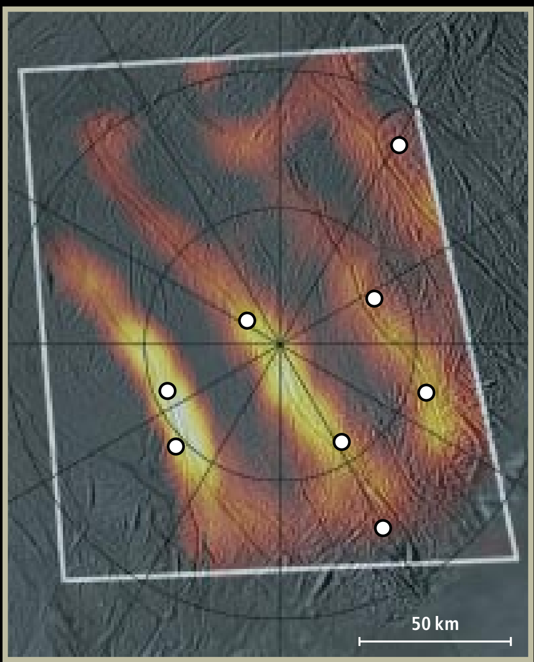
Yet even these special circumstances are not enough. Jennifer Meyer and Jack Wisdom of the Massachusetts Institute of Technology have examined the orbital configuration of Enceladus and found that the amount of tidal energy being injected into the body falls short of the energy coming out of Enceladus's south pole by a factor of five. This result is completely independent of how tidal energy is internally dissipated. Enceladus, in its present orbit, simply lacks enough energy to explain its heat output.

The Silly Putty Moon

The paradox arises only if you assume that Enceladus's present-day tidal heating should precisely match its present-day heat output. What if Enceladus is still giving off heat from an earlier heating episode? One possible scenario, first examined in 1986 for Io by Greg Ojakangas and David Stevenson, both then at the California Institute of Technology, is that the orbit of a

LIFE ON ENCELADUS?

Enceladus has three of the essential requirements for life: liquid water, organic compounds and energy. Have these putative habitable conditions persisted long enough for life to develop there? No one knows how long it would take. Judging from the geologic record, microbes emerged on Earth very quickly in geologic terms: within a few hundred million years (or even sooner) after the planet's final throes of formation.



A thermal map shows temperatures up to 180 kelvins along the stripes, much too hot to be explained by solar heating. The jets originate in the very hottest regions (*white circles*).

moon and the consistency of its interior can play off each other, leading to a cyclic variation of both orbital eccentricity and heat output.

Imagine starting with a cold, mostly rigid Enceladus in a nearly circular orbit. The rate of tidal heating is relatively low. Dione forces the orbital eccentricity to increase, which leads to greater flexure and viscous heating in the ice shell. The eccentricity and heating continue to increase until, at some point, the heating rate exceeds the ability of the moon to lose its heat. The internal temperature then starts to rise, and the interior material becomes softer and less rigid, which leads to yet more tidal heating. In another possible oscillatory scheme, the moon becomes less rigid not because it becomes more pliable but because cracks develop. Tidal stresses fracture the ice and cause shear motions. Friction between the crack surfaces leads to tidal energy dissipation and heating along the cracks.

In either case, the additional dissipation causes the moon's orbit to become more circular, and eventually the trend reverses; tidal heating begins to decrease and eventually falls below the rate of heat loss from the surface. The moon begins to cool off and either the ice returns to being stiff or, in the second scenario, the cracks heal. The cycle, which can take tens of millions of years, then begins anew. The idea illustrates how we might happen on a moon at a time when its heat input and output are not in a steady state. In such an oscillatory scheme, the energy input and output balance only over the full cycle. At any given instant, the moon's heat output might be found to be above or below average—and above or below its instantaneous heating rate.

Ojakangas and Stevenson have shown that a cycle mediated by the temperature dependence of the viscosity of ice may work for Io, which, like Enceladus, has a mismatch of heat input and output. Unfortunately, it cannot work for Enceladus: Meyer and Wisdom have concluded that the moon is not sufficiently massive. The crack-mediated cycle may be possible but has yet to be fully investigated.

What Lies Beneath?

Gabriel Tobie of the University of Nantes in France and his collaborators have examined another possible solution: that a zone of weakness at the south pole can focus tidal energy there and sustain itself through time. They simulated the response of Enceladus to tidal forcing assuming that underlying the south pole is a sector of low viscosity, making this part of Enceladus more pliable than the rest. This model can reproduce the observed heat output, but only under two conditions that revolutionize our view of Enceladus.

First, the ice in the zone must be warm—near its melting point—and, second, there must be a liquid layer wedged between the overlying ice shell and the rocky core. This layer must underlie nearly the entire southern hemisphere. Without it, not only would flexure and hence viscous heating be insufficient, it would tend to occur at the equator rather than the pole.

The idea of a subsurface sea becomes all the more compelling when one considers that Enceladus's south polar cap is actually a half-kilometer-deep basin carved into the moon's overall figure. According to work by Geoffrey Collins of Wheaton College and Jason Goodman of the Woods Hole Oceanographic Institution, this basin could be the surface expression of a subsurface sea. Liquid water is denser than ice, so the total volume of water in this region is lower. In essence, the entire south polar region is a giant sinkhole.

In fact, a sea could indirectly account for much of Enceladus's geologic diversity. Isamu Matsuyama of the Carnegie Institution of Wash-

WHY THE SOUTH POLE?

How did geologic activity on Enceladus come to be concentrated at the south pole? Chance may be the answer. Perhaps an event in the moon's past—a meteor impact into the moon, like those that created the huge basins on other moons of Saturn, such as Iapetus and Tethys—initially cracked or otherwise weakened its outer ice shell, focusing tidal energy there. The ice shell might then have slid around over time in a process known as true polar wander, in which case centrifugal forces would have shifted low-density regions to the poles. Paul Helfenstein of Cornell University has found evidence for such movement: a region called Sarandib Planitia near the equator looks like an eroded version of the south polar terrain. It might once have been at the pole and since moved to its present location.

ington and Francis Nimmo of the University of California, Santa Cruz, have shown that the position and orientation of the moon's major geologic features—in particular, the north-south trending cracks and the circumpolar mountains—are a sign that the moon's ice shell has slipped relative to its spin axis. The moon acts like a giant gyroscope whose outer shell is free to pivot around.

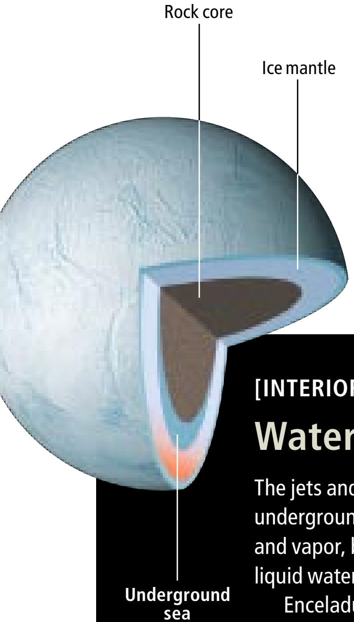
This idea would explain why the geologically active region is exactly at the south pole: a warm region, with lower than average density, will naturally drift toward the axis of rotation. Furthermore, a warmer zone under the south pole would rise in convective motion under the uppermost brittle layer of the ice shell, explaining the spreading-center characteristics of the south polar terrain. For the ice shell to move in this way requires a liquid layer to decouple the ice from the deeper interior.

The full cause of Enceladus's activity may be a combination of these effects. If Enceladus undergoes a crack-mediated heating cycle and if the rate of tidal deformation of the moon's outer ice shell is fast enough, cracks may propagate into the underlying ductile warm zone and perhaps all the way down to the sea. Frictional heating within these fractures would contribute to the overall viscous heating under the south pole. Ice might melt along the deep cracks, and the meltwater would substantially enhance the heating rate. In this way, an underground sea might be self-sustaining, with the liquid water in the overlying shell supplying the sea below. As long as the sea never completely freezes during the cooling phase of the cycle, the whole process would continue as long as Enceladus remains in orbital synchrony with Dione.

To top it off, liquid water could naturally account for the observed eruptions. Michael Manga of the University of California, Berkeley, has shown that partial freezing of an underground sea would increase its pressure and force liquid up. As the pressure is released on ascent, dissolved gases such as carbon dioxide would come out of solution and form bubbles, which, like shaking a bottle of champagne, can assist the rising liquid. If liquid is indeed making it all the way to the surface, it provides a ready answer to the question of how heat gets from where it is produced, deep within the moon, to the surface: flowing water is very efficient in carrying heat. It also implies that the jets in fact are geysers and originate in subterranean liquid reservoirs.

Enceladus as the Abode of Life

We are still testing and refining our notions about how Enceladus has come to be the way it is. But in all, it is almost unavoidable that liquid water is present somewhere below its surface. If so, we face the thrilling possibility that within this little moon is an environment where life, or at least its precursor steps, may be stirring. Everything life needs appears to be available: liquid water, the requisite chemical elements and excess energy. The best analogues for an Enceladan ecosystem are terrestrial subsurface volcanic strata where liquid water circulates around hot rocks, in the complete absence of sunlight and anything produced by sunlight. Here are found organisms that consume either hydrogen and carbon dioxide, creating methane, or hydro-

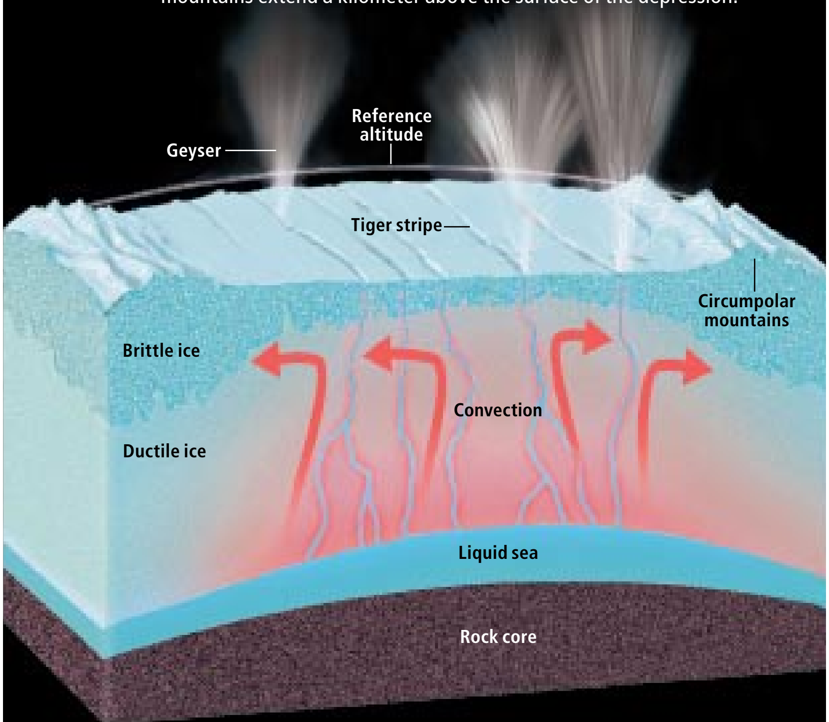


[INTERIOR OF ENCELADUS]

Waterworld

The jets and warm temperatures strongly suggest that Enceladus has underground liquid water. Not only do the jets spout water ice particles and vapor, but the intense heating that drives them seems to require liquid water to facilitate tidal energy deposition by Saturn.

Enceladus may consist of a rock core surrounded by a thick layer of water ice. The entire south polar area is a half-kilometer-deep depression in the moon's figure, perhaps the result of a subsurface sea. Circumpolar mountains extend a kilometer above the surface of the depression.

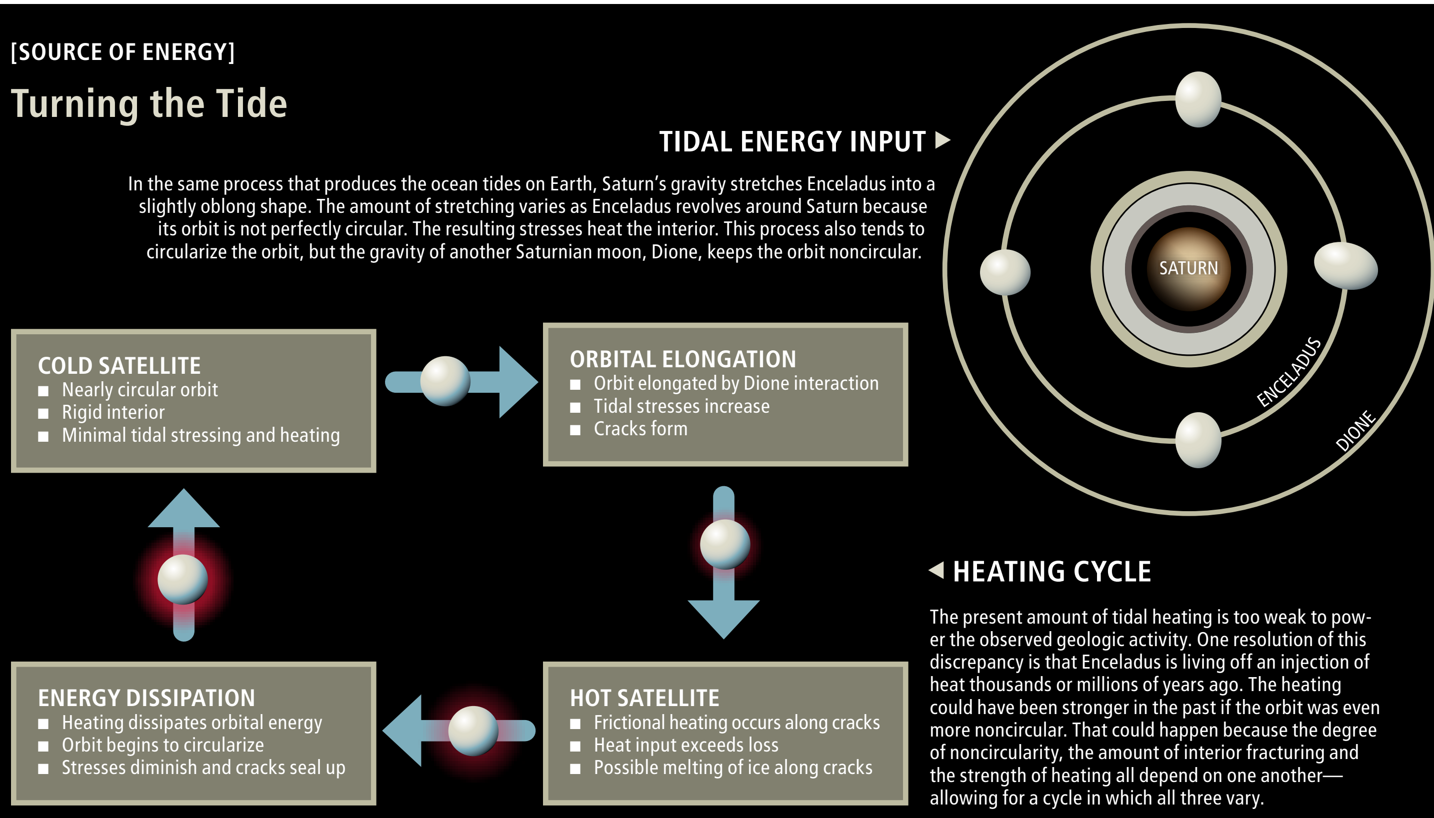


From a liquid sea at the base of the ice, water under pressure, helped by dissolved gases, could flow up through deep cracks and vent at the surface. Friction within the cracks might create enough heat to melt ice. Convection currents below the south polar terrain could cause the surface to spread outward and create the circumpolar mountains.

RON MILLER

[SOURCE OF ENERGY]

Turning the Tide



TIDAL ENERGY INPUT In the same process that produces the ocean tides on Earth, Saturn's gravity stretches Enceladus into a slightly oblong shape. The amount of stretching varies as Enceladus revolves around Saturn because its orbit is not perfectly circular. The resulting stresses heat the interior. This process also tends to circularize the orbit, but the gravity of another Saturnian moon, Dione, keeps the orbit noncircular.

HEATING CYCLE The present amount of tidal heating is too weak to power the observed geologic activity. One resolution of this discrepancy is that Enceladus is living off an injection of heat thousands or millions of years ago. The heating could have been stronger in the past if the orbit was even more noncircular. That could happen because the degree of noncircularity, the amount of interior fracturing and the strength of heating all depend on one another—allowing for a cycle in which all three vary.

MELISSA THOMAS

gen and sulfate—all powered not by the sun but by Earth's own internal heat.

The Enceladus of today is very much the child of yesterday, and we are only just beginning to assemble its past from the precious clues littered on its surface. Many questions remain that even Cassini, as capable as it is, cannot answer—questions that are and will remain beyond our reach until we set a specially equipped spacecraft in orbit around the moon or a lander down on its surface. An orbiter could fully map the moon's gravity field and surface topography, revealing its internal distribution of mass, including any subsurface liquid layer. A small lander, equipped with a seismometer, could detect the rumblings of underground liquids.

The sheer cost and long development time of complex missions mean we have to be very selective in where we go. Many scientists are eager to return to Europa, because this moon of Jupiter is also apparently endowed with a subterranean ocean that could harbor extraterrestrial life [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; Scientific American, October 1999]. To my mind, however, further exploration of Enceladus is so much more promising. Because scientists do not know of any active vents on Europa, sampling its interior to test for the presence of an ecosystem would require drilling to great depths, an enterprise so challenging it will surely not happen in our lifetime. By comparison, to sample the interior of Enceladus, all you have to do is fly through the plume or land on the south polar terrain, look up and stick your tongue out.

In addition, because Saturn's magnetosphere is anemic compared with Jupiter's, a spacecraft on or around Enceladus does not have to contend with a severe, mission-limiting radiation field, as would a Europa orbiter. Finally, a journey to Enceladus could permit tandem exploration of Titan, another Saturnian destination offering a possible look at life's chemical beginnings [see "The Mystery of Methane on Mars and Titan," by Sushil K. Atreya; Scientific American, May 2007].

For now, we delight in knowing that humanity's first in-depth survey of Saturn and its retinue of worlds has uncovered something wondrous at the southern tip of this small, enigmatic moon: a fantastic and restless place of deep, icy chasms and soaring ghostly fountains, a rare realm whose discovery has rewarded both mind and soul. As planetary explorers, we could not have asked for more. ■

MORE TO EXPLORE

Cassini Observes the Active South Pole of Enceladus. C. C. Porco et al. in *Science*, Vol. 311, pages 1393–1401; March 10, 2006.

Life on a Tiny Moon: NOVA Voyage to the Mystery Moon. Interview with Carolyn Porco, March 2006. **www.pbs.org/wgbh/nova/titan/porco.html**

Cassini: The First One Thousand Days. Carolyn C. Porco in *American Scientist*, Vol. 95, No. 4, pages 334–341; July/August 2007.

Solid Tidal Friction above a Liquid Water Reservoir as the Origin of the South Pole Hotspot on Enceladus. G. Tobie, O. Čadek and C. Sotin in *Icarus*, Vol. 196, No. 2, pages 642–652; August 2008.

The Possible Origin and Persistence of Life on Enceladus and Detection of Biomarkers in the Plume. C. P. McKay et al. in *Astrobiology*, Vol. 8, No. 5, pages 909–922; October 2008.