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Forces OF NATURE

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FORCES OF NATURE

Earthquakes, volcanoes, tornadoes, hurricanes. For all the control humankind holds over its environment, sometimes Nature just can't be contained. Life on Earth has endured the mighty sting of these events since time immemorial but not without suffering devastating losses: the planet is rife with battle scars old and new telling tales of mass destruction.

Scientists may never be able to tame these thrilling and terrifying forces, but advances in understanding them are leading to ways to save lives. In this exclusive online issue, experts share their insights into asteroid impacts, tornado formation, earthquake prediction, and hurricane preparedness. Other articles probe the mysteries of lightning and contemplate the future of an increasingly menacing volcano. —*The Editors*

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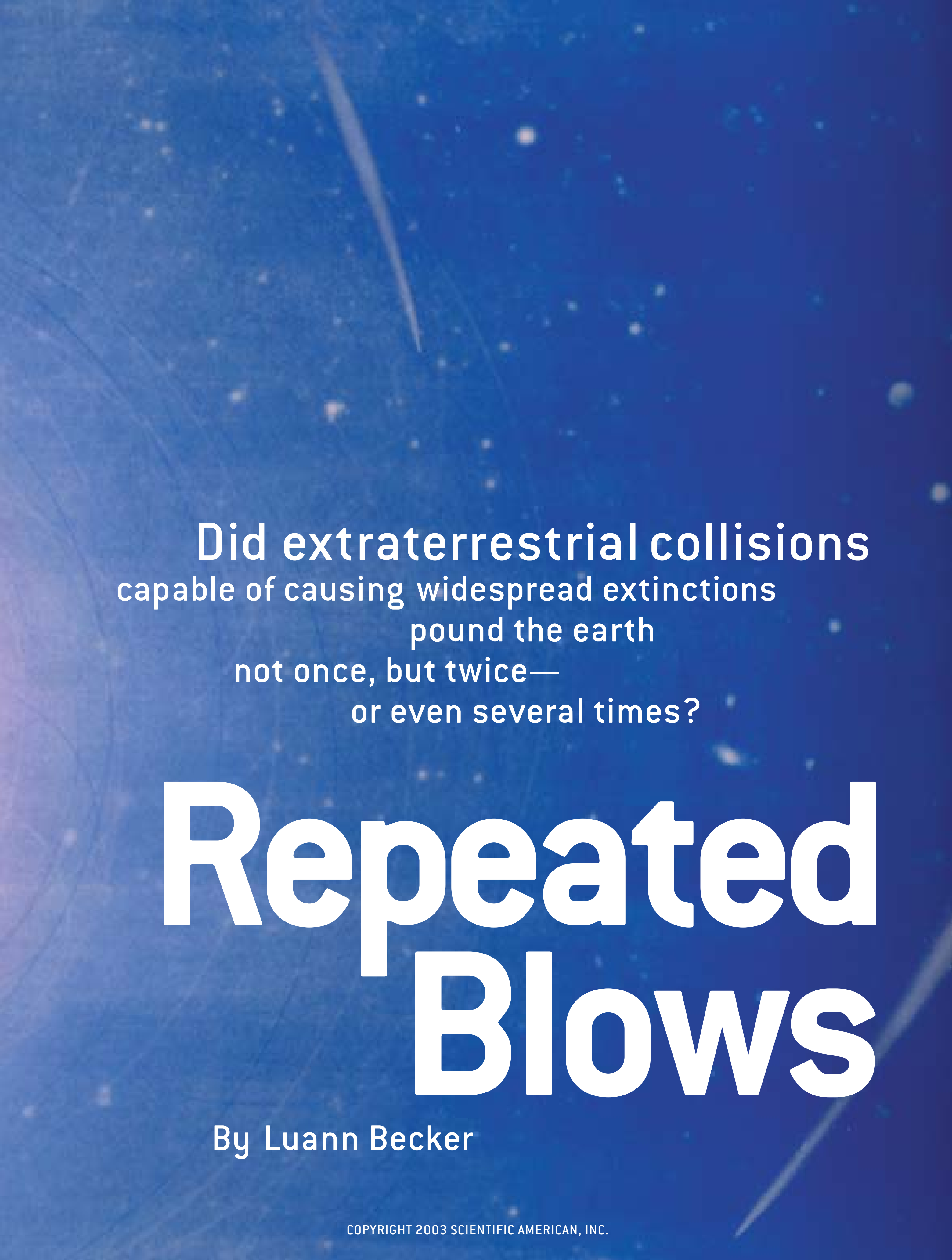


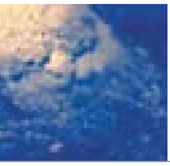
Did extraterrestrial collisions capable of causing widespread extinctions pound the earth not once, but twice—or even several times?

Repeated Blows

By Luann Becker

Most people are unaware of it, but our planet is under a constant barrage by the cosmos. Our galactic neighborhood is littered with comets, asteroids and other debris left over from the birth of the solar system. Most of the space detritus that strikes the earth is interplanetary dust, but a few of these cosmic projectiles have measured five kilometers (about 3.1 miles) or more across. Based on the number of craters on the moon, astronomers estimate that about 60 such giant space rocks slammed into the earth during the past 600 million years. Even the smallest of those collisions would have left a scar 95 kilometers (about 60 miles) wide and would have released a blast of kinetic energy equivalent to detonating 10 million megatons of TNT.

Such massive impacts are no doubt capable of triggering drastic and abrupt changes to the planet and its inhabitants. Indeed, over the same time period the fossil record reveals five great biological crises in which, on average, more than half of all living species ceased to exist. After a period of heated controversy, scientists began to accept that an asteroid impact precipitated one of these catastrophes: the demise of the dinosaurs 65 million years ago. With that one exception, however, compelling evidence for large impacts coincident with severe mass extinctions remained elusive—until recently.



The evidence for impacts acting as culprits in widespread die-offs is getting stronger.

During the past two years, researchers have discovered new methods for assessing where and when impacts occurred, and the evidence connecting them to other widespread die-offs is getting stronger. New tracers of impacts are cropping up, for instance, in rocks laid down at the end of the Permian period—the time 250 million years ago when a mysterious event known as the Great Dying wiped out 90 percent of the planet's species. Evidence for impacts associated with other extinctions is tenuous but growing stronger as well.

Scientists find such hints of multiple life-altering impacts in a variety of forms. Craters and shattered or shocked rocks—the best evidence of an ancient impact—are turning up at key time intervals that suggest a link with extinction. But more often than not, this kind of physical evidence is buried under thick layers of sediment or is obscured by erosion. Researchers now understand that the biggest blows also leave other direct, as well as indirect, clues hidden in the rock record. The first direct tracers included tiny mineral crystals that had been fractured or melted by the blast. Also found in fallout layers have been elements known to form in space but not on the earth. Indeed, my colleagues and I have discovered extraterrestrial gases trapped inside carbon molecules called fullerenes in several suspected impact-related sediments and craters.

Equally intriguing are the indirect tracers that paleontologists have recognized: rapid die-offs of terrestrial vegetation and abrupt declines in the productivity of marine organisms coincident with at least three of the five great extinctions. Such severe and rapid perturbations in the earth's ecosystem are rare, and some scientists suspect that only a catastrophe as abrupt as an impact could trigger them.

Overview/*Deadly Barrage?*

- About 60 meteorites five or more kilometers across have hit the earth in the past 600 million years. The smallest ones would have carved craters some 95 kilometers wide.
- Most scientists agree that one such impact did in the dinosaurs, but evidence for large collisions coincident with other mass extinctions remained elusive—until recently.
- Researchers are now discovering hints of ancient impacts at sites marking history's top five mass extinctions, the worst of which eliminated 90 percent of all living species.

Dinosaur Killer

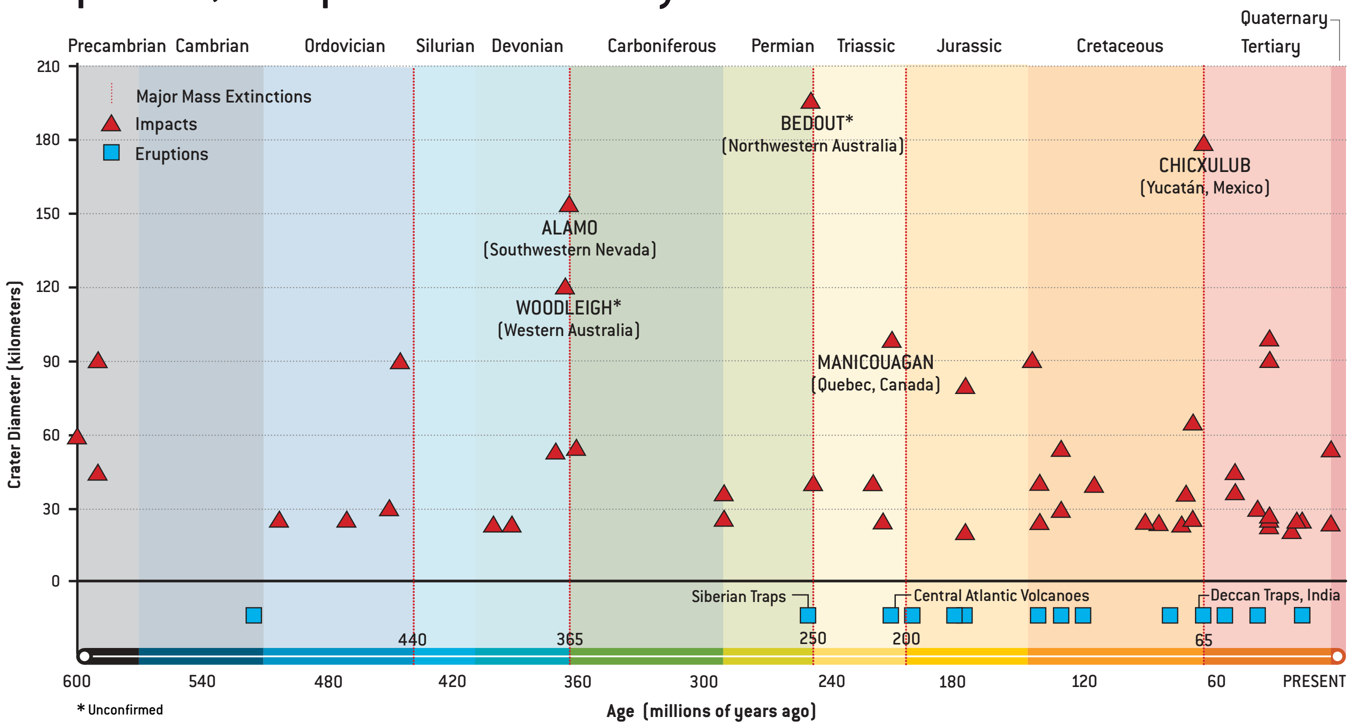
THE FIRST IMPACT TRACER linked to a severe mass extinction was an unearthly concentration of iridium, an element that is rare in rocks on our planet's surface but abundant in many meteorites. In 1980 a team from the University of California at Berkeley—led by Nobel Prize–winning physicist Luis Alvarez and his son, geologist Walter Alvarez—reported a surprisingly high concentration of this element within a centimeter-thick layer of clay exposed near Gubbio, Italy. The Berkeley team calculated that the average daily delivery of cosmic dust could not account for the amount of iridium it measured. Based on these findings, the scientists hypothesized that it was fallout from a blast created when an asteroid, some 10 to 14 kilometers (six to nine miles) across, collided with the earth.

Even more fascinating, the clay layer had been dated to 65 million years ago, the end of the Cretaceous period. From this iridium discovery came the landmark hypothesis that a giant impact ended the reign of the dinosaurs—and that such events may well be associated with other severe mass extinctions over the past 600 million years. Twenty years ago this bold and sweeping claim stunned scientists, most of whom had been content to assume that the dinosaur extinction was a gradual process initiated by a contemporaneous increase in global volcanic activity. The announcement led to intense debates and reexaminations of end Cretaceous rocks around the world.

Out of this scrutiny emerged three additional impact tracers: dramatic disfigurations of the earthly rocks and plant life in the form of microspherules, shocked quartz and high concentrations of soot. In 1981 Jan Smit, now at the Free University in Amsterdam, uncovered microscopic droplets of glass, called microspherules, which he argued were products of the

KAMIL VOJNAR *(preceding two pages)*

Impacts, Eruptions and Major Mass Extinctions



rapid cooling of molten rock that splashed into the atmosphere during the impact. Three years later Bruce Bohor and his colleagues at the U.S. Geological Survey were among the first researchers to explain the formation of shocked quartz. Few earthly circumstances have the power to disfigure quartz, which is a highly stable mineral even at high temperatures and pressures deep inside the earth's crust.

At the time microspherules and shocked quartz were introduced as impact tracers, some still attributed them to extreme volcanic activity. Powerful eruptions can indeed fracture quartz grains—but only in one direction, not in the multiple directions displayed in Bohor's samples. The microspherules contained trace elements that were markedly distinct from those formed in volcanic blasts. Scientists subsequently found enhanced iridium levels at more than 100 end Cretaceous sites worldwide and shocked quartz at more than 30 sites.

Least contentious of the four primary impact tracers to come out of the 1980s were soot and ash, which measured tens of thousands of times higher than normal levels, from impact-triggered fires. The most convincing evidence to support the impact scenario, however, was the recognition of the crater itself, known today as Chicxulub, in Yucatán, Mexico. Shortly after the Alvarez announcement in 1980, geophysicists Tony Camargo and Glen Penfield of the Mexican national oil company, PEMEX, reported an immense circular pattern—later estimated to be some 180 kilometers (about 110 miles) across—while surveying for new oil and gas prospects buried in the Gulf of Mexico. Other researchers confirmed the crater's existence in 1991.

Finding a reasonable candidate for an impact crater marked a turning point in the search for the causes of extreme climate perturbations and mass extinctions—away from earthly sources such as volcanism and toward a singular, catastrophic event. Both volcanoes and impacts eject enormous quantities of toxic pollutants such as ash, sulfur and carbon dioxide into the atmosphere, triggering severe climate change and environmental degradation. The difference is in the timing. The instantaneous release from an impact would potentially kill off species in a few thousand years. Massive volcanism, on the other hand, continues to release its pollutants over millions of years, drawing out its effects on life and its habitats.

While geologists were searching for craters and other impact tracers, paleontologists were adding their own momentum to the impact scenario. Fossil experts had long been inclined to agree with the volcanism theory because the disappearance of species in the fossil record appeared to be gradual. A convincing counterargument came from paleontologists Philip Signor of the University of California at Davis and Jere Lipps,

AARON FIRTH (BASED ON GRAPHIC BY MICHAEL PAINE)

THE AUTHOR

LUANN BECKER has studied impact tracers since she began her career as a geochemist at the Scripps Institution of Oceanography in La Jolla, Calif., in 1990. In 1998 Becker participated in a meteorite-collecting expedition in Antarctica and in July 2001 was awarded the National Science Foundation Antarctic Service Medal. The following month she joined the faculty at the University of California, Santa Barbara, where she continues to study fullerenes and exotic gases trapped within them as impact tracers. This summer she and her colleagues will conduct fieldwork at end Permian extinction sites in South Africa and Australia. Part of this expedition will be included in a television documentary, scheduled to air this fall, about mass extinctions and their causes.

Enduring Traces

Craters are the best evidence for an impact, but ejecta from the affiliated blast contains other clues that can settle to the earth and persist in the rock record for millions of years. Such impact tracers are especially prevalent with large, devastating collisions like the hypothetical one illustrated here: an asteroid 10 kilometers (six miles) wide slams into a coastline, transmitting temperatures of several thousand degrees and pressures a million times greater than the weight of the earth's atmosphere.

IMPACT TRACER
SHOCKED MINERALS
Extreme pressure and heat fracture quartz crystals and metamorphose iron-nickel-silica grains.

IMPACT TRACER
DISFIGURED ROCKS
Shock waves are captured in rock as shattercones. Bedrock fractures; some ejected debris resettles as breccia.

IMPACT TRACER
MICROSPHERULES
Tiny glass droplets form during the rapid cooling of molten rock that splashes into the atmosphere.

IMPACT TRACER
IRIDIUM
This element, which is rare in earthly rocks but abundant in some meteorites, may be preserved in a fallout layer of clay.

IMPACT TRACER
EXTRATERRESTRIAL FULLERENES
Caged carbon molecules trap extraterrestrial noble gases in space and travel to the earth in the impactor.

IMPACT TRACER
SOOT AND ASH
Fires transform vegetation into soot that accumulates to levels tens of thousands of times higher than normal.

INITIAL DEVASTATION

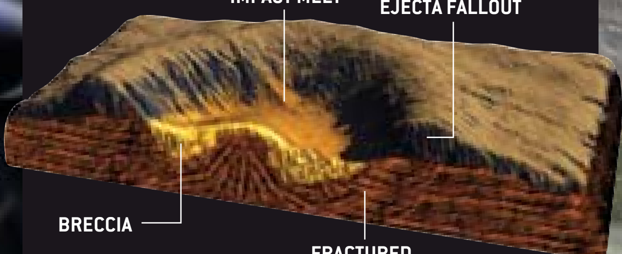
INTO ORBIT
The explosion ejects some 21,000 cubic kilometers (5,000 cubic miles) of debris, about 1,700 cubic kilometers of which is launched into orbit at 50 times the speed of sound.

CHOKED SKY
Little sunlight can penetrate to the ground for several months as ejected debris rains through the atmosphere, and temperatures drop below freezing for up to half a year.

KILLER WAVES
Tsunamis as high as 90 meters (300 feet) destroy coastal ecosystems within hundreds or even thousands of kilometers of the impact.

TERRIBLE TREMOR
A magnitude 13 earthquake—a million times greater than the strongest tremor recorded in human history—courses through the planet.

DISMAL AFTERMATH



This hypothetical catastrophe excavates a crater up to 100 kilometers (60 miles) across and 40 kilometers (25 miles) deep. The nearly instantaneous release of climate-changing pollutants such as ash, sulfur and carbon dioxide kills off species and degrades environments in a few thousand years or less. This geologically rapid timing is reflected in recent scientific studies indicating that species disappear quickly during the worst mass extinctions. Massive volcanism ejects similar pollutants, but its damaging effects are prolonged over millions of years.

illustrations: DON FOLEY; SOURCE: *THE MISTAKEN EXTINCTION*, BY LOWELL DINGUS AND TIMOTHY ROWE. W. H. FREEMAN, 1998. *photographs:* ALAN HILDEBRAND (*quartz*); WALTER PEREDERY (*shattercones*); TIM CULLER *University of California, Berkeley/* APOLLO 11 CREW/NASA (*microspherules*); W. ALVAREZ/SPL/PHOTO RESEARCHERS, INC. (*fallout layer*); WENDY S. WOLBACH *DePaul University* (*soot*)

now at Berkeley. In 1982 they recognized that the typical approach for defining the last occurrence of a given species did not take into account the incompleteness of the fossil record or the biases introduced in the way the fossils were collected.

Many researchers subsequently conducted high-resolution studies of multiple species. These statistically more reliable assessments indicate that the actual extinction time periods at the end of the Cretaceous—and at the end of the Permian—were abrupt (thousands of years) rather than gradual (millions of years). Although volcanically induced climate change no doubt contributed to the demise of some species, life was well on its way to recovery before the volcanism ceased—making the case for an impact trigger more compelling.

Extraterrestrial Hitchhikers

THE RECOGNITION of a shorter time frame for the Great Dying prompted several scientists to search for associated impact tracers and craters. By the early 1990s scientific papers were citing evidence of iridium and shocked quartz from end Permian rocks; however, the reported concentrations were 10- to 100-fold lower than those in the end Cretaceous clay. This finding prompted some paleontologists to claim that the impact that marked the end of the age of dinosaurs was as singular and unique as the animals themselves.

Other scientists reasoned that perhaps an impact had occurred but the rocks simply did not preserve the same clues that were so obvious in end Cretaceous samples. At the end of the Permian period the earth's landmasses were configured into one supercontinent, Pangea, and a superocean, Panthalassa. An asteroid or comet that hit the deep ocean would not generate shocked quartz, because quartz is rare in ocean crust. Nor would it necessarily lead to the spread of iridium worldwide, because not as much debris would be ejected into the atmosphere. Supporting an ocean-impact hypothesis for more ancient extinctions such as the Great Dying, it turned out, would require new tracers.

One of the next impact tracers to hit the scene—and one that would eventually turn up in meteorites and at least two impact craters—evolved out of the accidental discovery of a new form of carbon. In the second year of my doctoral studies at the Scripps Institution of Oceanography in La Jolla, Calif., my adviser, geochemist Jeffrey Bada, showed me an article that had appeared in a recent issue of *Scientific American* [see "Fullerenes," by Robert F. Curl and Richard E. Smalley; October 1991]. It outlined the discovery of a new form of carbon, closed-cage structures called fullerenes (also referred to as buckminsterfullerenes or "buckyballs," after the inventor of the geodesic domes that they resemble). A group of astrochemists and physical chemists had inadvertently created fullerenes in 1985 during laboratory experiments designed to mimic the formation of carbon clusters, or stardust, in some stars. Additional experiments revealed that fullerenes, unlike the other solid forms of carbon, diamond and graphite, were soluble in some organic solvents, a property that would prove their existence and lead to a Nobel Prize in Chemistry for Curl, Smalley and Harold W. Kroto in 1996.

Knowing that stardust, like iridium, is delivered to our plan-

Rough Neighborhood

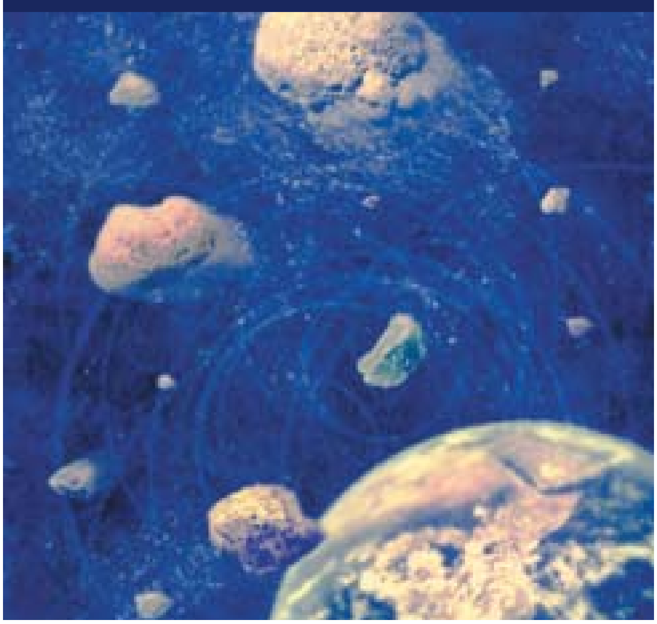
The search for Earth-crossing asteroids expands

ON JANUARY 7 a shopping mall–size rock reminded everyone just how cluttered the solar system really is. Roughly 300 meters in diameter, asteroid 2001 YB5 was small enough to escape notice until late December but big enough to carve a crater the size of a small city had it struck land. Fortunately, its closest approach to Earth was 830,000 kilometers (about twice the distance to the moon), and we are in no danger of a YB5 collision for at least the next several centuries.

But what about the 1,500 other known near-Earth asteroids? (They are so dubbed because they have broken away from the main asteroid belt between Mars and Jupiter and now pose a potential impact risk.) YB5-size space rocks fly this close nearly every year, says David Morrison of the NASA Ames Research Center, but they strike Earth only about every 20,000 to 30,000 years.

Finding hazardous objects long before they become a threat is the aim of the U.K.'s new information center on near-Earth objects, which is scheduled to debut in early April at the National Space Science Center in Leicester. Asteroid hunters at the U.K. center and a handful of other institutions worldwide are especially concerned with objects one kilometer (six tenths of a mile) in diameter, the low-end estimate for the size required to wreak global havoc. The odds of such a catastrophe occurring in the next 100 years range between one in 4,000 and one in 8,600, according to recent calculations by Alan Harris of the Jet Propulsion Laboratory in Pasadena, Calif. NASA's ongoing Spaceguard Survey, which aims to find 90 percent of the Earth-crossing asteroids this size or larger by 2008, will help sharpen this prediction.

—Sarah Simpson, contributing editor



KAMIL VOJNAR

et in the form of cosmic dust, asteroids and comets, we decided to search for these exotic carbon molecules in earthly sediments. We chose a known impact site—the 1.85-billion-year-old Sudbury crater in Ontario, Canada—because of its unique lining of carbon-rich breccia, a mixture of shattered target rocks and other fallout from the blast. (Not unlike the Chicxulub controversy, it took the discovery of shocked quartz and shatter-cones, features described as shock waves captured in the rock, to convince most scientists that the crater was an impact scar rather than volcanic in origin.)

Because fullerene is a pure-carbon molecule, the Sudbury breccia offered a prime location for collecting promising samples, which we did in 1993. By exploiting the unique solubility properties of fullerene, I was able to isolate the most stable molecules—those built from 60 or 70 carbon atoms each—in the laboratory. The next critical questions were: Did the fullerenes hitch a ride to the earth on the impactor, surviving the catastrophic blast? Or were they somehow generated in the intense heat and pressures of the event?

Meanwhile organic chemist Martin Saunders and his colleagues at Yale University and geochemist Robert Poreda of the University of Rochester were discovering a way to resolve this question. In 1993 Saunders and Poreda demonstrated that fullerenes have the unusual ability to capture noble gases—such as helium, neon and argon—within their caged structures. As soon as Bada and I became aware of this discovery, in 1994, we asked Poreda to examine our Sudbury fullerenes. We knew that the isotopic compositions of noble gases observed in space (like those measured in meteorites and cosmic dust) were clearly distinct from those found on the earth. That meant we had a simple way to test where our exotic carbon originated: measure the isotopic signatures of the gases within them.

What we found astounds us to this day. The Sudbury fullerenes contained helium with compositions similar to some meteorites and cosmic dust. We reasoned that the molecules must have survived the catastrophic impact, but how? Geologists agree that the Sudbury impactor was at least eight kilometers (about five miles) across. Computer simulations predicted that all organic compounds in an asteroid or comet of this size would be vaporized on impact. Perhaps even more troubling was the initial lack of compelling evidence for fullerenes in meteorites.

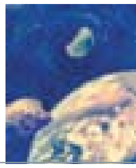
We, too , were surprised that the fullerenes survived. But as for their apparent absence in meteorites, we suspected that previous workers had not looked for all the known types. In the original experiment designed to simulate stardust, a family of large fullerenes formed in addition to the 60- and 70-atom molecules. Indeed, on a whim, I attempted to isolate larger fullerenes in some carbon-rich meteorites, and a whole series of cages with up to 400 carbon atoms were present. Like their smaller counterparts from the Sudbury crater, these larger structures contained extraterrestrial helium, neon and argon.

With the discovery of the giant fullerenes in meteorites, Poreda and I decided to test our new method on sediments associated with mass extinctions. We first revisited fullerene samples that other researchers had discovered at end Cretaceous sites. One group, led by Dieter Heymann of Rice University, had proposed that the exotic carbon was part of the soot that accumulated in the wake of the massive, impact-ignited fires. The heat of such a fire may have been intense enough to transform plant carbon into fullerenes, but it could not account for the extraterrestrial helium that we found inside them.

Inspired by this success, we wondered whether fullerenes would be a reliable tracer of large impacts elsewhere in the fossil record. Sediments associated with the Great Dying became our next focus. In February 2001 we reported extraterrestrial helium and argon in fullerenes from end Permian locations in China and Japan. In the past several months we have also begun to look at end Permian sites in Antarctica. Preliminary investigations of samples from Graphite Peak indicate that fullerenes are present and contain extraterrestrial helium and argon. These end Permian fullerenes are also associated with shocked quartz, another direct indicator of impact.

As exciting as these new impact tracers linked to the Great Dying have been, it would be misleading to suggest that fullerenes are the smoking gun for a giant impact. Many scientists still argue that volcanism is the more likely cause. Some have suggested that cosmic dust is a better indicator of an impact event than fullerenes are. Others are asking why evidence such as shocked quartz and iridium are so rare in rocks associated with the Great Dying and will remain skeptical if an impact crater cannot be found.

Whatever stimulated these mass extinctions made possible our own existence.



Forging Ahead

UNDAUNTED BY SKEPTICISM, a handful of scientists continues to look for potential impact craters and tracers. Recently geologist John Gorter of Agip Petroleum in Perth, Australia, described a potential, enormous end Permian impact crater buried under a thick pile of sediments offshore of northwestern Australia. Gorter interpreted a seismic line over the region that suggests a circular structure, called the Bedout, some 200 kilometers (about 125 miles) across. If a future discovery of shocked quartz or other impact tracers proves this structure to be ground zero for a life-altering impact, its location could explain why extraterrestrial fullerenes are found in China, Japan and Antarctica—regions close to the proposed impact—but not in more distant sites, such as Hungary and Israel.

Also encouraging are the recent discoveries of other tracers proposed as direct products of an impact. In September 2001 geochemist Kunio Kaiho of Tohoku University in Japan and his colleagues reported the presence of impact-metamorphosed iron-silica-nickel grains in the same end Permian rocks in Meishan, China, where evidence for abrupt extinctions and extraterrestrial fullerenes has cropped up. Such grains have been reported in several end Cretaceous impact sites around the world as well.

In the absence of craters or other direct evidence, it still may be possible to determine the occurrence of an impact by noting symptoms of rapid environmental or biological changes. In 2000, in fact, Peter Ward of the University of Washington and his colleagues reported evidence of abrupt die-offs of rooted plants in end Permian rocks of the Karoo Basin in South Africa. Several groups have also described a sharp drop in productivity in marine species associated with the Great Dying—and with the third of the five big mass extinctions, in some 200-million-year-old end Triassic rocks. These productivity crashes, marked by a shift in the values of carbon isotopes, correlate to a similar record at the end of the Cretaceous, a time when few scientists doubt a violent impact occurred.

Only more careful investigation will determine if new impact tracers—both direct products of a collision and indirect evidence for abrupt ecological change—will prove themselves reliable in the long run. So far researchers have demonstrated that several lines of evidence for impacts are present in rocks that record three of our planet's five most devastating biological crises. For the two other largest extinctions—one about 440 million years ago and the other about 365 million years ago—iridium, shocked quartz, microspherules, potential craters and productivity collapse have been reported, but the causal link between impact and extinction is still tenuous at best. It is important to note, however, that the impact tracers that typify the end of the Cretaceous will not be as robust in rocks linked to older mass extinctions.

The idea that giant collisions may have occurred multiple times is intriguing in its own right. But perhaps even more compelling is the growing indication that these destructive events may be necessary to promote evolutionary change. Most paleontologists believe that the Great Dying, for instance, enabled dinosaurs to thrive by opening niches previously occupied by other animals. Likewise, the demise of the dinosaurs allowed mammals to flourish. Whatever stimulated these mass extinctions, then, also made possible our own existence. As researchers continue to detect impact tracers around the world, it's looking more like impacts are the culprits of the greatest unresolved murder mysteries in the history of life on earth. SA

MORE TO EXPLORE

Impact Event at the Permian-Triassic Boundary: Evidence from Extraterrestrial Noble Gases in Fullerene. Luann Becker, Robert J. Poreda, Andrew G. Hunt, Theodore E. Bunch and Michael Rampino in *Science*, Vol. 291, pages 1530–1533; February 23, 2001.

Accretion of Extraterrestrial Matter throughout Earth's History. Edited by Bernhard Peucker-Ehrenbrink and Birger Schmitz. Kluwer Academic/Plenum Publishers, 2001.

MOUNT ETNA'S FEROCIOUS FUTURE

Originally published in April 2003

Europe's biggest and most active volcano is growing more dangerous. Luckily, the transformation is happening slowly

By Tom Pfeiffer

Translated by Alexander R. McBirney

LAST OCTOBER ABOUT 1,000 ITALIANS FLED THEIR HOMES AFTER MOUNT ETNA, THE FAMOUS VOLCANO ON THE ISLAND OF SICILY, RUMBLED TO LIFE.

Shooting molten rock more than 500 meters into the air, Etna sent streams of lava rushing down its northeastern and southern flanks. The eruption was accompanied by hundreds of earthquakes measuring up to 4.3 on the Richter scale. As a huge plume of smoke and ash drifted across the Mediterranean Sea, residents of Linguaglossa (the name means "tongues" of lava) tried to ward off the lava flows by parading a statue of their patron saint through the town's streets.

Perhaps because of divine intervention, nobody was hurt and damage was not widespread. But the episode was unnerving because it was so similar to an erratic eruption on the volcano's southern flank in the summer of 2001 that destroyed parts of a tourist complex and threatened the town of Nicolosi. Some of the lavas discharged in both events were of an unusual type last produced in large amounts at the site about 15,000 years ago. At that time, a series of catastrophic eruptions led to the collapse of one of Etna's predecessor volcanoes.

The Sicilians living near Mount Etna have long regarded the volcano as a restless but relatively friendly neighbor. Though persistently active, Etna has not had a major explosive eruption—such as the devastating 1980 event at Mount Saint Helens in Washington State—for hundreds of years. But now some researchers believe they have found evidence that Etna is very gradually becoming more dangerous. It is unlikely that Etna will explode like Mount Saint Helens in the near future, but fierce eruptions may become more common.

Mountain of Fire

THE NAME "ETNA" is derived from an old Indo-Germanic root meaning "burned" or "burning." Extensive reports and legends record about 3,000 years of the volcano's activity, but a reliable chronicle has been available only since the 17th century. Most of the earlier accounts are limited to particularly violent eruptions, such as those occurring in 122 B.C. and A.D. 1169, 1329, 1536 and 1669. During the eruption in 1669, an enormous lava flow buried part of the city of Catania before pouring into the sea.

With a surface area of approximately 1,200 square kilometers, Etna is Europe's largest volcano [*see map on page 13*]. Its 3,340-meter-high peak is often covered with snow. Only the upper 2,000 meters consists of volcanic material; the mountain rests on a base of sedimentary rock beds. Blocks of this material are occasionally caught in the magma—the molten rock moving upward—and ejected at the surface. Numerous blocks of white sandstone were blown out during the 2001 and 2002 eruptions. This phenomenon occurs whenever magma must open new paths for its ascent, as is usually the case with lateral eruptions (those that occur on the volcano's flanks).

Overview/*Etna's Evolution*

- Long regarded as a relatively tame volcano, Mount Etna has rocked the Italian island of Sicily over the past two years. Eruptions on Etna's flanks have produced lava flows that have destroyed tourist facilities and threatened nearby towns.
- Researchers believe that some of Etna's molten rock is being generated by the collision of two tectonic plates. If this hypothesis is correct, the volcano may eventually become much more violent and explosive.

LAVA FOUNTAIN erupts on Mount Etna's southern flank on October 30, 2002.

The volcano is more than 500,000 years old. Remnants of its earliest eruptions are still preserved in nearby coastal regions in the form of pillow lavas, which emerge underwater and do in fact look like giant pillows. At first, a shield volcano—so called because it resembles a shield placed face-up on the ground—grew in a depression in the area where Etna now stands. Today a much steeper cone rests on the ancient shield volcano. It consists of at least five generations of volcanic edifices that have piled up during the past 100,000 to 200,000 years, each atop the remnants of its eroded or partly collapsed predecessor. The present-day cone has been built in the past 5,000 to 8,000 years. Among Etna's special features are the hundreds of small cinder cones scattered about its flanks. Each marks a lateral outbreak of magma. One of the world's most productive volcanoes, Etna has spewed about 30 million cubic meters of igneous material each year since 1970, with a peak eruption rate of 300 cubic meters a second.

Etna is also one of the most puzzling volcanoes. Why has the magma that produced it risen to the surface at this particular spot, and why does it continue to do so in such large quantities? The an-

TOM PFEIFFER (*above*)

swers should be found in the theory of plate tectonics, which posits that the earth's outermost shell consists of about a dozen vast plates, each between about five and 150 kilometers thick. The plates constitute the planet's crust and the uppermost part of the mantle. Like pieces of ice floating on the ocean, these plates drift independently, sometimes moving apart and at other times colliding. The 530 active volcanoes of the world are divided into three major types according to their positions on or between these plates.

The first and most numerous type is found along the rift zones, where two plates are moving apart. The best examples are the long midocean ridges. Forces beneath the plates rip them apart along a fracture, and the separation causes an upwelling of hotter material from the underlying mantle. This material melts as it rises, producing basalt (the most common kind of magma), which contains large amounts of iron and magnesium. The basaltic melt fills the space created by the separating plates, thus continuously adding new oceanic crust.

The second type is located along the subduction zones, where two plates converge. Normally, a colder and heavier oceanic plate dives below a continental plate. The process that leads to the formation of magma in this environment is completely different: water and other fluids entrained with the sinking plate are released under increasing pressure and temperature, mainly at depths of about 100 kilometers. These fluids rise into the overlying, hotter mantle wedge and lower the melting temperature of the rocks. The resulting magmas, which are more viscous and gas-rich than the basaltic melts of the rift zones, contain less iron and magnesium and more silica and volatile components (mainly water and carbon dioxide).

These factors make the volcanoes in subduction zones far more menacing than volcanoes in rift zones. Because the viscous, gas-rich magma does not flow easily out of the earth, pressure builds up until the molten rock is ejected explosively. The sudden release of gases fragments the magma into volcanic projectiles, including bombs (rounded masses of lava), lapilli (small stony or glassy pieces) and

MUSHROOM CLOUD of ash rises from Etna's northeastern flank on October 28, 2002.

TOM PFEIFFER

ash. Such volcanoes typically have steep cones composed of alternating layers of loose airborne deposits and lava flows. Some of the best-known examples of subduction-zone volcanoes rise along the margins of the Pacific Ocean and in the island arcs. This Ring of Fire includes Mount Saint Helens, Unzen in Japan and Pinatubo in the Philippines, all of which have erupted in the past three decades.

The third type of volcano develops independently of the movements of the tectonic plates and is found above hot spots caused by mantle plumes, currents of unusually hot material that ascend by thermal convection from deep in the earth's mantle. As the mantle plumes approach the surface, decreasing pressure causes them to produce melts that bore their way through the crust, creating a chain of hot-spot volcanoes. Most hot-spot volcanoes produce highly fluid lava flows that build large, flat shield volcanoes, such as Mauna Loa in Hawaii.

At the Crossroads

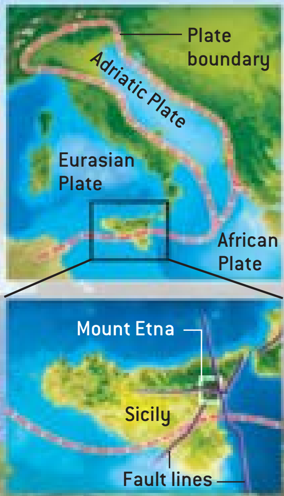
ETNA, HOWEVER, cannot be assigned to any of the three principal categories of volcanoes. It is located in a geologically complex area, which owes its current form to tectonic processes that have been active for the past 50 million to 60 million years. An ocean basin that formerly existed between Eurasia and the northward-moving African continent was swallowed to a large extent by the Eurasian plate. About 100 million years ago two smaller plates, Iberia and Adria, split off from the Eurasian and African plates because of enormous shearing stresses related to the separation of North America from Eurasia (and the opening of the Atlantic Ocean).

Mountain belts arose along the fronts where the plates collided. Italy's Apennines developed when the Iberian and Adriatic plates met. During this process, the Italian peninsula was rotated counterclockwise by as much as 120 degrees to its current position. Today Etna is sit-

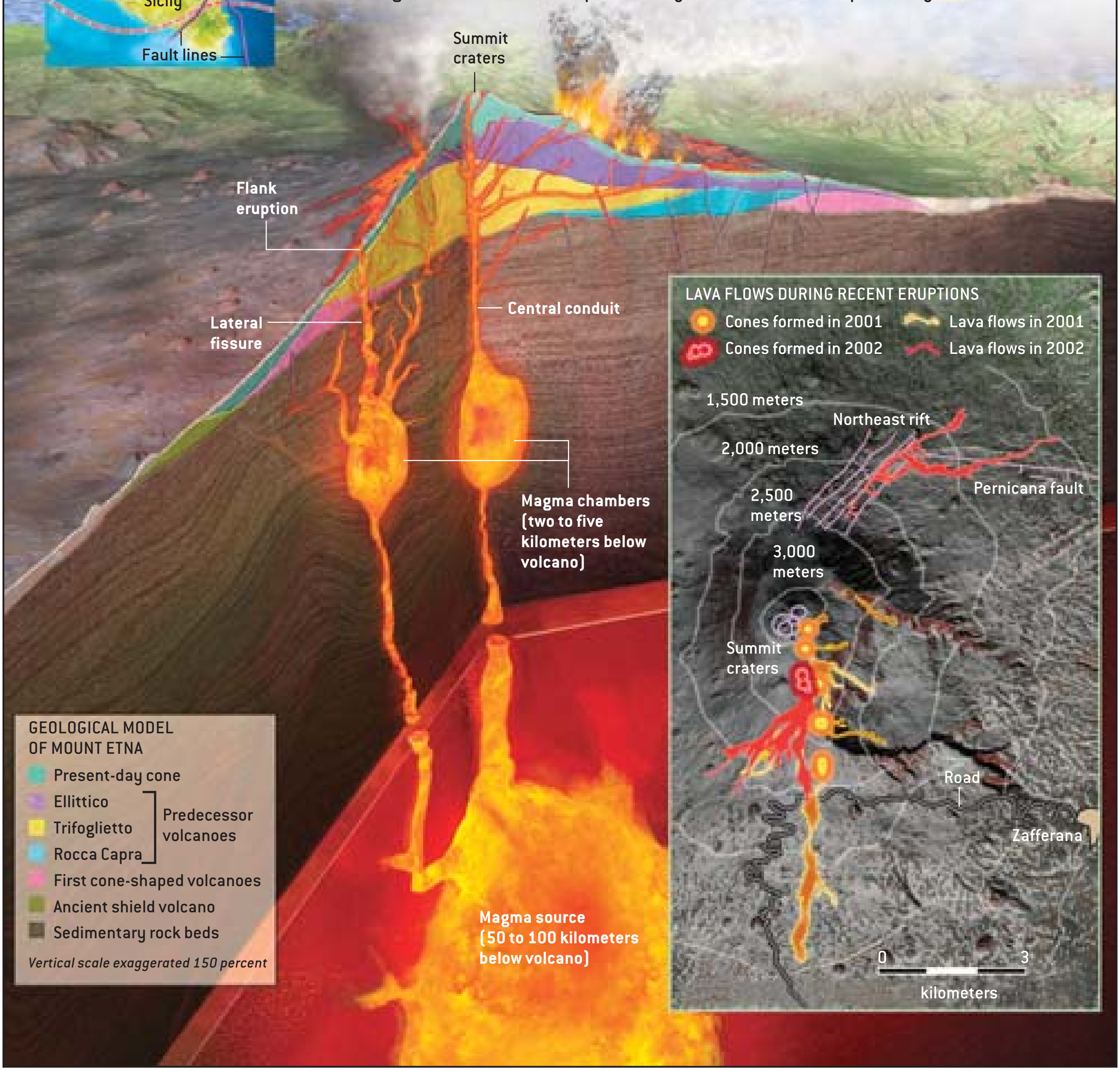
THE AUTHOR

TOM PFEIFFER has become very familiar with Mount Etna, photographing many of the volcano's recent eruptions. He is a Ph.D. student in the department of earth sciences at the University of Århus in Denmark. Pfeiffer has done research at the Hawaiian Volcano Observatory at Kilauea volcano and the Vesuvius Observatory in Naples. His dissertation is about the Minoan eruption on the Greek island of Santorini that devastated the eastern Mediterranean region around 1645 B.C. An earlier version of this article appeared in the May 2002 issue of *Spektrum der Wissenschaft, Scientific American*'s sister publication in Germany.

PORTRAIT OF A VOLCANO



MOUNT ETNA is situated close to the juncture of the Eurasian, African and Adriatic tectonic plates (*left*). The movements of these plates have fractured Sicily's crust along fault lines. A cross section of Etna (*below*) reveals much of the volcano's 500,000-year history. First, a flat shield volcano spread across the sedimentary rock beds; then a cone-shaped volcano rose above it. The succeeding generations of volcanic edifices—named Rocca Capra, Trifoglietto and Ellittico—piled atop their predecessors, forming the foundation for the present-day cone (dubbed Mongibello Recente). Recent eruptions on Etna's flanks seem to arise from a fissure that is not connected to the volcano's central feeding system. The two conduits appear to have separate magma chambers about two to five kilometers below the volcano's summit, although they share the same magma source 50 to 100 kilometers farther down. (This part of the cross section is not drawn to scale.) A contour map (*bottom right*) shows the locations of the flank eruptions and lava flows that have occurred in the past two years. —*T.P.*



DAVID FIERSTEIN

uated close to the junction of the African, Eurasian and Adriatic plates. Individual blocks from these plates have been superimposed and welded together on Sicily. Major tectonic faults cross the area around the volcano as a result of intense regional stresses within the crust.

For a long time researchers believed that Etna's position at the crossroads of these faults was the explanation for its volcanism. The presence of faults, however, accounts only for the ability of magma to reach the surface; it does not explain why the magma is produced in the first place. According to most theories, the prevailing forces in the Sicilian crust are similar to those in rift zones—extensional stresses that cause thinning of the crust and upwelling of the underlying mantle. But at Sicily the African and Eurasian plates are colliding, so one would expect the stresses to be compressive rather than extensional. Moreover, only about 20 percent of the magma erupted at Etna has a chemical composition similar to that of a rift-zone volcano.

Judging from its magma and pattern of activity, Etna is most similar to hotspot volcanoes such as those in Hawaii. Recent theories suggest that it has developed above an active mantle plume, but no direct evidence for this plume has been detected. So far scientists have been unable to explain all the characteristics of this enigmatic volcano. For example, Etna is one of the few volcanoes in which magma is almost continuously rising. Its active periods can last for years or even decades and are interrupted only by short intervals of quietness. This pattern implies the existence of two things: first, a constant flow of magma from the mantle to the deep and shallow magma reservoirs beneath the volcano and, second, an open conduit through which magma can rise. In fact, the conduits between Etna's magma chambers and the summit craters seem to be very long lived structures. Seismic investigations have shown that the rising magma produces little noise and appears to move rather smoothly, without encountering major obstacles.

The kind of activity that prevails at Etna depends primarily on the level of magma inside its conduits. The low pressure in the upper part of the magma column allows the dissolved gases (mainly water and carbon dioxide) to escape. The resulting bubbles rise within the magma column and pop at the surface, throwing out liquid and solid fragments. When the level of the magma column is fairly deep inside the volcano, only gases and fine ash particles reach the crater rim. When it is closer to the surface, larger fragments (lapilli and bombs) are thrown out as well. In the rare cases when the magma column itself reaches the crater rim, the degassing magma pours over the rim or through a crack and forms a lava flow.

Besides lava flows, Etna produces an almost constant, rhythmic discharge of steam, ash and molten rock. Known as a strombolian eruption (named after Stromboli, a volcano on one of the Aeolian Islands about 100 kilometers north of Etna), this activity sometimes culminates in violent lava fountains jetting hundreds of meters into the air. During the spectacular series of eruptions at Etna's southeast crater in the first half of 2000, these fountains rose as high as 1,200 meters above the crater's rim—a stunning height rarely observed at any volcano.

To witness such an eruption from close range can be extremely dangerous, as I have learned from experience. In February 2000, violent eruptions at Etna's southeast crater were occurring at 12- or 24-hour intervals. On the evening of February 15, while I was observing the crater from about 800 meters away with a group of spectators, a white cloud of steam rose from the crater's mouth. It rapidly became thicker and denser. After a few minutes, the first red spots began dancing above the crater, rising and falling back into it. The explosions grew stronger, first slowly, then with breathtaking speed, throwing bombs more than 1,000 meters above the rim. Soon the volcanic cone surrounding the crater was covered with glowing rocks. At the same time, a fountain of lava started to rise from a fracture on the flank of the cone. Several other fountains rose from the crater and formed a roaring, golden curtain that illuminated

ASH PLUME from Mount Etna is clearly visible in this image taken by NASA's Terra satellite.

HO, NASA, TERRA SATELLITE *AP Photo*

STROMBOLIAN EXPLOSIONS illuminate newly formed craters on Etna's northern flank.

TOM PFEIFFER

the scene like daylight. Some larger bombs crashed into the snow not far from us, but we felt secure in our viewing position. The fountain was nearly vertical, and a strong wind carried the mass of glowing lapilli and ash gently away from us.

Suddenly the lava fountain changed direction, sending a lateral outburst straight toward us. Just in time we reached the shelter of an abandoned mountain hut with a thick concrete roof. A heavy rain of incandescent stones fell around us; lava bombs of all sizes tumbled down, spraying thousands of sparks. Fortunately, our shelter was not hit by anything large, although a two-meter-wide bomb plunged into the snow nearby. After an endless two minutes, the lava fountain rose vertically again and stayed in this position for another 10 minutes. Then its supply of magma from below seemed to be exhausted. The fountain collapsed as if it were sucked back into the crater. The entire spectacle was finished 30 minutes after it began. In front of us, the 300-meter-high cone still glowed red but was completely silent.

Natural Air Polluter

ETNA'S REPUTATION as a relatively friendly volcano stems mainly from the fact that its lavas are very fluid. Such lavas are easily ejected to the surface, unlike the viscous magmas produced by subduction-zone volcanoes. But Etna's magmas also contain a great amount of gas, which can make eruptions much more explosive. During a particularly violent phase, Etna expels up to 20,000 tons of sulfur dioxide a day, making the volcano one of nature's worst air polluters. The high sulfur content of Etna's magma is hard to understand; this characteristic is more typical of subduction-zone volcanoes than of basaltic volcanoes.

What is more, Etna's composition indicates that the volcano has indeed experienced major explosive eruptions similar in size to those of Pinatubo in 1991 and Mount Saint Helens in 1980. Etna's last big explosion appears to have occurred in 122 B.C. During that event, more than one cubic kilometer of basaltic lava erupted in a giant column loaded with lapilli and ash. Deposits formed by this eruption are up to two meters thick on Etna's upper slopes and are still exposed in some areas. In Catania, about 30 kilometers from the summit, the deposits are between 10 and 25 centimeters thick. If such an event were to occur today, it would be a disaster. The roofs of many houses in the area would collapse from the weight of the ash.

The unusual flank eruptions of 2001 and 2002 made it clear that Etna is not tame. In 2001 as many as five fractures opened on both sides of the mountain, through which huge masses of lava started to pour. A new crater was born at an elevation of 2,500 meters. Extremely active, it spewed lava fountains and dense clouds of ash, growing within a few days to a cone about 100 meters high. Especially spectacular were the giant magma bubbles that rose within the new crater and detonated with awesome power. Even at a distance of several kilometers, the force of the explosions rattled doors and windows.

Researchers soon determined that two distinct eruptions were occurring simultaneously. The opening of the fractures near Etna's summit (between 2,700 and 3,000 meters above sea level) was a continuation of the volcanic activity that had been roiling the summit craters for years. But the eruptions at the lower fractures (at elevations between 2,100 and 2,500 meters) produced a more evolved type of magma that obviously had rested for a prolonged period in a separate chamber, where it could change its chemical composition. (A similar pattern was also evident in the 2002 eruptions.) This second kind of magma included centimeter-size crystals of the mineral amphibole, which is very rarely found in Etna's lavas. Besides iron, magnesium and silica, amphibole incorporates water in its crystal structure. The mineral can form only from a magma that contains sufficient amounts of water. Obviously, two different plumbing systems of the volcano were active at the same time: one associated with the central, more or less constantly active conduit and the other with an independent conduit off to the side.

The magmas ejected through this second conduit were last produced in large quantities at Etna about 15,000 years ago, when devastating eruptions caused the collapse of one of Etna's predecessors, the Ellittico volcano. Is their reappearance a sign that a catastrophic explosive eruption will happen in the near future? The answer depends on where Etna's magmas come from. Identifying their origins can be tricky: analyzing the erupted magma can be misleading, because the chemical composition of the original melt often changes during its ascent through the crust. Geologists have learned, however, that surface lavas sometimes contain crystals that preserve the composition of the original magma. If a crystal begins to form at an early stage in the life of a magma, it may include minuscule droplets of the primitive melt and grow around them. These melt inclusions are thus isolated from all subsequent chemical changes.

Analyzing such melt inclusions, though, is difficult. Until recently, almost no suitable data were available for Etna.

LAVA FLOWS block roads and cut through forests on Mount Etna's northern side in November 2002.

TOM PFEIFFER

In 1996 a French-Italian research team consisting of Pierre Schiano (Blaise Pascal University in France), Roberto Clocchiatti (National Center for Scientific Research in France), Luisa Ottolini (National Research Council in Italy) and Tiziana Busà (then at the University of Catania in Italy) began a comprehensive investigation of the magmas of Etna and neighboring volcanoes. The researchers looked for glassy inclusions in olivine crystals, which are among the first to form from a primitive melt. The tiny inclusions they discovered, each less than two tenths of a millimeter in diameter, were remelted on a heating plate, then quenched to create a homogeneous glass. The team determined the chemical composition of the inclusions using a microprobe (which directs narrow beams of x-rays at a sample) and a secondary ion mass spectrometer (which employs ion beams).

Changing Character

THE SCIENTISTS PAID special attention to the trace elements, such as cesium and barium, which are rare in igneous rocks. When a melt forms deep underground, the trace elements in the source rock migrate almost completely to the magma. Because their relative concentrations remain nearly unchanged, the trace elements offer a geologic fingerprint of the origin of the melt. The magmas that erupted at Etna more than about 100,000 years ago had compositions similar to those from the older, now extinct volcanoes of the Iblean Mountains in southern Sicily. The trace-element patterns were also close to those found in magmas from hot-spot volcanoes in Hawaii and the Azores. The early volcanism at Etna was apparently fueled by a mantle plume, probably the same one that fed the Iblean volcanoes about 100 kilometers to the south.

But the analysis of the younger magmas (those that have been expelled within the past 100,000 years) revealed a much different picture. They have large concentrations of trace elements such as cesium, potassium, rubidium and barium, but they appeared to be depleted of elements such as titanium and zirconium. Remarkably similar patterns are found at the Aeolian Island volcanoes, which include Stromboli and Vulcano. This island arc most likely owes its existence to tectonic forces—specifically, the subduction of oceanic crust from the Ionian Sea under the Calabrian block (the southernmost part of the Italian mainland). Schiano and Clocchiatti are convinced that the similarity of the magmas is no coincidence. They believe that Etna has two sources of magma: the mantle plume that gave birth to the volcano and a second component that is identical to the magma feeding the Aeolian volcanoes. Furthermore, Etna's youngest magmas have the greatest amounts of this second component.

How does Etna produce its fiery mix of magmas? One possibility is that the two magmas form at different locations and mix somewhere within Etna's plumbing system. This hypothesis would imply that the magma below the Aeolian Islands travels more than 100 kilometers along a tectonic fault to Etna. It is considered highly unlikely, though, that such an underground magma passage exists. Researchers think it is more probable that the two magma *sources* are mixing. According to this model, part of the subducted slab of the Ionian plate has slowly migrated southward and come within reach of the plume beneath Etna. When the rising plume passes by the edge of the sinking slab, it creates the mix of magmas that emerges from the volcano.

Etna's activity has increased markedly since 1970, with more frequent eruptions and more volcanic material ejected. Researchers cannot be certain, however, whether this upsurge is caused by tectonic forces or by a fresh batch of magma rising from the mantle. If Etna is indeed transforming into an explosive subduction-zone volcano, the process will be a gradual one. As Schiano and Clocchiatti emphasize, "The observed change [from a hot-spot toward an island-arc volcano] is taking place in geological time and not in a human lifetime." Thus, Etna is unlikely to experience a catastrophic explosive eruption soon.

But if the researchers' hypothesis is correct, Etna's eruptions will grow increasingly violent. Some tens of thousands of years from now, Etna may well become as dangerous as Mount Saint Helens or Pinatubo. Fortunately, the Sicilians should have plenty of time to adapt to the new situation. SA

MORE TO EXPLORE

Mount Etna: Anatomy of a Volcano. B. K. Chester, A. M. Duncan, J. E. Guest and C.R.J. Kilburn. Chapman and Hall, 1985.

Transition of Mount Etna Lavas from a Mantle-Plume to an Island-Arc Magmatic Source. P. Schiano, R. Clocchiatti, L. Ottolini and T. Busà in *Nature,* Vol. 412, No. 6850, pages 900–904; August 30, 2001.

More information about Mount Etna, Stromboli and other volcanoes is available at **boris.vulcanoetna.com, www.stromboli.net** and **www.decadevolcano.net**

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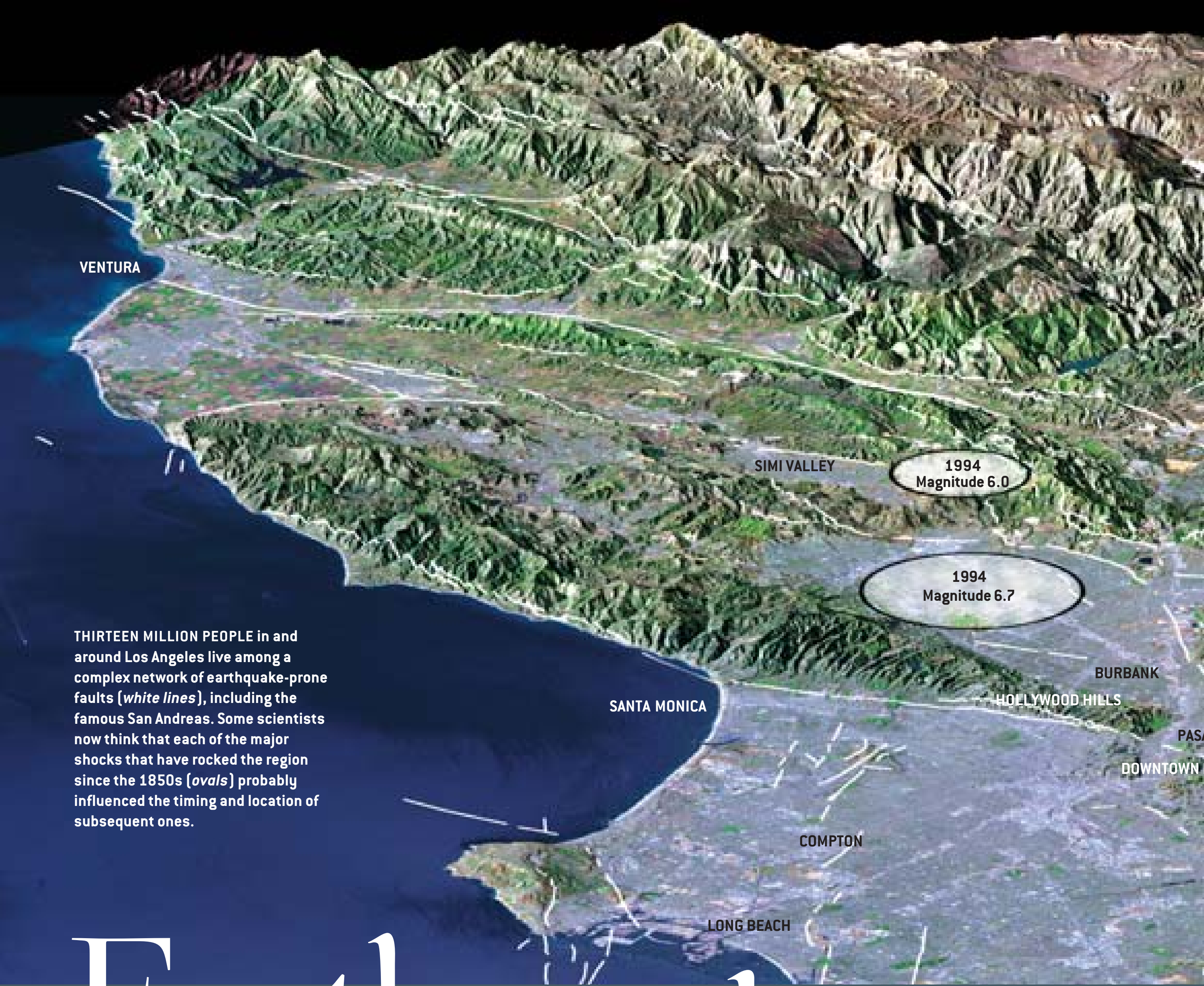


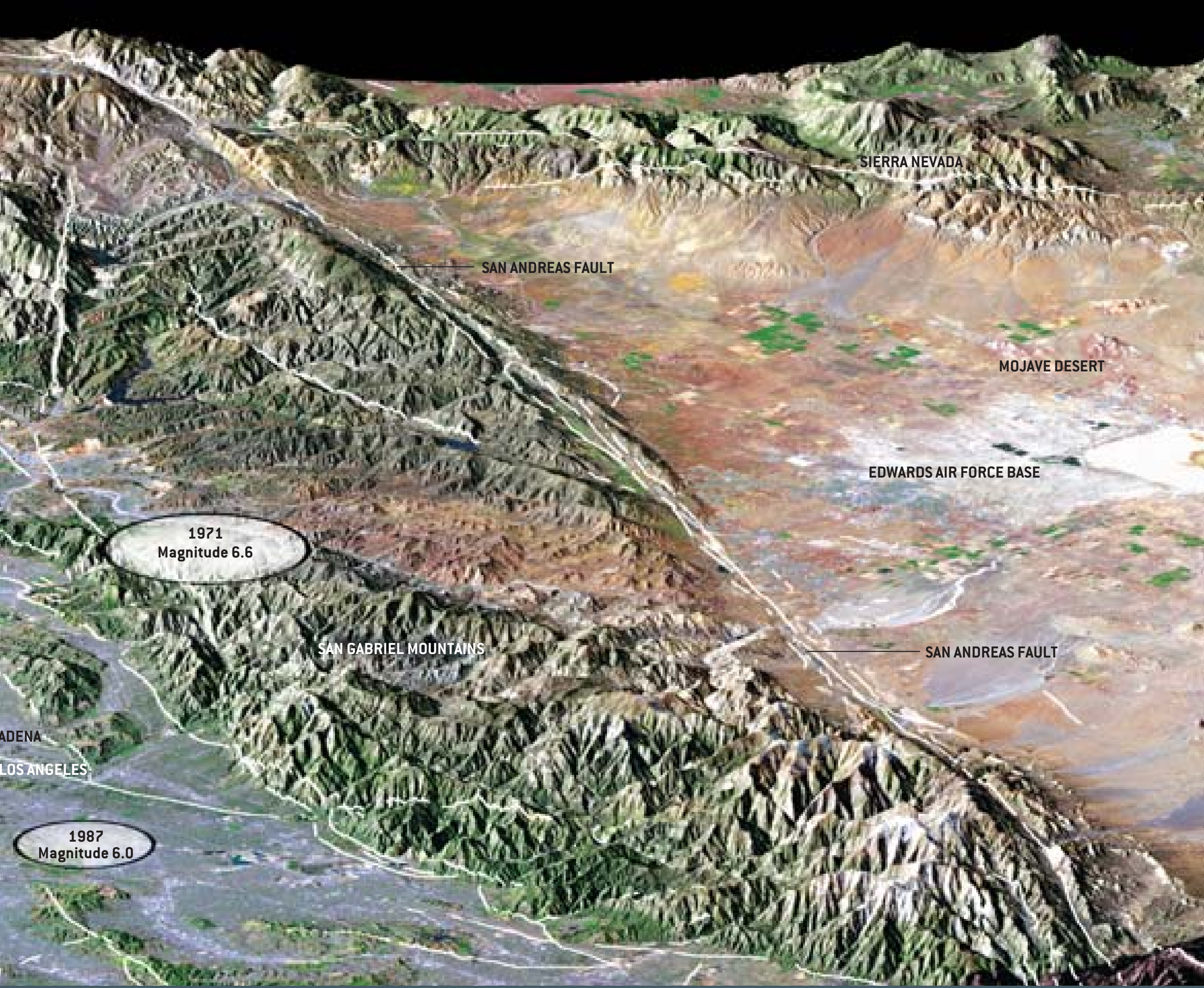
THIRTEEN MILLION PEOPLE in and around Los Angeles live among a complex network of earthquake-prone faults (*white lines*), including the famous San Andreas. Some scientists now think that each of the major shocks that have rocked the region since the 1850s (*ovals*) probably influenced the timing and location of subsequent ones.

Earthquake Conversations

Contrary to prevailing wisdom, large earthquakes can interact in unexpected ways. This exciting discovery could dramatically improve scientists' ability to pinpoint future shocks

By Ross S. Stein

Originally published in January 2003



For decades, earthquake experts dreamed of being able to divine the time and place of the world's next disastrous shock. But by the early 1990s the behavior of quake-prone faults had proved so complex that they were forced to conclude that the planet's largest tremors are isolated, random and utterly unpredictable. Most seismologists now assume that once a major earthquake and its expected aftershocks do their damage, the fault will remain quiet until stresses in the earth's crust have time to rebuild, typically over hundreds or thousands of years. A recent discovery—that earthquakes interact in ways never before imagined—is beginning to overturn that assumption.

This insight corroborates the idea that a major shock relieves stress—and thus the likelihood of a second major tremor—in some areas. But it also suggests that the probability of a succeeding earthquake elsewhere along the fault or on a nearby fault can actually jump by as much as a factor of three. To the people who must stand ready to provide emergency services or to those who set prices for insurance premiums, these refined predictions can be critical in determining which of their constituents are most vulnerable.

At the heart of this hypothesis—known as stress triggering—is the realization that faults are unexpectedly responsive to subtle stresses they acquire as neighboring faults shift and shake. Drawing on records of past tremors and novel calculations of fault behavior, my colleagues and I have learned that the stress relieved during an earthquake does not simply dissipate; instead it moves down the fault and concentrates in sites nearby. This jump in stress promotes subsequent tremors. Indeed, studies of about two dozen faults since 1992 have convinced many of us that earthquakes can be triggered even when the stress swells by as little as one eighth the pressure required to inflate a car tire.

Such subtle cause-and-effect relations among large shocks were not thought to exist—and never played into seismic forecasting—until now. As a result, many scientists have been understandably skeptical about embracing this basis for a new approach to forecasting. Nevertheless, the stress-triggering hypothesis has continued to gain credibility through its ability to explain the location and frequency of earthquakes that followed several destructive shocks in California, Japan and Turkey. The hope of furnishing better warnings for such disasters is the primary motivation behind our ongoing quest to interpret these unexpected conversations between earthquakes.

Aftershocks Ignored

CONTRADICTING the nearly universal theory that major earthquakes strike at random was challenging from the start—especially considering that hundreds of scientists searched in vain for more than three decades to find predictable patterns in global earthquake activity, or seismicity. Some investigators looked for changing rates of small tremors or used sensitive instruments to measure the earth's crust as it tilts, stretches and migrates across distances invisible to the naked eye. Others tracked underground movements of gases, fluids and electromagnetic energy or monitored tiny cracks in the rocks to see whether they open or close before large shocks. No matter what the researchers examined, they found little consistency from one major earthquake to another.

Despite such disparities, historical records confirm that about one third of the world's recorded tremors—so-called aftershocks—cluster in space and time. All true aftershocks were thought to hit somewhere along the segment of the fault that slipped during the main shock. Their timing also follows a routine pattern, according to observations first made in 1894 by Japanese seismologist Fusakichi Omori and since developed into a basic principle known as Omori's law. Aftershocks are most abundant immediately after a main shock. Ten days later the rate of aftershocks drops to 10 percent of the initial rate, 100 days later it falls to 1 percent, and so on. This predictable jump and decay in seismicity means that an initial tremor modifies the earth's crust in ways that raise the prospect of succeeding ones, contradicting the view that earthquakes occur randomly in time. But because aftershocks are typically smaller than the most damaging quakes scientists would like to be able to predict, they were long overlooked as a key to unlocking the secrets of seismicity.

Once aftershocks are cast aside, the remaining tremors indeed appear—at least at first glance—to be random. But why ignore the most predictable earthquakes to prove that the rest are without order? My colleagues and I decided to hunt instead for what makes aftershocks so regular. We began our search in one of the world's most seismically active regions—the San Andreas Fault system that runs through California. From local records of earthquakes and aftershocks, we knew that on the day following a magnitude 7.3 event, the chance of another large shock striking within 100 kilometers is nearly 67 percent—20,000 times the likelihood on any other day. Something about the first shock seemed to dramatically increase the odds of subsequent ones, but what?

That big leap in probability explains why no one was initially surprised in June 1992 when a magnitude 6.5 earthquake struck near the southern California town of Big Bear only three hours after a magnitude 7.3 shock occurred 40 kilometers away, near Landers. (Fortunately, both events took place in the sparsely populated desert and left Los Angeles unscathed.) The puzzling contradiction to prevailing wisdom was that the Big Bear shock struck far from the fault that had slipped during Landers's shaking. Big Bear fit the profile of an aftershock in its timing but not in its location. We suspected that its mysterious placement might hold the clue we were looking for.

By mapping the locations of Landers, Big Bear and hundreds of other California earthquakes, my colleagues and I began to notice a remarkable pattern in the distribution not only of true aftershocks but also of other, smaller earthquakes that

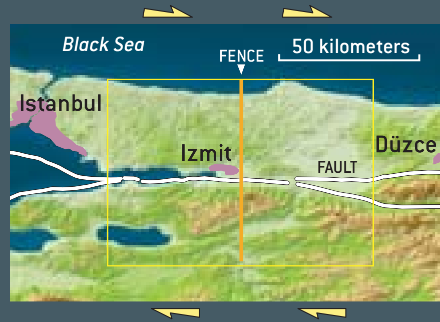
Overview/*Shifting Priorities*

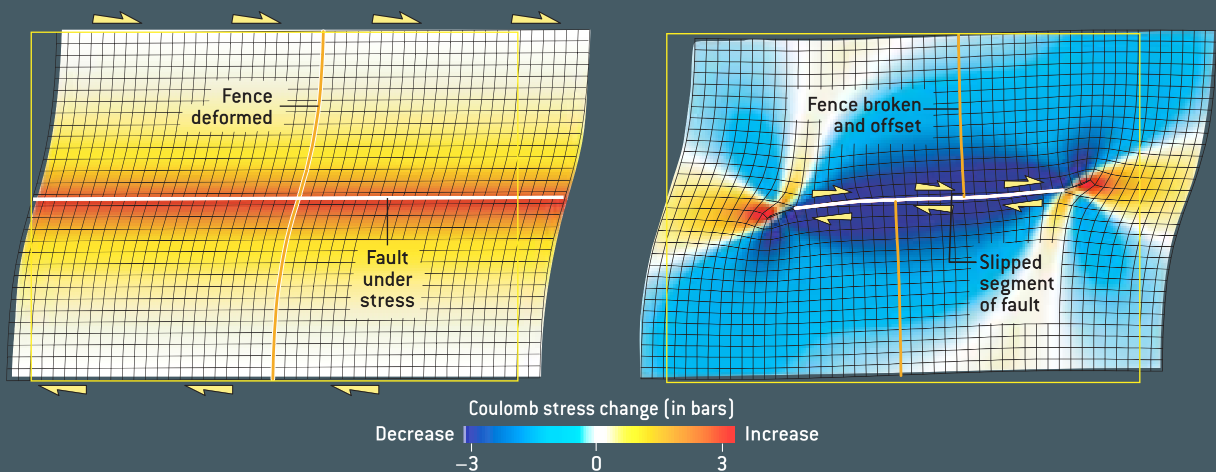
- Scientists used to think that one large earthquake has no notable influence on the timing or location of the next one, but a surprising new discovery is challenging that perspective.
- Earthquake-prone faults are now proving to be unexpectedly responsive to subtle stresses they acquire during shocks that strike along nearby faults.
- All else being equal, the regions in the earth's crust where the stress rises—even by a small amount—will be the sites of the next earthquakes.
- If this hypothesis turns out to be right, its implications could dramatically improve the ability of nations, cities and individuals to evaluate their earthquake vulnerability.

ROBERT E. CRIPPEN *Jet Propulsion Laboratory (preceding pages)*

STRESSED OUT

BUILDUP AND RELEASE of the stress that accumulates slowly as the earth's tectonic plates grind past one another mark the cycle of all great earthquakes. Along Turkey's North Anatolian fault (*white line*), the land north of the fault is moving eastward relative to the land to the south (*yellow arrows*) but gets stuck along the fault. When the stress finally overcomes friction along the fault, the rocks on either side slip past one another violently. A catastrophic example of this phenomenon occurred on August 17, 1999, when a magnitude 7.4 shock took 25,000 lives in and around the city of Izmit. Calculations of stress before and after the Izmit earthquake (*below*) reveal that, after the shock, the so-called Coulomb stress dropped along the segment of the fault that slipped but increased elsewhere. *—R.S.S.*





BEFORE THE EARTHQUAKE

The segment of the North Anatolian fault near Izmit accumulated significant stress (red) during the 200 years since its last major stress-relieving shock. An imaginary deformed fence and grid superimposed over the landscape illustrate this high stress. Squares along the fault are stretched into parallelograms (exaggerated 15,000 times), with the greatest change in shape, and thus stress, occurring closest to the fault.

AFTER THE EARTHQUAKE

The earthquake relieved stress (blue) all along the segment of the fault that slipped. The formerly deformed fence broke and became offset by several meters at the fault, and the grid squares closest to the fault returned to their original shape. High stress is now concentrated beyond both ends of the failed fault segment, where the grid squares are more severely contorted than before the shock struck.

SERKAN BOZKURT *U.S. Geological Survey*

follow a main shock by days, weeks or even years. Like the enigmatic Big Bear event, a vast majority of these subsequent tremors tended to cluster in areas far from the fault that slipped during the earthquake and thus far from where aftershocks are supposed to occur [*see box on page 23*]. If we could determine what controlled this pattern, we reasoned, the same characteristics might also apply to the main shocks themselves. And if that turned out to be true, we might be well on our way to developing a new strategy for forecasting earthquakes.

Triggers and Shadows

WE BEGAN BY LOOKING at changes within the earth's crust after major earthquakes, which release some of the stress that accumulates slowly as the planet's shifting tectonic plates grind past each other. Along the San Andreas Fault, for instance, the plate carrying North America is moving south relative to the one that underlies the Pacific Ocean. As the two sides move in opposite directions, shear stress is exerted parallel to the plane of the fault; as the rocks on opposite sides of the fault press against each other, they exert a second stress, perpendicular to the fault plane. When the shear stress exceeds the frictional resistance on the fault or when the stress pressing the two sides of the fault together is eased, the rocks on either side will slip past each other suddenly, releasing tremendous energy in the form of an earthquake. Both components of stress, which when added together are called Coulomb stress, diminish along the segment of the fault that slips. But because that stress cannot simply disappear, we knew it must be redistributed to other points along the same fault or to other faults nearby. We also suspected that this increase in Coulomb stress could be sufficient to trigger earthquakes at those new locations.

Geophysicists had been calculating Coulomb stresses for years, but scientists had never used them to explain seismicity. Their reasoning was simple: they assumed that the changes were too meager to make a difference. Indeed, the amount of stress transferred is generally quite small—less than 3.0 bars, or at most 10 percent of the total change in stress that faults typically experience during an earthquake. I had my doubts about whether this could ever be enough to trigger a fault to fail. But when Geoffrey King of the Paris Geophysical Institute, Jian Lin

Forecasting under Stress

So many features of earthquake behavior are still unknown that scientists have directed their limited insight to playing the odds

How people perceive the threat of an earthquake in their part of the world depends in great part on what kind of warnings are presented to them. Most of today's seismic forecasts assume that one earthquake is unrelated to the next. Every fault segment is viewed as having an average time period between tremors of a given size—the larger the shock, the greater the period, for example—but the specific timing of the shocks is believed to be random. The best feature of this method, known as a Poisson probability, is that a forecast can be made without knowing when the last significant earthquake occurred. Seismologists can simply infer the typical time period between major shocks based on geologic records of much older tremors along that segment of the fault. This conservative strategy yields odds that do not change with time.

In contrast, a more refined type of forecast called the renewal probability predicts that the chances of a damaging shock climb as more time passes since the last one struck. These growing odds are based on the assumption that stress along a fault increases gradually in the wake of a major earthquake. My colleagues and I build the probabilities associated with earthquake interactions on top of this second traditional technique by including the effects of stress changes imparted by nearby earthquakes. Comparing the three types of forecasts for Turkey's North Anatolian fault near Istanbul illustrates their differences, which are most notable immediately after a major shock.

In the years leading up to the catastrophic Izmit earthquake of August 1999, the renewal probability of a shock of magnitude 7 or greater on the four faults within 50 kilometers of Istanbul had been rising slowly since the last large earthquake struck each of them, between 100 and 500 years ago. According to this type of forecast, the August shock created a sharp drop in the likelihood of a second major tremor in the immediate vicinity of Izmit, because the faults there were thought to have relaxed. But the quake caused no change in the 48 percent chance of severe shaking 100 kilometers to the west, in Istanbul, sometime in the next 30 years. Those odds will continue to grow slowly with time—unlike the Poisson probability, which will remain at only 20 percent regardless of other tremors that may occur near the capital city.

When the effects of my team's new stress-triggering hypothesis were added to the renewal probability, everything changed. The most dramatic result was that the likelihood of a second quake rocking Istanbul shot up suddenly because some of the stress relieved near Izmit during the 1999 shock moved westward along the fault and concentrated closer to the city. That means the Izmit shock raised the probability of an Istanbul quake in the next 30 years from 48 percent to 62 percent. This so-called interaction probability will continue to decrease over time as the renewal probability climbs. The two forecasts will then converge at about 54 percent in the year 2060—assuming the next major earthquake doesn't occur before then. —***R.S.S.***

of the Woods Hole Oceanographic Institution in Massachusetts and I calculated the areas in southern California where stress had increased after major earthquakes, we were amazed to see that the increases—small though they were—matched clearly with sites where the succeeding tremors had clustered. The implications of this correlation were unmistakable: regions where the stress rises will harbor the majority of subsequent earthquakes, both large and small. We also began to see something equally astonishing: small reductions in stress could inhibit future tremors. On our maps, earthquake activity plummeted in these so-called stress shadows.

Coulomb stress analysis nicely explained the locations of certain earthquakes in the past, but a more important test would be to see whether we could use this new technique to forecast the sites of *future* earthquakes reliably. Six years ago I joined geophysicist James H. Dieterich of the U.S. Geological Survey (USGS) and geologist Aykut A. Barka of Istanbul Technical University to assess Turkey's North Anatolian fault, among the world's most heavily populated fault zones. Based on our calculations of where Coulomb stress had risen as a result of past earthquakes, we estimated that there was a 12 percent chance that a magnitude 7 shock or larger would strike the segment of the fault near the city of Izmit sometime between 1997 and 2027. That may seem like fairly low odds, but in comparison, all but one other segment of the 1,000-kilometer-long fault had odds of only 1 to 2 percent.

We did not have to wait long for confirmation. In August 1999 a magnitude 7.4 quake devastated Izmit, killing 25,000 people and destroying more than $6.5 billion worth of property. But this earthquake was merely the most recent in a falling-domino-style sequence of 12 major shocks that had struck the North Anatolian fault since 1939. In a particularly brutal five-year period, fully 700 kilometers of the fault slipped in a deadly westward progression of four shocks. We suspected that stress transferred beyond the end of each rupture triggered the successive earthquake, including Izmit's.

In November 1999 the 13th domino fell. Some of the Coulomb stress that had shifted away from the fault segment near Izmit triggered a magnitude 7.1 earthquake near the town of Düzce, about 100 kilometers to the east. Fortunately, Barka had calculated the stress increase resulting from the Izmit shock and had published it in the journal *Science* two months earlier. Barka's announcement had emboldened engineers to close school buildings in Düzce that were lightly damaged by the first shock despite pleas by school officials who said that students had nowhere else to gather for classes. Some of these buildings were flattened by the November shock.

If subsequent calculations by Parsons of the USGS, Shinji Toda of Japan's Active Fault Research Center, Barka, Dieterich and me are correct, that may not be the last of the Izmit quake's aftermath. The stress transferred during that shock has also raised the probability of strong shaking in nearby Istanbul, sometime this year from 1.9 percent to 4.2 percent. Over the next 30 years we estimate those odds to be 62 percent; if we assumed large shocks occur randomly, the odds would be just 20 percent [*see box above*].

The stress-triggering hypothesis offers some comfort alongside such gloom and doom. When certain regions are put on high alert for earthquakes, the danger inevitably drops in others. In Turkey the regions of reduced concern happen to be sparsely populated relative to Istanbul. But occasionally the opposite is true. One of the most dramatic examples is the relative lack of seismicity that the San Francisco Bay Area, now home to five million people, has experienced since the great magnitude 7.9 earthquake of 1906. A 1998 analysis by my USGS colleagues Ruth A. Harris and Robert W. Simpson demonstrated that the stress shadows of the 1906 shock fell across several parallel strands of the San Andreas Fault in the Bay Area, while the stress increases occurred well to the north and south. This could explain why the rate of damaging shocks in the Bay Area dropped by an order of magnitude compared with the 75 years preceding 1906. Seismicity in the Bay Area is calculated to slowly emerge from this shadow as stress rebuilds on the faults; the collapsed highways and other damage wrought by the 1989 Loma Prieta shock may be a harbinger of this reawakening.

Bolstering the Hypothesis

EXAMINATIONS OF the earthquakes in Turkey and in southern California fortified our assertion that even tiny stress changes can have momentous effects, both calming and catastrophic. But despite the growing number of examples we had to support this idea, one key point was difficult to explain: roughly one quarter of the earthquakes we examined occurred in areas where stress had *decreased*. It was easy for our more skeptical colleagues to argue that no seismicity should occur in these shadow zones, because the main shock would have relieved at least some stress and thus pushed those segments of the fault further from failure. We now have an answer. Seismicity never shuts off completely in the shadow zones, nor does it turn on completely in the trigger zones. Instead the *rate* of seismicity—the number of earthquakes per unit of time—merely drops in the shadows or climbs in the trigger zones relative to the preceding rate in that area.

We owe this persuasive extension of stress triggering to a theory proposed by Dieterich in 1994. Known as rate/state friction, it jettisons the comfortable concept of friction as a property that can only vary between two values—high friction when the material is stationary and lower friction when it is sliding. Rather, faults can become stickier or more slippery as the rate of movement along the fault changes and as the history of motion, or the state, evolves. These conclusions grew out of lab experiments in which Dieterich's team sawed a miniature fault into a Volkswagen-size slab of granite and triggered tiny earthquakes.

When earthquake behavior is calculated with friction as a variable rather than a fixed value, it becomes clear that Omori's law is a fundamental property not just of so-called aftershocks but of *all* earthquakes. The law's prediction that the rate of shocks will first jump and then diminish with time explains why a region does not forever retain the higher rate of seismicity that results from an increase in stress. But that is only half the story. Dieterich's theory reveals a characteristic of the seismicity that Omori's law misses entirely. In areas where a main shock relieves stress, the rate of seismicity immediately plunges but will slowly return to preshock values in a predictable manner. These points may seem subtle, but rate/state friction allowed us for the first time to make predictions of how jumps or declines in seismicity would change over time. When calculating Coulomb stresses alone, we could define the general location of new earthquakes but not their timing.

Our emerging ideas about both the place and the time of stress-triggered earthquakes were further confirmed by a global study conducted early last year. Parsons considered the more than 100 earthquakes of magnitude 7 or greater that have occurred worldwide in the past 25 years and then examined all subsequent shocks of at least magnitude 5 within 250 kilometers of each magnitude 7 event. Among the more than 2,000 shocks in this inventory, 61 percent occurred at sites where a preceding shock increased the stress, even by a small amount. Few of these triggered shocks were close enough to the main earthquake to be considered an aftershock, and in all instances the rate of these triggered tremors decreased in the time period predicted by rate/state friction and Omori's law.

Now that we are regularly incorporating the concept of rate/state friction into our earthquake analyses, we have begun to uncover more sophisticated examples of earthquake interaction than Coulomb stress analyses alone could have illuminated. Until recently, we had explained only relatively simple situations, such as those in California and Turkey, in which a large earthquake spurs seismicity in some areas and makes it sluggish in others. We knew that a more compelling case for the stress-triggering hypothesis would be an example in which successive, similar-size shocks are seen to turn the frequency of earthquakes up and down in the same spot, like a dimmer switch on an electric light.

Toda and I discovered a spectacular example of this phenomenon, which we call toggling seismicity. Early last year we began analyzing an unusual pair of magnitude 6.5 earthquakes that struck Kagoshima, Japan, in 1997. Immediately following the first earthquake, which occurred in March, a sudden burst of seismicity cropped up in a 25-square-kilometer region just beyond the west end of the failed segment of the fault. When

THE AUTHOR

ROSS S. STEIN is a geophysicist with the U.S. Geological Survey's Earthquake Hazards Team in Menlo Park, Calif. He joined the survey in 1981 after earning a Ph.D. from Stanford University in 1980 and serving as a postdoctoral fellow at Columbia University. Stein's research, which has been devoted to improving scientists' ability to assess earthquake hazards, has been funded by U.S. agencies such as the Office of Foreign Disaster Assistance and by private companies, including the European insurance company Swiss Re. For the work outlined in this article, Stein received the Eugene M. Shoemaker Distinguished Achievement Award of the USGS in 2000. He also presented the results in his Frontiers of Geophysics Lecture at the annual meeting of the American Geophysical Union in 2001. Stein has appeared in several TV documentaries, including *Great Quakes: Turkey* (Learning Channel, 2001).

we calculated where the initial earthquake transferred stress, we found that it fell within the same zone as the heightened seismicity. We also found that the rate immediately began decaying just as rate/state friction predicted. But when the second shock struck three kilometers to the south only seven weeks later, the region of heightened seismicity experienced a sudden, additional drop of more than 85 percent. In this case, the trigger zone of the first earthquake had fallen into the shadow zone of the second one. In other words, the first quake turned seismicity up, and the second one turned it back down.

A New Generation of Forecasts

EAVESDROPPING ON the conversations between earthquakes has revealed, if nothing else, that seismicity is highly interactive. And although phenomena other than stress transfer may influence these interactions, my colleagues and I believe that enough evidence exists to warrant an overhaul of traditional probabilistic earthquake forecasts. By refining the likelihood of dangerous tremors to reflect subtle jumps and declines in stress, these new assessments will help governments, the insurance industry and the public at large to better evaluate their earthquake risk. Traditional strategies already make some degree of prioritizing possible, driving the strengthening of buildings and other precautions in certain cities or regions at the expense of others. But our analyses have shown that taking stress triggering into account will raise different faults to the top of the high-alert list than using traditional methods alone will. By the same token, a fault deemed dangerous by traditional practice may actually be a much lower risk.

An important caveat is that any type of earthquake forecast is difficult to prove right and almost impossible to prove wrong. Regardless of the factors that are considered, chance plays a tremendous role in whether a large earthquake occurs, just as it does in whether a particular weather pattern produces a rainstorm. The meteorologists' advantage over earthquake scientists is that they have acquired millions more of the key measurements that help improve their predictions. Weather patterns are much easier to measure than stresses inside the earth, after all, and storms are much more frequent than earthquakes.

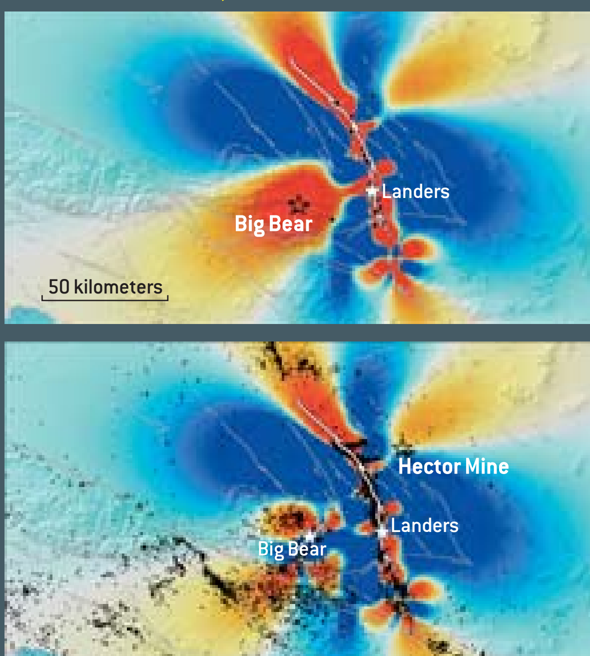
Refining earthquake prediction must follow the same path, albeit more slowly. That is why my team has moved forward by building an inventory of forecasts for large earthquakes near the shock-prone cities of Istanbul, Landers, San Francisco and Kobe. We are also gearing up to make assessments for Los Angeles and Tokyo, where a major earthquake could wreak trillion-dollar devastation. Two strong shocks along Alaska's Denali fault in the fall of 2002—magnitude 6.7 on October 23 and magnitude 7.9 on November 3—appear to be another stress-triggered sequence. Our calculations suggest that the first shock increased the likelihood of the second by a factor of 100 during the intervening 10 days. We are further testing the theory by forecasting smaller, nonthreatening earthquakes, which are more numerous and thus easier to predict.

In the end, the degree to which any probabilistic forecast will protect people and property is still uncertain. But scientists have plenty of reasons to keep pursuing this dream: several hundred million people live and work along the world's most active fault zones. With that much at stake, stress triggering—or any other phenomenon that has the potential to raise the odds of a damaging earthquake—should not be ignored. SA

EARTHQUAKE CLUSTERS

PLACES WHERE STRESS JUMPS (*red*) after major earthquakes (*filled stars*) tend to be the sites of subsequent tremors, both large (*open stars*) and small (*black dots*). Conversely, few tremors occur where the stress plummets (*blue*), regardless of the location of nearby faults (*white lines*). —*R.S.S.*

SOUTHERN CALIFORNIA, U.S.



MAGNITUDE 7.3 SHOCK in the southern California desert near Landers in 1992 increased the expected rate of earthquakes to the southwest, where the magnitude 6.5 Big Bear shock struck three hours later (*top*). Stresses imparted by the combination of the Landers and Big Bear events coincided with the regions where the vast majority of tremors occurred over the next seven years, culminating with the magnitude 7.1 Hector Mine quake in 1999 (*bottom*).

SERKAN BOZKURT *USGS*, KEITH RICHARDS-DINGER *U.S. Navy* AND SHINJI TODA *Japan's Active Fault Research Center*

MORE TO EXPLORE

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Heightened Odds of Large Earthquakes Near Istanbul: An Interaction-Based Probability Calculation. Tom Parsons, Shinji Toda, Ross S. Stein, Aykut Barka and James H. Dieterich in *Science*, Vol. 288, pages 661–665, April 28, 2000.

View earthquake animations and download Coulomb 2.2 (Macintosh software and tutorial for calculating earthquake stress changes) at **http://quake.usgs.gov/~ross**

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Lightning Control with Lasers

Scientists seek to deflect damaging lightning strikes using specially engineered lasers

by Jean-Claude Diels, Ralph Bernstein, Karl E. Stahlkopf and Xin Miao Zhao

Despite centuries of scientific scrutiny—including Benjamin Franklin's famous experiment with a kite—lightning has remained a strangely mysterious phenomenon. Although scientists from Franklin's time onward have understood that electrical charges can slowly accumulate in clouds and then create brilliant flashes when the stored energy suddenly discharges, they puzzled for years over the exact physical mechanisms governing this process. How quickly do lightning strokes travel? What determines the path the energy takes? What happens to the bolt of electric current after it penetrates the ground? Such questions eventually yielded to scientific investigation. And this research has not only expanded the fundamental understanding of lightning, it has raised the prospect of exerting control over where lightning strikes—something traditionally considered a matter of divine whim.

Although lightning is inherently erratic, its aggregate effect is enormous. Every year in the U.S. (where about 20 million individual flashes hit the ground), lightning kills several hundred people and causes extensive property damage, including forest fires. Lightning is also responsible for about half the power failures in areas prone to thunderstorms, costing electric utility companies in this country perhaps as much as $1 billion annually in damaged equipment and lost revenue. Lightning can also disrupt the navigational devices on commercial airliners (or even on rockets bound for space), and it has caused one serious malfunction at a nuclear power plant.

So it is no wonder that people have sought ways to prevent lightning from doing harm. Unlike the ancients who tried to protect themselves by offering sacrifices to the gods, scientists and engineers have come up with solutions that have proved moderately successful. People can often avoid the worst effects of lightning by mounting well-grounded lightning rods on buildings, as first suggested by Franklin soon after he reeled in his experimental kite in 1752. Although he initially believed that such pointed rods worked because "the electrical fire would... be drawn out of the cloud silently, before it could come near enough to strike," Franklin later realized that these devices either channel the discharge or work to direct lightning away. This same principle—to divert rather than to prevent a strike—provides the basis for currently used methods of protection (such as lightning arrestors or grounded shielding) as well as our own efforts toward controlling lightning with lasers.

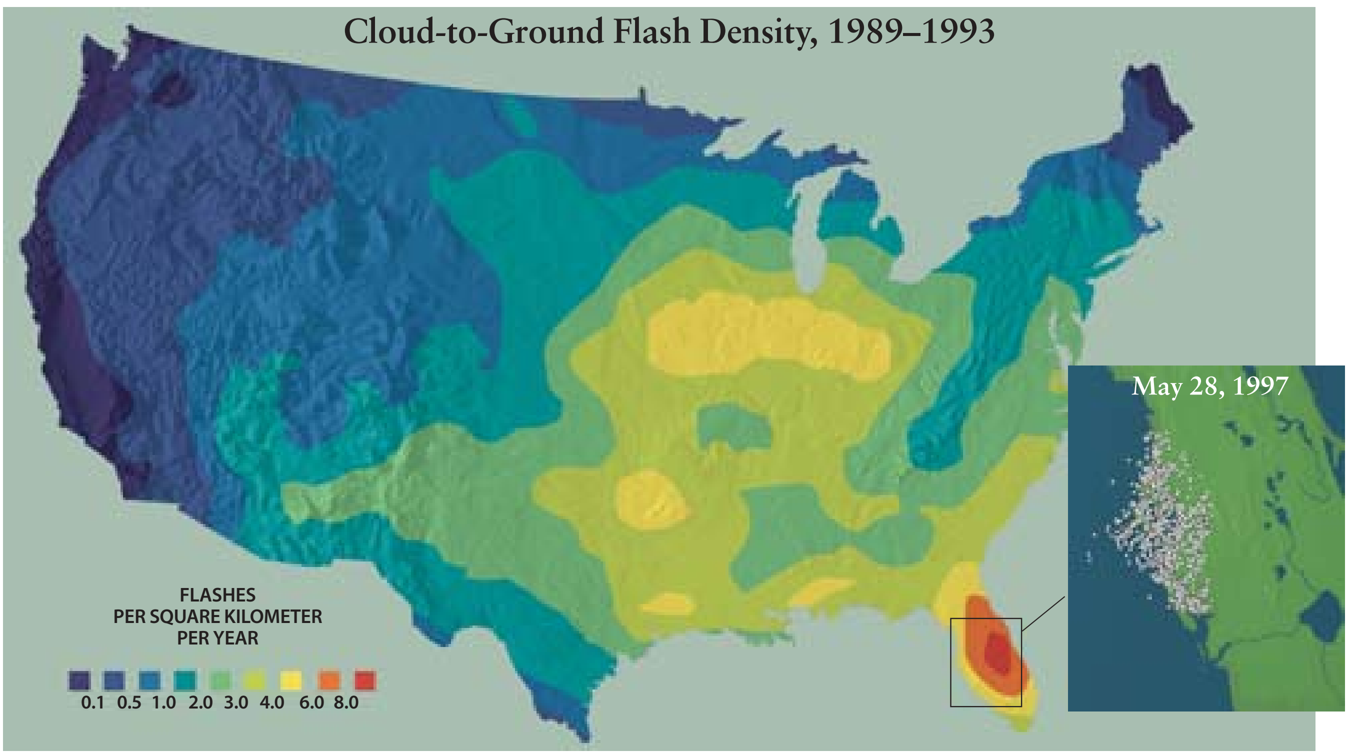
Locating the Problem

Beginning in the late 1970s, researchers at the State University of New York at Albany established a small network of direction-finding antennas that served to track cloud-to-ground lightning strikes over a limited area of their state. Throughout the 1980s, that network of specialized detectors slowly expanded to include other states, and by 1991 (the year commercial operations started), this group of specialized antennas could sense the occurrence of lightning anywhere in the country.

That vast array, now known as the National Lightning Detection Network, consists of about 100 stations that monitor lightning by sensing the exact timing and direction of the bursts of electromagnetic energy given off by these discharges. The stations relay their many measurements through communications satellites to a control center in Tucson, Ariz., where a computer processes this information and continually disseminates reports about lightning activity. Hundreds of subscribers benefit from this service, including various electric utility companies, airlines and even the U.S. Strategic Air Command. The managers of some electric utilities, for example, have been able to save more than half a million dollars annually by using this information to dispatch repair crews swiftly to sites where lightning might soon strike or where it has already damaged the lines. But the people who oversee particularly sensitive installations—including nuclear power plants and electric power substations—await even more sophisticated methods to make lightning less of a threat.

Efforts to satisfy that need include research being conducted at a unique field laboratory near Starke, Fla. In 1993 two of us (Bernstein and Stahlkopf), along with other members of the Electric Power Research Institute in Palo Alto, Calif., arranged for Power Technologies in Schenectady, N.Y., to build a special facility at the Camp Blanding Florida National Guard station to test the susceptibility of various underground and overhead structures to damage from lightning. Rather than waiting for a chance strike, researchers working at this field site (which is now operated by the University of Florida) can trigger lightning using small rockets that trail a thin, grounded wire.

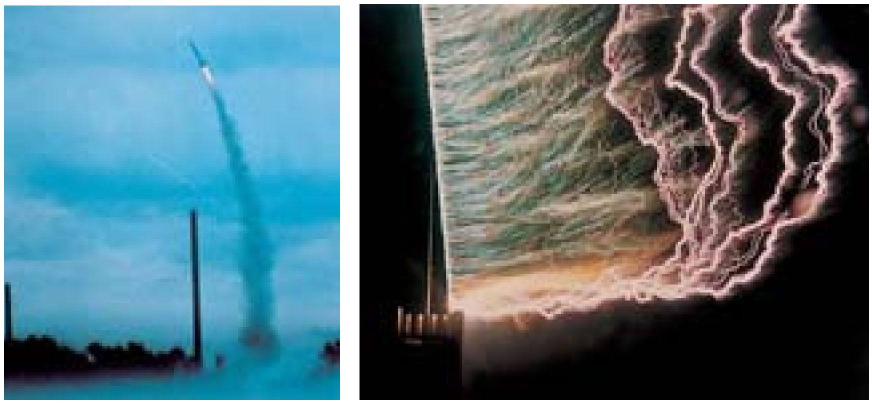
Unlike such triggered discharges, a natural lightning bolt begins with a barely visible precursor, called the leader phase, which propagates downward from the cloud toward the ground in stepwise fashion, knocking electrons loose from molecules of atmospheric gas



SOURCE: GLOBAL ATMOSPHERICS, INC.; LAURIE GRACE (*map*); WILLIAM F. HAXBY (*inset*)

NATIONAL LIGHTNING DETECTION NETWORK, which is now run by Global Atmospherics in Tucson, Ariz., monitors lightning activity across the U.S., where the density of lightning flashes varies enormously. By tracking the timing and direction of electromagnetic pulses given off by lightning, this network of sensors can pinpoint the location of individual flashes and estimate their magnitudes. The inset shows the many flashes that struck western Florida during a spring thunderstorm.

along the way and creating a channel of ionized air that then serves as a conductive conduit. Immediately after the leader phase connects with the ground, the bright and energetic "return phase" erupts. As happens during the leader phase, the return stroke, which carries currents that range from a few thousand amperes up to about 300,000 amperes (household wiring typically carries no more than a few tens of amperes), is driven by the tremendous voltage potential—hundreds of millions of volts—between the ground and the thunderclouds overhead. This dazzling bolt travels at speeds that can approach half the speed of light, and the huge electric current it carries with it can easily destroy an object caught in its path.



ROCKETS trigger lightning in various field experiments. The small, specially constructed missile carries at its base a spool of thin, grounded wire that unwinds in flight (*left*). The first stroke triggered in this way follows this copper filament and creates a conductive channel of ionized air; later strokes of the same flash event (which can occur repeatedly within a fraction of a second) travel along increasingly tortuous routes as the wind deforms the conductive path (*right*).

COURTESY OF RALPH BERNSTEIN

Averting Catastrophe

Just as rockets trailing grounded wires represent a modern version of Franklin's kite experiment, we believe that in the near future laser beams may serve as high-tech lightning rods, offering a way to divert lightning from especially critical sites where it might do great harm. Decades ago some forward-thinking people envisioned using lasers to trigger lightning by creating an electrically conductive channel of ionized air. But their attempts—including some that employed the most intense lasers available—were unsuccessful. Those lasers ionized the air so thoroughly as to make it essentially opaque to the beam, which then could not penetrate any farther.

Two teams of Japanese scientists have recently endeavored to overcome this difficulty by using powerful infrared lasers. Rather than trying to create a continuous channel of ionized particles, these scientists have worked out a way to focus one or more laser beams at successively displaced points so as to create a dotted line of separate plasma bubbles along the intended path of the lightning bolt. They have achieved a controlled discharge more than seven meters long in laboratory tests. Still, they were able to achieve that feat only with extreme electrical fields, when the air was already close to the point of breaking down spontaneously.

Two of us (Diels and Zhao) have explored another approach that uses ultraviolet light from a relatively low energy laser. At first glance, this technique does not seem at all promising. Such beams do not ionize the air molecules in their paths particularly effectively, and the few negatively charged electrons that are shaken loose by the ultraviolet light quickly combine with neutral oxygen molecules nearby, forming negative oxygen ions (which reduce the conductivity of the channel). Nevertheless, this method can produce uniform ionization along an extended straight path. That ionized line then acts much as a lightning rod, concentrating the electrical field so intensely at its tip that the air ahead breaks down and adds more length to the conductive path.

We have also found that directing a second visible-light laser along the path of the ultraviolet beam counteracts the tendency for free electrons to attach to neutral oxygen molecules, forming negative oxygen ions. This tactic works because photons of the visible-light beam carry sufficient energy to knock electrons free from the negative ions.

Although the ultraviolet laser we have tested operates at low power levels overall, it ionizes air surprisingly well. The key is to use extremely short laser pulses. The brief duration of these bursts (less than a trillionth of a second) makes it possible for the laser light to have high peak intensity, although the average power consumed by the apparatus is quite modest.

What is more, we can take advantage of the physics of laser propagation in air and impart a particular shape to the pulses emitted by the laser. The pulses will then tend to compress as they propagate through the atmosphere. The higher energies jammed into these compact packages of light compensate for energy lost along the way from scattering or absorption.

Although we have not yet tried to trigger lightning in this way, the agreement of our theoretical calculations, numerical simulations and small-scale laboratory experiments makes us confident that we are well on the way. We have, for example, succeeded in using short pulses of ultraviolet laser light to create a conductive channel between two highly charged electrodes spaced 25 centimeters apart. The lasers are able to trigger an electrical discharge when the voltage difference between the electrodes is less than half of what is normally required for the air to break down. That is, we can force laboratory-scale lightning to form along a prescribed channel well in advance of the point that a discharge would spontaneously occur.

Moving Outdoors

With the help of Patrick Rambo, our colleague at the University of New Mexico, we have recently built an ultraviolet laser that is 100 times more powerful than any we have previously tested. We plan to fire this laser 10 times each second during a thunderstorm. Although we are anxious to see just how effective such a laser can be, we have not yet arranged the proper preliminary tests, which require a special high-voltage facility, such as the one operated by Mississippi State University.

Unfortunately, our laser is too delicate and cumbersome to move across the country. But we hope soon to complete a mobile ultraviolet laser, which (when coupled to a suitable visible-light laser) should be able to trigger laboratory dis-

ALFRED T. KAMAJIAN

LASER DIVERSION of lightning might take various forms. Engineers initially imagined that powerful infrared lasers could produce a conductive path in the sky, but these beams completely ionize the air in front of them, which then becomes opaque and scatters the light (*a*). Researchers in Japan are experimenting with multiple beams that are focused using a series of mirrors to form a line of ionized pockets that should help channel a lightning bolt (*b*). The authors' method relies on paired ultraviolet and visible-light laser beams (aimed upward with a single mirror), which should be able to form a straight path of ionization for lightning to follow (*c*). Grounded rods would interrupt the resulting lightning strike, protecting the mirror and the laser apparatus. Alternatively, the beam could be arranged to graze a tall grounded mast as it shoots skyward.

charges many meters long. Perhaps the same laser pair will finally provide the means to set off lightning from clouds—an accomplishment that has so far eluded our various competitors working with other types of lasers.

If any of these approaches to sparking lightning with laser beams ultimately succeeds, application of the technique could be commonplace. Lasers might one day scan the skies over nuclear power plants, airports and space launch centers. And electric utilities of the 21st century, with their growing network of equipment at risk, may finally acquire the means to act on the threat of a gathering storm, instead of being destined to react only after the damage is done.

The Authors

JEAN-CLAUDE DIELS, RALPH BERNSTEIN, KARL E. STAHLKOPF and XIN MIAO ZHAO became involved in lightning diversion for somewhat different reasons. Diels, a professor in the department of physics and astronomy at the University of New Mexico, and Zhao, a researcher at Los Alamos National Laboratory, began working together in 1990 with "ultrafast" pulsed lasers and quickly saw the possibility of using such devices to control lightning. After two years of further research, they received a patent for their invention. Bernstein, a project manager at the Electric Power Research Institute, and Stahlkopf, a vice president working with him, both trained as electrical engineers; they earned, respectively, a master's degree from Syracuse University and a doctorate from the University of California, Berkeley. Their wish to speed the development of technologies to lessen the damage from lightning motivated them to provide funding for lightning detection, rocket-triggered lightning experiments and, most recently, lightning control with lasers.

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 Originally published in August 1997

Lightning between Earth and Space

Scientists discover a curious variety of electrical activity going on above thunderstorms

by Stephen B. Mende, Davis D. Sentman and Eugene M. Wescott

STEPHEN B. MENDE AND R. L. RAIRDEN; COLORIZATION BY LAURIE GRACE

SPRITES are high-altitude luminous flashes that take place above thunderstorms in a part of the atmosphere called the mesosphere. Although sprites are usually rare, some storms can spawn them frequently. Typically the upper parts of clouds are charged positively and the lower parts negatively. Most often, it is the negative base of the cloud that flashes to the ground. But at times the upper, positive part can discharge directly to the earth, producing a lightning flash of exceptional intensity. About one out of 20 such positive cloud-to-ground lightning bolts are sufficiently energetic that they spawn sprites. These examples, recorded from the ground with a monochromatic video camera, have been colorized to match a color image obtained from an aircraft.

Since ancient times, lightning has both awed and fascinated people with its splendor and might. The early Greeks, for instance, associated the lightning bolt with Zeus, their most powerful god. And even after a modern understanding of the electrical nature of lightning developed, certain mysteries persisted. Many observers described luminous displays flickering through the upper reaches of the night sky. Some of these curiosities could be explained as auroras or weirdly illuminated clouds, but others were more baffling. In particular, pilots flying through the darkness occasionally observed strange flashes above thunderstorms. But the scientific community largely regarded these reports as apocryphal—until 1990, when John R. Winckler and his colleagues at the University of Minnesota first captured one of these enigmatic phantoms using a video camera. Their images revealed lightning of a completely new configuration.

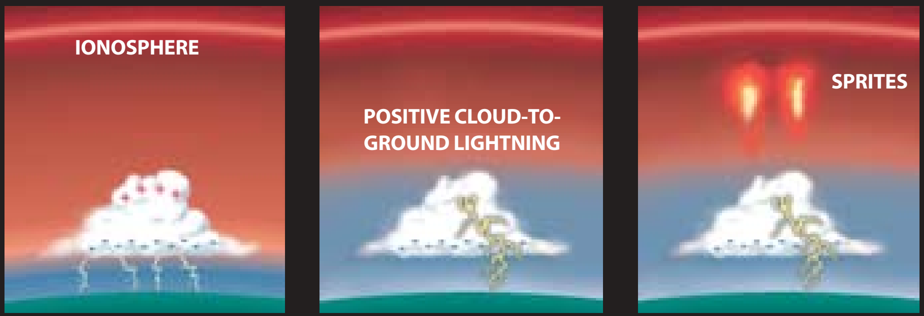
Winckler's achievement ushered in a flurry of activity to document such high-altitude electrical phenomena. And hundreds of similar observations—from the space shuttle, from aircraft and from the ground—have since followed. The result has been a growing appreciation that lightninglike effects are not at all restricted to the lower atmospheric layers sandwiched between storm clouds and the ground. Indeed, scientists now realize that electrical discharges take place regularly in the rarefied air up to 90 kilometers above thunderclouds.

It is remarkable that these events, many of which are visible to the naked eye, went undiscovered for so long. In retrospect, the existence of some form of lightning high in the atmosphere should not have come as a surprise to scientists. They have long known that well above the turbulent parts of the atmosphere, ultraviolet rays from the sun strike gas molecules and knock electrons loose from them. This process forms the ionosphere, an electrically conductive layer that encircles the earth. Large differences in voltage can exist between storm clouds and the ionosphere, just as they do between clouds and the ground. Impelled by such enormous voltages, lightning can invade either zone when the air—which is typically an electrical insulator—breaks down and provides a conductive path for electric currents to follow.

Because the atmosphere becomes less dense with increasing altitude, the lightning that happens at greater heights involves fewer air molecules and produces colors not seen in typical discharges. Usually they appear red and are only faintly visible. Thus, researchers must employ sensitive video cameras to record these events against the backdrop of the darkened night sky. The feebleness of the light given off and the transient nature of such emissions combine to present severe technical challenges to the researchers involved in studying these ghostly atmospheric events. Nevertheless, in just a few years investigators have made considerable progress in understanding them.

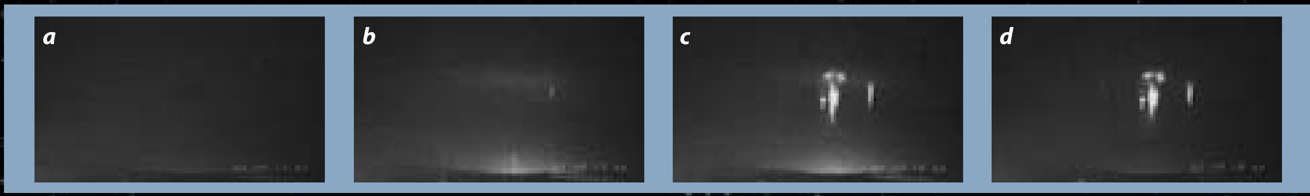
Two of us (Sentman and Wescott) have mounted airborne research campaigns using specially outfitted jets. All three of us (and many others) have also studied high-altitude electrical activity from the ground: for example, we gather every year at the invitation of Walter A. Lyons, a scientist at ASTeR in Fort Collins, Colo., and set up our equipment in his backyard laboratory—a site that offers an unobstructed view of the night sky over the thunderstorms of the Great Plains. (The images on pages 28 and 30 are views from this informal observatory.) Umran S. Inan and his colleagues at Stanford University have also recorded low-frequency radio waves from Lyons's home, measurements that have helped them to formulate theoretical models.

The newly discovered electrical events of the upper atmosphere fall into four categories. Two types of high-level lightning, termed sprites and elves, appear (despite their fanciful names) to be manifestations of well-understood atmospheric physics. The causes for the other two varieties, called blue jets and gamma-ray events, remain more speculative. But our research group and many others around the world are still amassing our observations in hopes of deciphering the physical mechanisms driving these strange occurrences as well. Until that time, we must admit something like the ancient sense of awe and wonder when we contemplate these curious bursts of energy that dance through the ethereal world between earth and space.



LIGHTNING (*left*) usually carries negative charge from the base of a cloud down to the earth. Sometimes powerful strokes (*center*) cause the positive charge that had built up near the top of the cloud to disappear abruptly. The large electrical field (*gradation in color*) created between the cloud top and the ionosphere pulls electrons upward, where they collide with gas molecules. If the electrical field is sufficiently strong and the air sufficiently thin, the electrons will accelerate unimpeded and reach the velocity needed to transfer their kinetic energy to the electronic structure of the molecules with which they collide, raising such molecules to an "excited state." The excited molecules give away their newly acquired energy by the emission of light, causing sprites (*right*). They typically span from 50 to 90 kilometers altitude.

BRYAN CHRISTIE



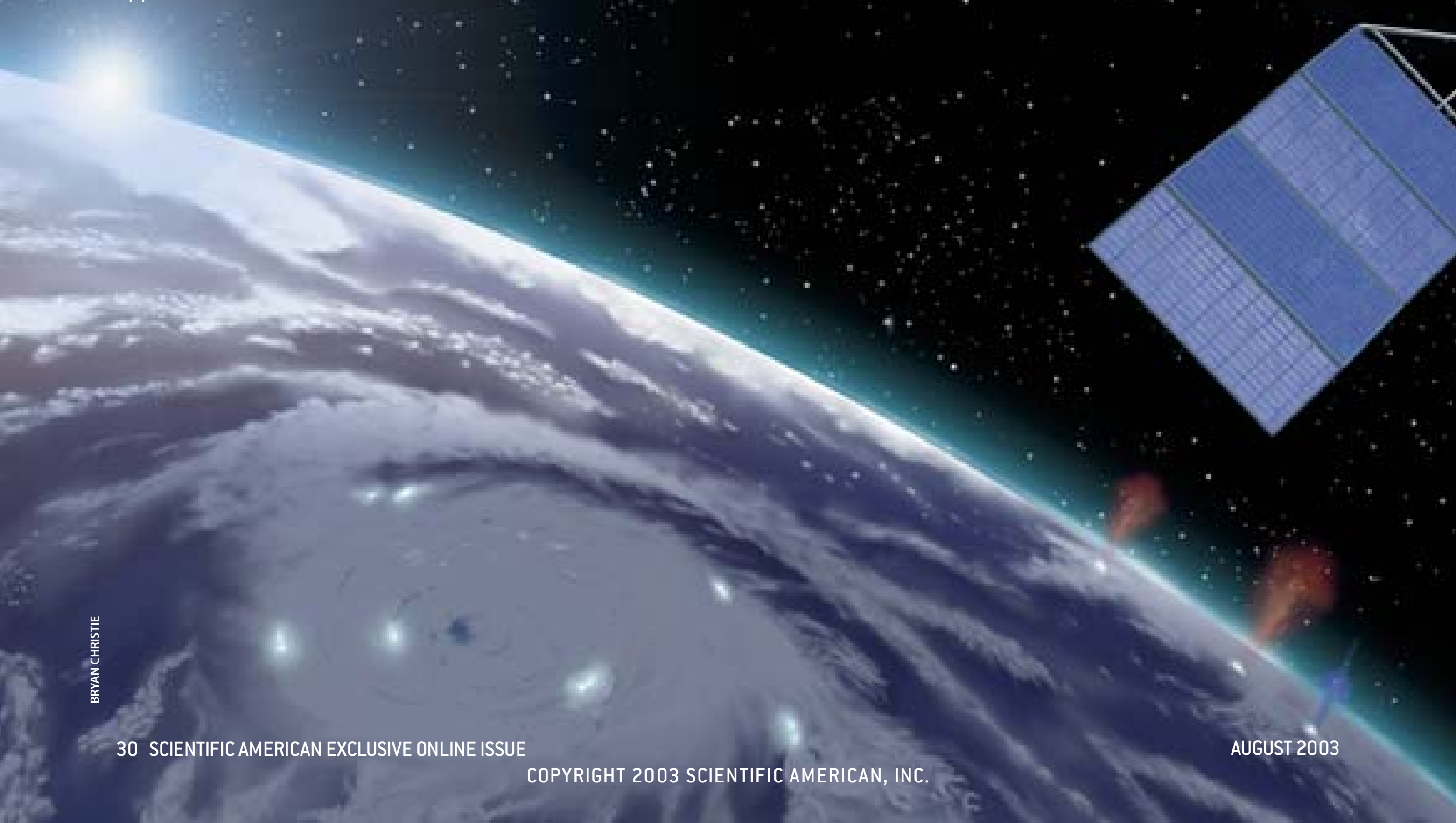
STEPHEN B. MENDE

ELVES, like sprites, are high-altitude manifestations of the electrical fields created by exceptionally intense conventional lightning. They show themselves as glowing, pancake-shaped layers (*below, right, colorized to match the most probable true appearance*). Elves can occur with sprites but form first and do not last as long. The sequence of video images (*above*) shows the relative timing: just before the conventional lightning strike occurs, the sky is uniformly dark (*a*). The ensuing flash illuminates the cloud deck and immediately spawns the flattened glow of elves high in the mesosphere (*b*). Momentarily, sprites erupt throughout this part of the atmosphere, adding their radiance to the faint light from the luminous layer (*c*). Finally, only the sprites persist (*d*).

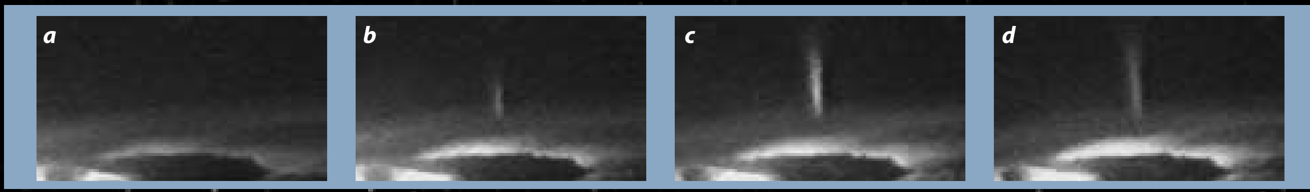
BRYAN CHRISTIE

STEPHEN B. MENDE

ELECTROMAGNETIC PULSES given off by strong lightning discharges create elves. Such a pulse, which is in essence an intense burst of radio static, propagates at the speed of light in all directions away from a lightning bolt. When the upward-going part of the pulse (*spherical shells*) reaches a critical height in the atmosphere (about 75 to 100 kilometers), the electrical field it carries accelerates electrons with great efficiency. These electrons strike air molecules, knocking them into an excited state that allows the release of light. This mechanism generates expanding rings of light along the intersection of the spherical pulse with the critical layer. This intersection widens so quickly (in fact, faster than the speed of light) that these expanding rings appear as flattened disks.



BRYAN CHRISTIE



BLUE JETS, which are restricted to the part of the atmosphere below about 40 kilometers altitude, are comparatively difficult to observe. So observation requires going above the dense lower atmosphere. Sentman and Wescott recorded such eerie cones of blue light for the first time while flying over an intense storm in Arkansas in 1994. This sequence of video images from a sensitive monochromatic camera (*a–d*) reveals how these lights jet upward from the top of thunderclouds at speeds of about 120 kilometers per second. Researchers are still trying to reconcile competing theories to explain exactly how blue jets come about.

GAMMA-RAY AND X-RAY events above thunderstorms are the most puzzling of all high-altitude electrical phenomena. Their existence was uncovered only recently by one of the instruments on the Compton Gamma Ray Observatory satellite (*left*), which showed gamma rays emanating from the direction of the earth. Gamma rays are usually taken as signatures of high-energy nuclear or cosmic sources and thus were not expected to be produced within the earth's atmosphere. In sprites, for example, electrons rarely reach energies above about 20 electron volts (the energy a single electron would gain when accelerated by a potential difference of 20 volts), whereas gamma rays require about one million electron volts. The discrepancy is the same as the difference between the energy of a chemical explosive and an atomic bomb. As is the case with blue jets, gamma-ray events are just now beginning to yield to scientific scrutiny. Future observations from satellites should help in this quest.

The Authors

STEPHEN B. MENDE, DAVIS D. SENTMAN and EUGENE M. WESCOTT have spent much of their time during recent years investigating curious electrical activity of the upper atmosphere. Mende received a Ph.D. in physics from Imperial College at the University of London in 1965. From 1967 to 1996 he worked for Lockheed Palo Alto Research Laboratory. Mende is currently a fellow at the space sciences laboratory of the University of California, Berkeley. Sentman studied space physics under James Van Allen at the University of Iowa, where he earned his doctorate in 1976. After 14 years at the University of California, Los Angeles, Sentman joined the physics department at the University of Alaska–Fairbanks, where he now serves on the faculty. Wescott received a Ph.D. in geophysics from the University of Alaska–Fairbanks in 1964. He worked for three years at the National Aeronautics and Space Administration Goddard Space Flight Center in Maryland before returning to the University of Alaska–Fairbanks as a professor of geophysics.

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Originally published in August 1995

Tornadoes

The storms that spawn twisters are now largely understood, but mysteries still remain about how these violent vortices form

by Robert Davies-Jones

This spring was a frenzied tornado season in the U.S. In May alone, an estimated 484 tornadoes killed some 16 people and ravaged millions of dollars of property. Day after day, forecasts of severe storms sent me and my colleagues rushing from the National Severe Storms Laboratory (NSSL) in Norman, Okla., to Texas or Kansas, returning sometimes at three in the morning. After the day's briefing at 9 A.M., we might set off again, fatigued but hoping once more to collect precious data on the birth of tornadoes.

On Tuesday, May 16, the weather maps revealed the threat of afternoon tornadoes in Kansas. By 5 P.M. a menacing thunderstorm had erupted, fed by warm, moist southerly winds that rose and rotated in an updraft. The storm was a highly organized "supercell," an ideal tornado breeding ground. As William Gargan, a graduate student at the University of Oklahoma, and I approached from the southeast in our instrumented car, called Probe 1, we glimpsed the 10-mile-high top of the monstrous storm, 60 miles away. The thunderstorm was sweeping east-northeast at 30 miles per hour, a quite typical motion in the Great Plains.

As we closed to within 10 miles along Route 50, we saw for the first time the long, dark cloud base. Within a few miles we spotted a twister, shaped like an elephant's trunk, hanging from the rear of the main cloud tower, near Garden City. In trying to maneuver closer on minor paved roads, we lost sight of the twister but spied it again four miles to our northwest. It was thin and trailed horizontally behind its parent cloud before bending abruptly toward the ground at a right angle. Clearly, it was being pushed away from the cloud by the cold air flowing down from the storm, and nearing the end of its life.

Supercells

Most tornadoes have damage paths 150 feet wide, move at about 30 miles per hour and last only a few minutes. Extremely destructive ones may be over a mile wide, travel at 60 miles per hour and may be on the ground for more than an hour. Tornadoes in the Northern Hemisphere, such as the devastating ones that occur in the U.S., northeastern India and Bangladesh, nearly always rotate counterclockwise when viewed from above. Southern Hemisphere tornadoes, such as those that form in Australia, tend to rotate clockwise. These directions are called cyclonic.

In 1949 Edward M. Brooks of St. Louis University discovered, by examining how air pressure changes at weather stations near tornadoes, that the twisters usually form within larger masses of rotating air known as mesocyclones. In 1953 a mesocyclone appeared on a radar screen at Urbana, Ill., as a hook-shaped appendage on the southwest side of a storm's radar echo. Because rain reflects the microwaves emitted by radar, the hook shape indicated that the rain was being drawn into a cyclonically rotating curtain. And in 1957 T. Theodore Fujita of the University of Chicago examined photographs and movies taken by local residents of the base and sides of a North Dakota tornadic storm and found that the entire cloud tower was rotating cyclonically.

In the 1960s Keith A. Browning, a British meteorologist visiting the NSSL's precursor, the National Severe Storms Project, pieced together from radar data a remarkably accurate picture of tornadic storms. He realized that most tornadoes are spawned inside particularly large and vicious storms that he dubbed supercells. These powerful systems develop in very unstable environments in which the winds vary markedly with height and cool, dry air lies atop warm, moist air about a mile deep over the earth's surface. A thin stable layer separates the two air masses, bottling up the instability.

This lid can be pried open if the low-level air is warmed by the sun or if a weather system invades. Fronts, jet streams and upper-level disturbances, common visitors to the Great Plains during tornado season, all may force low-level air upward. Because air pressure falls with height, the rising parcels of air expand and cool. At sufficient height they become cold enough that their water vapor starts to condense into misty droplets, forming a flat cloud base.

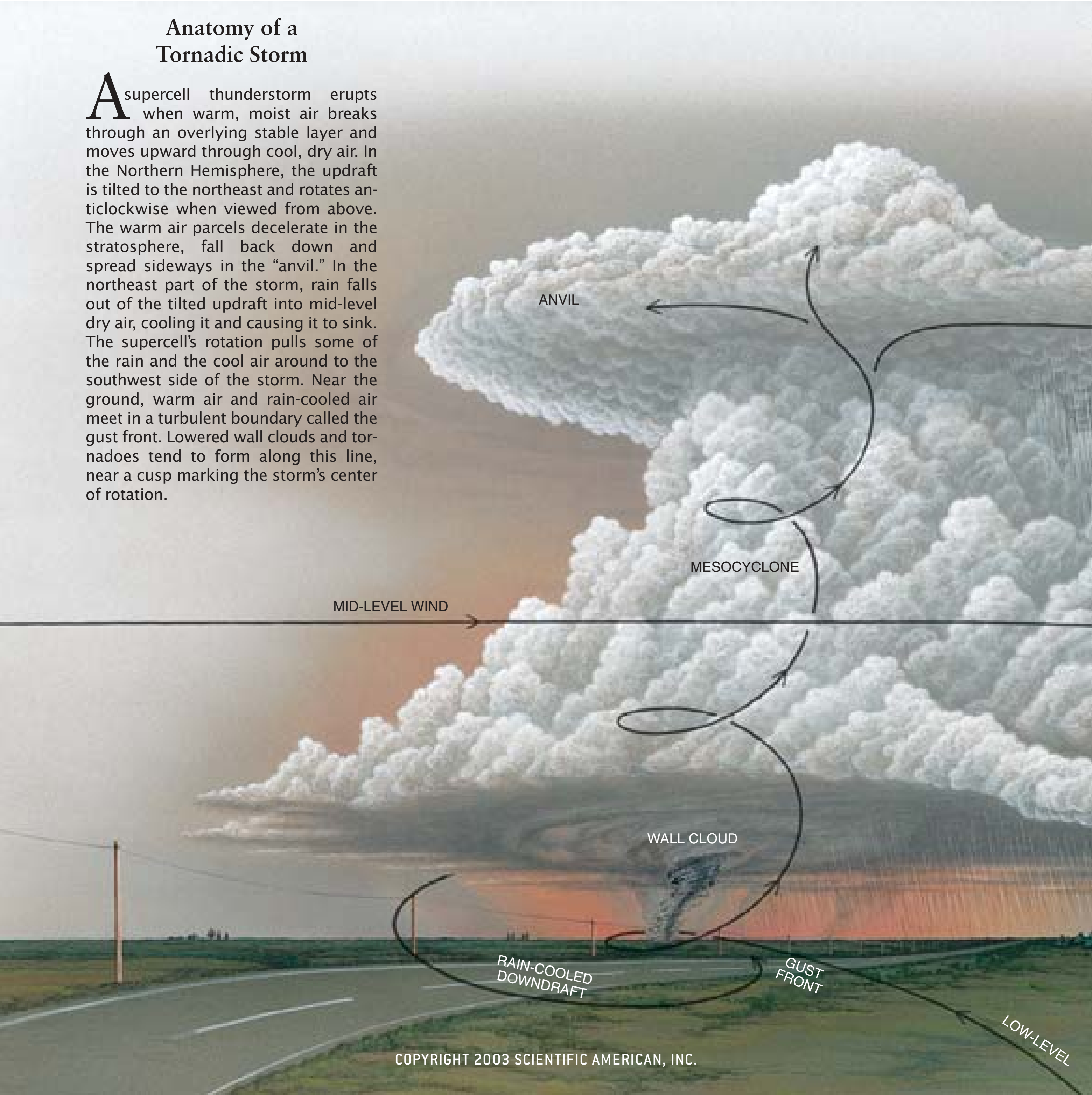
In condensing, the vapor releases latent heat, warming the air parcels. They reach a level at which they become warmer than their environment and rise freely to great heights at speeds up to 150 miles per hour, forming a towering thunderhead. Shearing winds tilt the updraft to the northeast.

As they ascend, cloud droplets coalesce into raindrops. The buoyancy of the air parcels is partly offset by the weight of their own water and ice. The parcels lose momentum in the stratosphere, sink down to about eight miles and flow out sideways, forming the storm's "anvil." Rain falling out of the tilted updraft evaporates in dry, mid-level air on the northeast side of the supercell, causing this air to cool and sink to the earth. With time the rain and cool downdraft are pulled around the updraft by the storm's rotation. The cool air has higher relative humidity than the warm air and if forced upward becomes cloudy at lesser heights. Thus, when some of this air is sucked into the updraft, a lowered wall cloud forms.

In contrast with most thunderstorms, which contain several updrafts and downdrafts that interfere with one another, supercells contain one or two cells, each with its own coexisting downdraft and broad rotating updraft. The high level of organization allows a supercell to live a long time in an al-

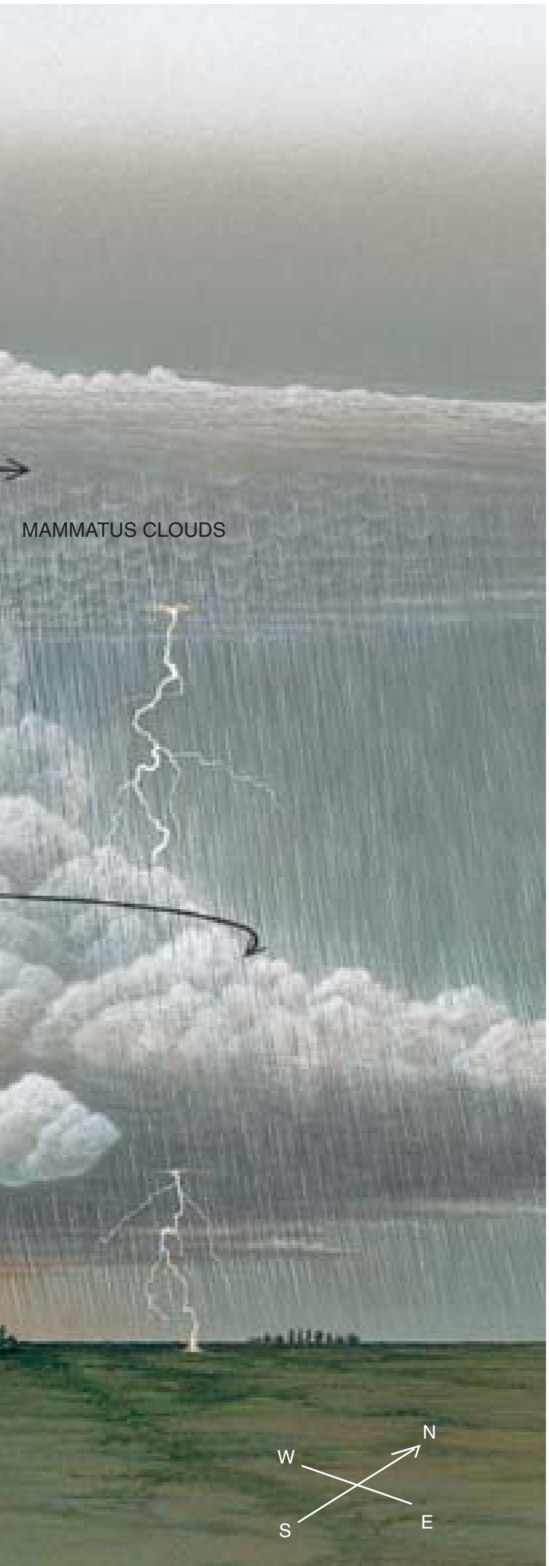
Anatomy of a Tornadic Storm

A supercell thunderstorm erupts when warm, moist air breaks through an overlying stable layer and moves upward through cool, dry air. In the Northern Hemisphere, the updraft is tilted to the northeast and rotates anticlockwise when viewed from above. The warm air parcels decelerate in the stratosphere, fall back down and spread sideways in the "anvil." In the northeast part of the storm, rain falls out of the tilted updraft into mid-level dry air, cooling it and causing it to sink. The supercell's rotation pulls some of the rain and the cool air around to the southwest side of the storm. Near the ground, warm air and rain-cooled air meet in a turbulent boundary called the gust front. Lowered wall clouds and tornadoes tend to form along this line, near a cusp marking the storm's center of rotation.



most steady and intense state that is conducive to tornado formation. A region of updraft one to three miles in radius may begin to rotate with wind speeds of 50 miles per hour or more, forming a mesocyclone. The storm may then develop low-level rotation and even a tornado—usually to the southwest side of the updraft and close to an adjacent downdraft, while the mesocyclone is mature or decaying.

Ultimately, the mesocyclone dies in a shroud of rain as its updraft is cut off near the earth's surface by very cold air flowing out of the heart of the downdraft. In persistent supercells, a new mesocyclone may have already formed a few miles southeast of the dying one, along the gust front—the boundary between the warm and cool air. A new tornado may develop rapidly.



TOMO NARASHIMA

Tornado Chasing

To pin down when and where a twister is most likely to appear, the NSSL conducted a Tornado Intercept Project from 1972 to 1986. The intercept teams initially acquired film footage for measuring extreme wind speeds and provided "ground truth" for radar observations. But other benefits ensued. The chasers observed that tornadoes often develop in parts of a storm that are free of rain and lightning, eliminating theories that relied on these stimuli to trigger tornadoes. And in 1975 a rare anticyclonic tornado was recorded. Its rotation, being opposite to that of the earth, was not simply an amplification of the planet's spin.

During the past two springs, the NSSL has been hosting another project, the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX). Measurements are being made in and near supercells by an armada of vehicles. One of these vans is piloted by the field coordinator, Erik N. Rasmussen of the NSSL, who works with meteorologists at headquarters in Norman to choose a target storm and coordinate the entire data collection. Five vans are equipped to obtain upper-air balloon soundings in and near storms, and 12 others have weather stations mounted on their roofs. These instruments are supported 10 feet above the ground, well above the vehicles' slipstream, with the data being stored and displayed on laptop computers inside.

One of these 12 cars aims to obtain film footage of tornadoes for analysis; two others deploy nine Turtles. Named thus because they resemble sea turtles in shape, Turtles are 40-pound instrument packages that are designed to withstand a tornado. They have well-shielded sensors to measure temperature and pressure and are placed on the ground ahead of tornadoes, at 100-yard intervals.

The remaining nine vans are called Probes; their sole mission is to collect weather data in specified regions of the storm. Probe 1's mission is to measure temperature gradients close to and north of the tornado or mesocyclone, a region where large hail frequently falls. Twice this season softball-size hail has smashed Probe 1's windshield.

That Tuesday in Kansas, as the twister died, we raced eastward to stay abreast of the storm and find a new mesocyclone. As we zigzagged in rain along the gravel roads, we encountered two rows of up to eight power poles that were lying in the fields, snapped off two feet above the ground. There must have been a strong tornado hidden in the rain to our northeast. (The next day I read in the newspaper that 150 poles had been downed.)

About 30 miles further east, we spotted a wall cloud, a rotating, pedestallike lowering, a few miles across, of the main cloud base. A narrow tornado appeared, not out of the dark wall cloud as is usual but from an adjacent higher cloud base. This vortex touched down briefly, raising debris, but lived out its few minutes of existence mainly as a funnel cloud aloft, without visible signs of contact with the ground.

A new wall cloud, which became ominously large and low, developed to the northeast. That, however, failed to produce a tornado. Near Jetmore, a fresh storm developed to the south of the one we were following. We went north to confirm that this older storm was indeed losing its tornado potential, then retraced our path and dropped south to the new one.

Signature of a Vortex

In addition to the aforementioned armada, VORTEX also uses two airplanes flying around a storm, as well as three more vehicles. All of these deploy Doppler radar, instruments that yield vital information about the airflow in tornadic storms. The newest, mobile Doppler radar, built this year by Joshua Wurman and Jerry M. Straka of the University of Oklahoma, has already yielded unprecedented details of tornadoes.

Doppler weather radars measure wind speeds from afar by emitting pulses of microwave radiation and catching their reflections off a group of raindrops or ice particles. If the drops are moving toward the radar, the reflected pulse has a shorter wavelength that betrays this component of the drops' velocity. (State troopers use similar instruments to catch speeding cars.)

The first Doppler measurements in 1971 confirmed that the winds within a "hook" are indeed rotating, at speeds of about 50 miles per hour. This circulation, first apparent at a height of about three miles, is followed by rotation at much lower levels, preceding the development of any intense tornado. In 1973 a small anomaly on the Doppler velocity map of a tornadic storm at Union City, Okla., turned out to coincide in time and space with a violent tornado.

The radar could not "see" or resolve the tornado directly but showed high winds changing direction abruptly across the twister and its precursor in the clouds. This vortex signature typically forms at around 9,000 feet 10 to 20 minutes before touchdown. It may extend upward as well as downward, occasionally reaching seven miles high for large tornadoes.

Although the vortex signature can be used to warn the public to seek shelter in a basement or an interior closet, it can be observed only at quite close range, generally 60 miles or less. At longer ranges of up to 150 miles, tornado warnings can be issued on the basis of Doppler radar detection of the parent mesocyclone. Federal agencies are currently installing a network of sophisticated Doppler radars across the country to improve warning capabilities.

In 1991, using a portable Doppler radar near a tumultuous tornado at Red Rock, Okla., Howard B. Bluestein of Oklahoma University measured wind speeds of up to 280 miles per hour. Although high, these speeds are a far cry from the 500 miles per hour postulated 40 years ago to explain freak happenings such as pieces of straw stuck in trees. (A more likely explanation for this phenomenon is that the wind forces apart the wood grains, which then snap shut, trapping the straw.)

Individual Doppler radar suffices for local warnings, but a second Doppler device that is about 25 to 35 miles away and views a storm from a significantly different angle supplies a far more complete picture for research. Such a dual-Doppler system, used by the NSSL and others since 1974, measures the velocity of the rain in two different directions. Knowing that the mass of air is conserved, and estimating the speed with which rain is falling relative to the moving air, meteorologists can reconstruct the three-dimensional wind field and compute quantities such as vorticity (or local spin in the air). Such data have led them to discover that a tornado is located to one side of its parent updraft, near a downdraft, and to verify that air flowing into a mesocyclone spins about its direction of motion.

Spinning Up

A major breakthrough in understanding the complex rotations in tornadic storms came in 1978, when computer simulations made by Robert Wilhelmson of the University of Illinois and Joseph B. Klemp of the National Center for Atmospheric Research (NCAR) reproduced realistic supercells complete with such features as hook-shaped precipitation patterns. Proceeding in small time steps, the scientists numerically solved the equations governing temperature, wind velocity and conservation of mass for air and water in various forms—vapor, cloud droplets and raindrops—on a three-dimensional array of points emulating space.

In the simulated world at least, scientists were in control. Even without any lateral variations in the initial environment, they were able to create supercells, thereby debunking the popular explanation that tornadoes are caused by colliding air masses. And by “turning off” the earth’s rotation, they established that it had little effect during the first few hours of a storm’s life. Rather wind direction that at low levels veered with height was crucial to the development of rotation.

In a typical supercell environment the wind near the ground is from the southeast, the wind half a mile above the ground is from the south, and the wind one mile high is from the southwest. Wind that changes speed or direction with height also contains spin. Envision how the wind would make an initially vertical stick rotate: if a south wind blows slowly near the ground and faster higher up, the stick will spin about an east-west axis.

But what if the wind, instead of changing speed, changes direction from southeast to southwest? Imagine the stick moving north, along with the mid-level wind, half a mile up. Then its top is pushed eastward and its bottom westward, so that it will turn about a north-south axis. Therefore, this air has “streamwise” vorticity—it spins about its direction of motion, much like a spiraling American football.

Air parcels with streamwise vorticity have their spin axes tilted upward as they enter an updraft. Thus, the updraft as a whole rotates cyclonically. First proposed by Browning in 1963 and proved analytically in the 1980s by Douglas K. Lilly of the University of Oklahoma and me, this theory explains how the updraft rotates at mid-levels. But it does not explain how rotation develops very close to the ground. As simulations by Klemp and Richard Rotunno of NCAR showed in 1985, low-level rotation depends on the supercell’s evaporatively cooled downdraft: it does not occur when the evaporation of rain is “switched off.”

The simulations revealed, surprisingly, that the low-level rotation originates north of the mesocyclone, in moderately rain-cooled, subsiding air. As the mid-level rotation draws the downdraft cyclonically around the updraft, some of the downdraft’s cool air travels southward with warm air on its left and much colder air on its right. Warm air, being buoyant, pulls the left sides of the air parcels upward; the cold air pulls their right sides downward. Then the cool air starts to rotate about its horizontal direction of motion. But as it descends, its spin axis is tilted downward, giving rise to anticyclonic spin.

Harold E. Brooks, also at the NSSL, and I showed in 1993 that, by a rather complex mechanism, the spin in the subsiding cool air reverses direction before the air completes its descent. Eventually, this cyclonically rotating air is present at very low levels. This moderately cool air flows along the surface and is sucked up into the southwest side of the updraft. Because the flow to the updraft is convergent, the air rotates faster, like an ice skater who spins more rapidly by drawing in her arms.

Despite understanding well how large-scale rotation develops at middle and low levels of a mesocyclone, we have yet to pin down why tornadoes are formed. The simplest explanation is that they are the result of surface friction. This observation seems paradoxical because friction generally reduces wind speeds. But the net effect of friction is much like that in a stirred cup of tea.

Drag does reduce speeds and therefore centrifugal forces in a thin layer near the bottom. It causes the fluid to move inward along the cup’s base, as made apparent by tea leaves bunching up at the center. But fluid near the top of this inflow spins faster as it falls in toward the axis because of the ice-skater effect. The result is a vortex along the axis of the cup. W. Stephen Lewellen of West Virginia University concludes that the highest wind speeds in a tornado are located in the lowest 300 feet.

Friction also explains the persistence of twisters. A tornado has a partial vacuum in its core; centrifugal forces prevent the air from spiraling inward through the sides of the tornado. In 1969 Bruce R. Morton of Monash University in Australia explained how the vacuum survives. Strong buoyancy

Destructive Power

The damage that tornadoes inflict on buildings and the distances that they carry heavy objects reveal the extreme wind speeds attained near the ground. In the 1970s the Institute for Disaster Research in Lubbock, Tex., concluded that the worst damage required winds of up to 275 miles per hour. The engineers also noted that windward walls of buildings, generally to the southwest, almost always fall inward—implying that structures are most often damaged by the brute force of a wind, not by the sudden drop in atmospheric pressure. As a result, residents of “Tornado Alley,” in the midwestern U.S., were no longer advised to open windows to reduce the pressure inside. The suggestion had caused many people to be cut by flying glass as they rushed to open the windows. Nor were residents told anymore to hide in the southwest corner of the house—where they were in the most danger of having walls fall in on them. Now residents are urged to shelter in a central closet because of the added protection of interior walls.

Far-Flung Debris

Heavy items such as roof fragments can travel tens of miles; in 1985 an airplane wing flew 10 miles. Most of the debris falls to the left of the tornado's path, often in well-defined bands according to weight.

Researchers at the University of Oklahoma are collecting accounts of fallout from tornadoes as a way of gauging airflow within the storms. Twisters appear to lift some objects several miles high, into the main storm. Light debris may return to the earth 200 miles away. For example, canceled checks from Wichita Falls, Tex., traveled to Tulsa, Okla., in April 1979. And, according to an account from 1953 collected by the researchers: "Emily McNutt of South Weymouth, Mass., found a wedding gown in her backyard. It was dirty, as would have been expected, but was intact and in surprisingly good condition. A label sewn into the gown read 'McDonald, Worcester,' indicating that the gown had been blown some fifty miles to its final landing place." (Excerpt from *Tornado!* by John M. O'Toole.)

Reports of tornado fallout can be sent by electronic mail to the Tornado Debris Project at debris@metgem.uoknor.edu

forces prevent air from entering the core through the top. Close to the ground, friction reduces tangential velocity and hence centrifugal forces, allowing a strong but shallow inflow into the core. But friction also acts to limit the inflow winds, not allowing enough air in to fill up the core. Tornadoes intensify and become more stable after they make strong contact with the ground because their inflows become restricted to a thin boundary layer.

The friction theory does not explain, however, why a tornadic vortex signature up in the clouds sometimes foreshadows the touchdown of a tornado by 10 to 20 minutes.

Touchdown

Many of the classic features of tornadoes were unexpectedly demonstrated to us on that May day in Kansas. By the time we had moved to the southern storm in the small town of Hanston, it was getting dark, and operations were ending. But then the field coordinator advised the teams of a rapidly rotating wall cloud in our vicinity. As the warning sirens started wailing, we watched a skinny, serpentine tornado touch down three miles to our southeast.

We took off to the north to place ourselves ahead of the tornado, unaware in the excitement of a deep drainage ditch in the street. It damaged our wheel and tilted our weather station, but we kept going. We turned on to a dirt road to take us east on the north side of the tornado, which had now become a wide column of dust with a bowl-shaped lowering of the cloud base above it. As we got ahead of the tornado, it transformed itself into several smaller vortices, all circling furiously around the tornado's central axis. (In 1967 Fujita observed that some tornadoes left behind beheaded cornstalks in several overlapping swaths. Neil B. Ward of the NSSL later attributed these curious patterns to such subsidiary twisters. Like a point on the rim of a bicycle wheel that circles the center as the wheel moves forward, these frenetic subvortices trace out cycloidal paths.)

Low on gas, we raced ahead of the twister, apprehensive because we did not know if and where the road ended. The tornado was perhaps a mile away and not moving perceptibly across our field of view, indicating that it was heading directly for us at 30 miles per hour. The field coordinator came to our rescue by informing us of a road north, toward Burdett, which we gratefully took. We stopped after a mile to watch the tornado, which had been on the ground for at least 14 miles and now had a classic stovepipe appearance, pass by to our south and recede into the darkness to our east.

We limped home, our car damaged, our data uncertain and our pulses racing, buoyed by the news that great radar data had been obtained from the air and from the new portable ground radar. Looking back, we should have just kept pace with the tornado instead of passing it and turning ourselves, the hunters, into the hunted.

Tabletop Tornado

Laboratory experiments have helped explain why tornadoes can take different forms. In the apparatus built in the 1960s by Neil B. Ward of the National Severe Storms Laboratory in Norman, Okla., and refined by John T. Snow and others at Purdue University, air is spun up by a rotating screen as it enters a lower compartment. It then flows up into the main chamber through a wide central hole, being pulled by exhaust fans at the top. The device has replicated many features of real tornadoes, such as the pattern of air pressures near the lower surface.

Reinterpreting Ward's results, I found in 1973 that the crucial parameter for tornado formation is the swirl ratio S, first used by W. Stephen Lewellen of West Virginia University. S is the ratio of the tangential velocity at the edge of the updraft hole (controlled by the screen's rotation) to the average upward velocity through the hole (determined by the fan). For S less than 0.1, there is no vortex. As S is increased, a vortex appears, having an intense upward jet at low levels. At S higher than 0.45, the vortex becomes fully turbulent with a central downdraft surrounded by a strong updraft. And at a critical swirl ratio of roughly 1.0, a pair of vortices form on opposite sides of the parent vortex. For still higher swirl ratios, up to six subsidiary vortices have been observed.

The Author

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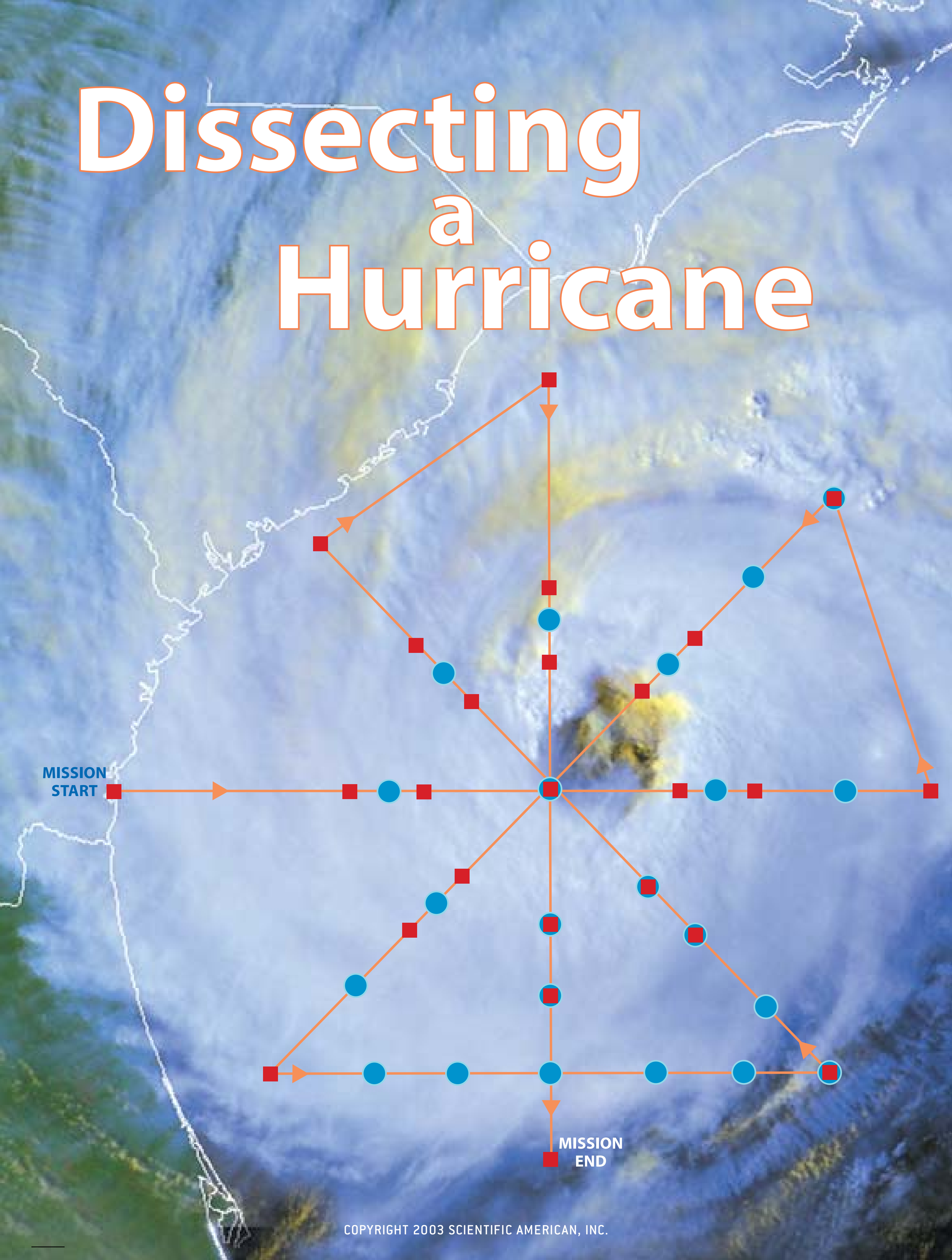
Dissecting a Hurricane



Flying into the raging tumult of Dennis, scientists suspected that the storm might transform into a monster—if they were lucky

by Tim Beardsley, *staff writer*

Originally published in March 2000

MACDILL AIR FORCE BASE, FLORIDA, AUGUST 29, 1999, 1:52 P.M.: Safety lectures are over and everyone is strapped into our four-engine WP3D turboprop plane, known affectionately as *Miss Piggy*. The aircraft, jammed with computers, four different radars and a variety of other instruments, is at last surging down the runway. The past few hours have been a metaphorical whirlwind: quickly arranged travel, a 6 A.M. flight from Baltimore, then briefing sessions with the flight crew interspersed with hurried explanations from Frank D. Marks, the lead scientist on the flight.

Our destination is a real whirlwind: Hurricane Dennis, now swirling 290 kilometers east of Jacksonville, Fla., powering 145-kilometer-per-hour winds and menacing the Carolinas. On land fearful vacationers and residents on North Carolina's barrier islands are boarding up windows, throwing bags into cars and fleeing the coming storm. But Marks and his fellow scientists from the National Oceanic and Atmospheric Administration regard Dennis with hope rather than dread. If our flight through its curved arms goes as planned, this storm will shed light on a central mystery about hurricanes and typhoons: whether it is the ocean below or the winds above that wield more power in determining whether a storm will swell to greater fury or unwind into a harmless region of low pressure.

Marks is among those pushing the idea that the ocean controls how hurricanes evolve by either adding or removing energy in the form of heat. Today's forecasting models, in contrast, treat the ocean as a passive bystander.

These models have conspicuously failed to predict when storms will intensify. Hurricane Andrew startled forecasters in 1992 when it intensified abruptly while passing over the warm waters of the Gulf Stream; it later killed 15 people and destroyed property worth $25 billion in southern Florida. In 1995 in the Gulf of Mexico, Hurricane Opal transformed overnight—after the 11 P.M. television news assured Gulf Coast residents that they had little to fear—from a Category 2 to a Category 4 terror capable of extreme devastation. Opal, too, had just passed over an eddy of deep warm water. Although the storm ebbed somewhat before coming ashore, it caused more than 28 deaths altogether. And earlier in 1999 Hurricane Bret followed what now seemed to be an emerging pattern, escalating from Category 2 to 4 after passing over warm water. Fortunately, it made landfall over unpopulated farmland in Texas.

If Marks and his colleagues are right, by analyzing in detail the heart of a hurricane they should be able to tease apart the web of factors that drive the storms to live, grow and die. The scientists will need to learn the temperature of the sea at different depths during the hurricane's passage. They will also want to know as much as possible about its winds and waves.

Dennis, now a strong Category 2 hurricane, has the same ominous potential for rapid intensification as Andrew and Opal did. When Hurricane Bonnie crossed the Gulf Stream in 1998—without intensifying—Marks had been frustrated by a lack of instruments to study it. But as he watched Dennis's course in late August, he recognized an opportunity. Equipment was available, and by good fortune Eric D'Asaro of the University of Washington had just dropped three high-tech floats in an east-west line across Dennis's path. The floats move up and down, monitoring temperature and salinity in the so-called mixed layer between the sea surface and about 200 meters' depth. These data could complement observations made from *Miss Piggy*. Marks scrambled his air team to launch a detailed examination of Dennis, which is what brought us to the jetway.

Our group will scan the storm from the inside out, penetrate it with falling

PLANNED TRACK of a research mission into Hurricane Dennis on August 29, 1999, sliced the storm every which way to measure how winds and waves interact. The National Oceanic and Atmospheric Administration sent its WP3D research aircraft *Miss Piggy* on the demanding expedition because Dennis threatened to intensify dangerously. The actual route deviated somewhat from that planned. Red squares (■) show where the crew dropped Global Positioning System sondes to measure winds; blue circles (●) show firings of Airborne Expendable Bathythermographs (AXBTs), which measure ocean temperature.

NOAA UNIVERSITY OF WISCONSIN–MADISON SPACE SCIENCE AND ENGINEERING CENTER (*photograph*); BRYAN CHRISTIE (*graphic composition*) probes, take its temperature and clock its winds. Over the past few days NOAA's Gulfstream IV jet has charted atmospheric conditions at various altitudes in the region. Our flight is to be the crux of the assessment: four straight passes through the eye of the tempest.

Marks has weathered dozens of routine flights through hurricanes, and he likes to quip that the most dangerous part of a sortie is the drive to the airport. But he also knows that the pilots face real challenges, especially near the deep banks of cumulonimbus clouds that mark the eye wall. Winds there change speed and direction unpredictably, and intense tornadolike vortices can appear with no warning. Ten years ago Marks was flying in our sister plane, *Kermit,* through Hurricane Hugo as the storm escalated to a Category 5. An engine failed while the plane was at low altitude inside the eye, and a vortex almost threw the plane into the sea. "I am lucky to be alive after that," Marks recounts.

This morning the crew displayed an easy bravado during the preflight briefing. Some experienced members sport badges on their blue flight suits celebrating the number of eye penetrations they have survived. But as we move up Florida's eastern coast, the flight engineer seems to enjoy reminding me that hurricanes can change their character within a few hours. Our flight could last nine or more. It seems important to count the number of people on board: 19, including six scientists as well as observers, instrument technicians and the flight crew.

The frailty of the complex equipment we are carrying is suddenly underscored when technician James Barr announces that the Doppler radar in the plane's tail is not producing intelligible data. This device, along with a second radar in the belly of the fuselage, can reveal wind speeds wherever rain is falling. Marks says we definitely want this information. The flight director approves a hold, and we fly in a circle while Barr and lead electronics technician Terry Lynch attempt a repair. They yank out equipment racks and swap a transmitter.

Ten minutes pass, but something is not right. Lynch is muttering under his breath and looking worried. After a few more anxious minutes, he declares victory. Everyone gets back to work.

At our starting point for the mission proper, off the coast a few kilometers north of the Florida-Georgia border, electrical engineer Richard McNamara takes the metallized plastic wrapping off a Global Positioning System (GPS) dropwindsonde. This device, which will be dropped into the storm, unfurls a parachute when it is in free fall and radios back its position to the plane. McNamara programs it by plugging it into his instrument rack for a few seconds, detaches it and places it in a transparent launch tube set in the floor. The flight director gives the "3, 2, 1," and then McNamara presses a trigger. The cabin air pressure blows the meter-long cylinder out of the fuselage with a loud whistling sound, and McNamara confirms the time.

Within seconds his workstation has acquired a signal: the sonde's parachute has deployed. He tracks the probe's location as Dennis whips it away from the plane, betraying the direction and the strength of the winds during its descent to the ocean. He will repeat this routine numerous times during the mission, gradually building a three-dimensional picture of the storm.

We are now heading east at 4,300 meters. The cheery banter of the early part of the flight has dwindled, and I feel a mounting excitement. As the coast recedes behind us and dark gray clouds loom ahead, the crew tap away at keyboards controlling a suite of instruments that will make Dennis the most minutely analyzed storm ever.

At 3:15 P.M. our imperturbable pilot, Ron Phillipsborn, comes on the intercom to warn of "weather" ahead. Dense rain now streams over the windows, and the blue sky we set off in is nowhere to be seen: only whiteness all about. People have been walking in the plane since we reached our cruising altitude, but now everyone heads to their seats to strap in.

The ride remains fairly smooth, however, and soon foot traffic in the aisle resumes. The spiral form winding on the radar screens is familiar from the Weather Channel, but it is far more compelling at this moment. Operators compile the maps every 30 minutes and send them by a slow satellite link to the National Hurricane Center at Florida International University in Miami. Researcher Christopher W. Landsea, furiously editing data at one of the consoles, estimates Dennis's eye to be 80 kilometers in diameter, which is larger than that of most hurricanes. The storm is moving slowly northward, brushing the coast. Its waves are now pounding jetties as its winds tear the shingles off roofs.

When we reach the point where we have to fire a probe called an Airborne Expendable Bathythermograph, or AXBT, McNamara flips a switch on his console. An explosive charge shoots the first of the AXBTs, which are preloaded in the plane's belly, out into the storm now engulfing us. AXBTs do nothing as they fall, but when they splash into the ocean they send a thermometer on a wire down to 300 meters and radio the temperature readings along the way.

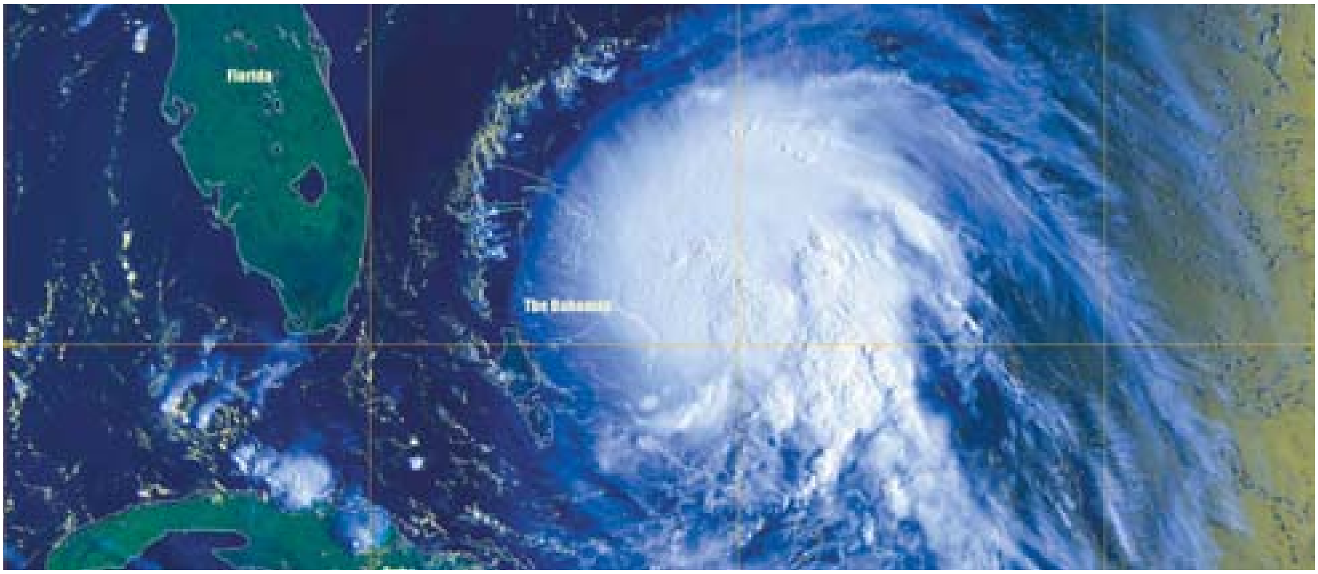
We approach the eye wall at about 500 kph, shooting out more GPS sondes and AXBTs as we go. Through occasional gaps in the dense clouds I can see the roiling ocean surface, flecked generously with patches of white.

These regions of bubbles, caused when the wind blows the tops off waves, look insubstantial in comparison to the cubic kilometers of air and water heaving all around us. But scientists suspect that they are crucial in determining how a hurricane will change, because they efficiently transfer energy between sea and air. One of the instruments we are carrying, a radiometer, can measure that foaminess by detecting microwave energy reflecting off the sea surface at six different frequencies. It can in principle, anyway. In practice, software glitches have so far hung up the device on all of its previous flights. Marks is hoping that NOAA scientist Peter Black, who is grounded in Florida with a cold, succeeded in his latest attempt to debug the code.

The fuselage shudders and heaves again, and my coffee makes a bid to escape from its plastic cup. Phillipsborn orders us back to our seats once more, but the floor and the seatbacks are now moving targets. We endure a couple of stomach-churning lurches. I start to wonder exactly how much the wings could flap like that before breaking off. McNamara, sitting across the aisle from me, is unfazed, repeatedly firing off GPS sondes alternated with an occasional AXBT. He seems too busy for any idle speculation.

I realize that the nausea-inducing plunges have stopped: we have pierced Dennis's eye. Overhead is the blue sky we left behind. Wind speed outside is about three knots, hardly enough to lift a flag. We hunt for the point where wind speed and pressure are lowest, to get a fix on the center. Not many kilometers distant, huge stacks of rain clouds are visible, strewn in a vast arc. We plunge into the eastern eye wall, dropping more sondes as we do so into the colossal heat engine turning around our plane.

Hours pass as we trace a compass rose



HURRICANE DENNIS did not turn into the nightmare storm it might have. But it yielded a wealth of information about hurricane evolution.

NOAA

centered on the eye. My tension has prevented hunger, but in the late afternoon I cautiously maneuver toward the galley for a sandwich, where I find a crew member calmly reading a newspaper.

The unpredictable drops become familiar but worsen on a slow upwind leg. The repaired Doppler radar is working imperfectly: its output will be less complete than Marks had wanted. Landsea announces that the instrument shows surface winds have reached about 160 kph. Dennis is indeed getting stronger. Yet as it intensifies, it stirs up cooler water from the depths. I learn later that Dennis cooled the water off the Georgia and South Carolina coasts by three degrees Celsius and roughly doubled the depth of the mixed water layer beneath its core. That effect in turn cooled Hurricane Floyd's fury when it passed the same way days later.

We are transmitting readings from the radiometer to the National Hurricane Center. But Marks is still uneasy about the device. Partway through the flight, he is surprised when the plane's radio operator patches through a phone call from Black. It must be urgent, because the radio interferes with the radars, so Marks figures he will be hearing about some new radiometer problem. In fact, Black exclaims that the instrument, which can reveal surface winds in detail, is working perfectly. Marks is sufficiently relieved to announce the good news over the intercom. The mood on the plane brightens noticeably.

The flight wears on. We make a long traverse over D'Asaro's floats, dropping AXBTs and GPS sondes as the whiteness outside fades into the black of night. On the fourth pass through the eye we again hunt for the center to see how far it has moved: center fixes are crucial for helping forecasters judge where a storm is headed. Dennis's western side is over the Gulf Stream and presumably picking up energy there, but the eye remains farther out in the Atlantic. Marks fears a landfall in North Carolina the following day.

On the way home we make a point of firing off some AXBTs and GPS sondes as close to ground-based measurement stations and buoys as we can, so that the scientists can make cross-checks of the instruments' performance. By the time we touch down at MacDill, it is 10:24 P.M. Marks seems more pleased with the day's work than exhausted by the nearly nine-hour journey.

The next day we rise to learn that Dennis has veered slightly eastward, moving parallel to the Gulf Stream. The churning that cooled the sea surface, along with Dennis's failure to pass right over the Gulf Stream, means that it will not turn into the nightmare storm it might have. Yet it has yielded a treasure trove of information.

The radiometer data are the main prize. But the happy conjunction of *Miss Piggy*'s flight and D'Asaro's floats have made it a scientific field day in other respects, too. We had launched 30 GPS sondes, several of them right into Dennis's eye wall. We had also fired off 15 operative AXBTs; three of these splashed on the east-west line south of the eye where D'Asaro's floats were at work. The Doppler radar data are adequate for most purposes. In addition, Ed Walsh of the National Aeronautics and Space Administration successfully used a scanning radar altimeter during the flight to bring in a good haul of measurements on the direction and height of Dennis's waves. They are highly asymmetric and resemble a pattern Walsh saw earlier in Hurricane Bonnie.

All this information will be grist for hurricane modelers' data mills for years to come. No single storm will answer all the questions about hurricane evolution. But Marks and his crew of technicians and investigators have shown that they can deploy a comprehensive array of high-tech instruments in a dangerous cyclone and emerge with valuable results. As long as they and other riders on the storm are willing to continue risking life and limb for science, the mystery of what makes a hurricane intensify seems likely to diminish—and with it, the opportunities for some future tempest to turn without warning into a killer. SA

Further Information

THERMODYNAMIC CONTROL OF HURRICANE INTENSITY. Kerry A. Emanuel in *Nature*, Vol. 401, pages 665–669; October 14, 1999.

NOAA's Hurricane page is available at hurricanes.noaa.gov/

Hurricane Dennis mission summary can be found at www.aoml.noaa.gov/hrd/Storm_pages/dennis99/990829I.html

Storm Atlas of NOAA's Hurricane Research Division is available at www.aoml.noaa.gov/hrd/Storm_pages/frame.html