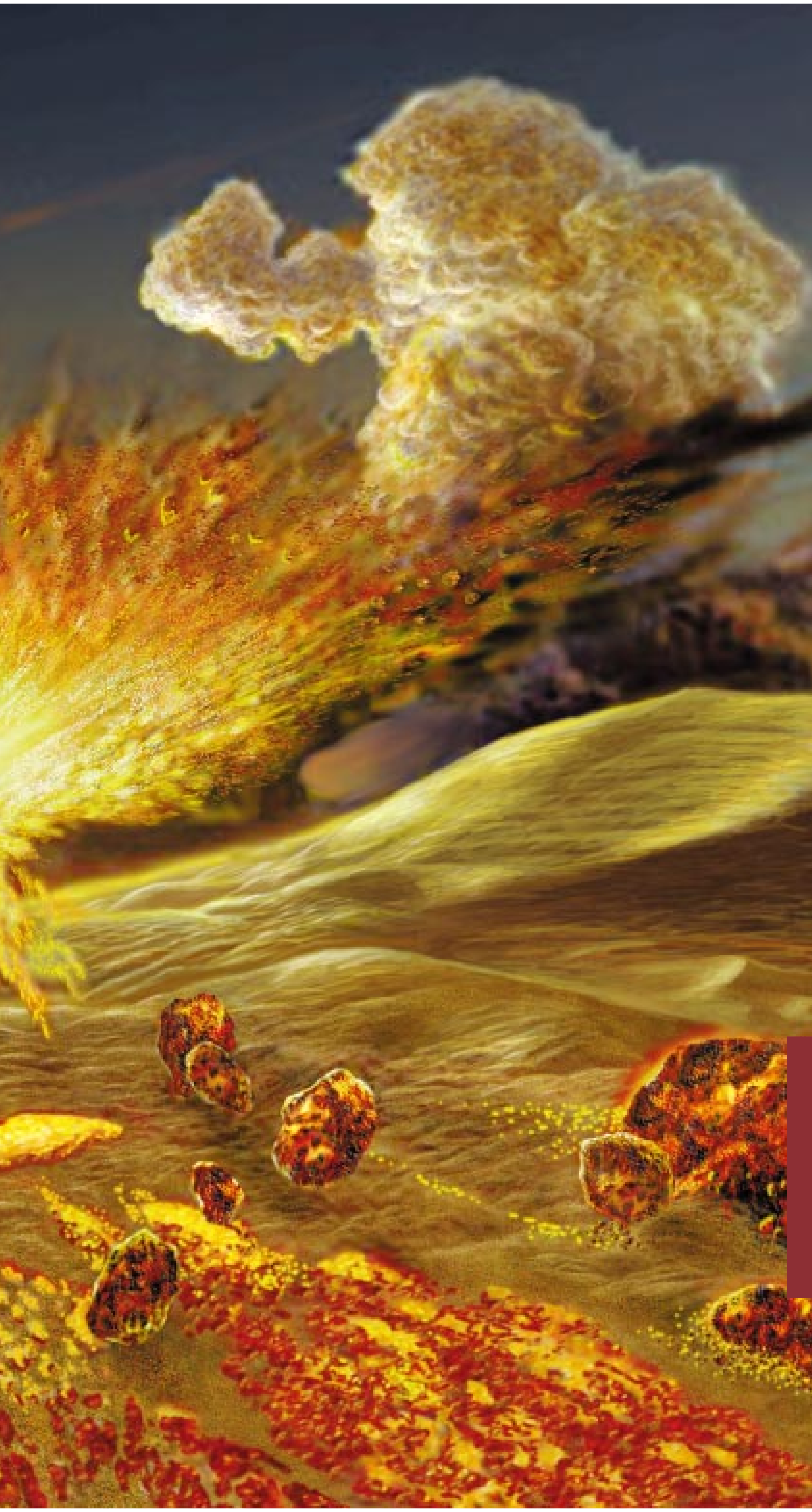
The Day the Sands Caught Fire

A desert impact site demonstrates the wrath of rocks from space

Fire

by Jeffrey C. Wynn and Eugene M. Shoemaker



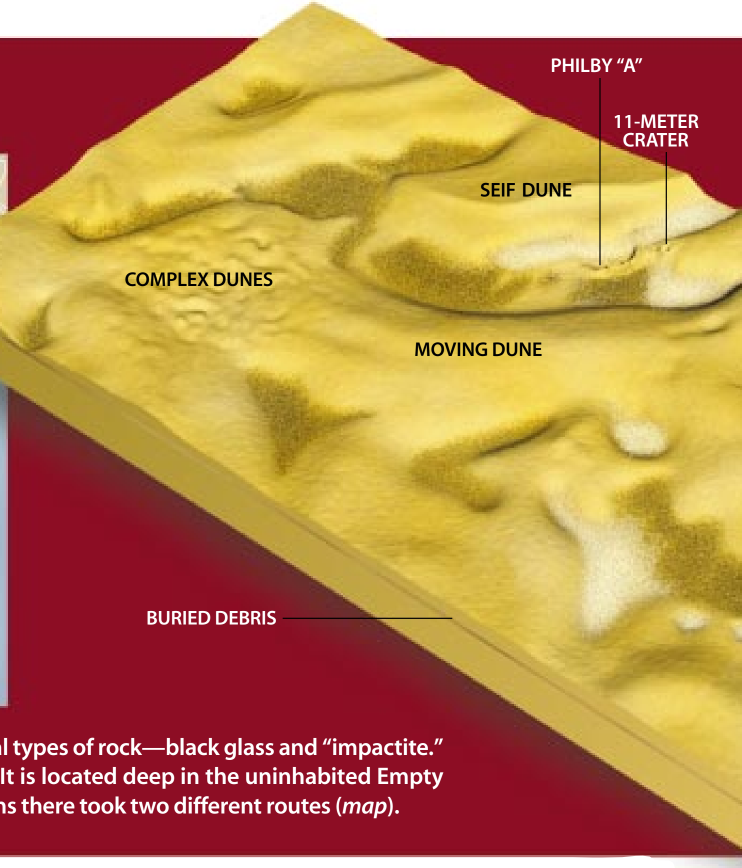
DON DIXON

Imagine, for a moment, that you are standing in the deep desert, looking northwest in the evening twilight. The landscape is absolutely desolate: vast, shifting dunes of grayish sand stretch uninterrupted in all directions. Not a rock is to be seen, and the nearest other human being is 250 kilometers away. Although the sun has set, the air is still rather warm—50 degrees Celsius—and the remnant of the afternoon sandstorm is still stinging your back. The prevailing wind is blowing from the south, as it always does in the early spring.

Suddenly, your attention is caught by a bright light above the darkening horizon. First a spark, it quickly brightens and splits into at least four individual streaks. Within a few seconds it has become a searing flash. Your clothes burst into flames. The bright objects flit silently over your head, followed a moment later by a deafening crack. The ground heaves, and a blast wave flings you forward half the length of a football field. Behind you, sheets of incandescent fire erupt into the evening sky and white boulders come flying through the air. Some crash into the surrounding sand; others are engulfed by fire.

Glowing fluid has coated the white boulders with a splatter that

The Wabar Meteorite Impact Site



WABAR SITE consists of three craters and a sprinkling of two unusual types of rock—black glass and "impactite." Much of the site has been buried by the ever shifting sand dunes. It is located deep in the uninhabited Empty Quarter of Saudi Arabia, or the Rub' al-Khali; the authors' expeditions there took two different routes (*map*).

first looks like white paint but then turns progressively yellow, orange, red and finally black as it solidifies—all within the few seconds it takes the rocks to hit the ground. Some pieces of the white rock are fully coated by this black stuff; they metamorphose into a frothy, glassy material so light that it could float on water, if there were any water around. A fiery mushroom cloud drifts over you now, carried by the southerly breeze, blazing rainbow colors magnificently. As solid rocks become froth and reddish-black molten glass rains down, you too become part of the spectacle—and not in a happy way.

Deep in the legendary Empty Quarter of Saudi Arabia—the Rub' al-Khali—lies a strange area, half a square kilometer (over 100 acres) in size, covered with black glass, white rock and iron shards. It was first described to the world in 1932 by Harry St. John "Abdullah" Philby, a British explorer perhaps better known as the father of the infamous Soviet double-agent Kim Philby. The site he depicted had been known to several generations of roving al-Murra Bedouin as *al-Hadida,* "the iron things."

There is a story in the Qur'an, the holy book of Islam, and in classical Arabic writings about an idolatrous king named Aad who scoffed at a prophet of God. For his impiety, the city of Ubar and all its inhabitants were destroyed by a dark cloud brought on the wings of a great wind. When Philby's travels took him to the forbidding Empty Quarter, his guides told him that they had actually seen the destroyed city and offered to take him there. Philby gladly accepted the offer to visit what he transliterated in his reports as "Wabar," the name that has stuck ever since.

What he found was neither the lost city of Ubar nor the basis for the Qur'anic story. But it was certainly the setting of a cataclysm that came out of the skies: the arrival of a meteorite. Judging from the traces left behind, the crash would have been indistinguishable from a nuclear blast of about 12 kilotons, comparable to the Hiroshima bomb. It was not the worst impact to have scarred our planet over the ages. Yet Wabar holds a special place in meteor research. Nearly all known hits on the earth have taken place on solid rock or on rock covered by a thin veneer of soil or water. The Wabar impactor, in contrast, fell in the middle of the largest contiguous sand sea in the world. A dry, isolated place, it is perhaps the best-preserved and geologically simplest meteorite site in the world. Moreover, it is one of only 17 locations—out of a total of nearly 160 known impact structures—that still contain remains of the incoming body.

In three grueling expeditions to the middle of the desert, we have reconstructed the sequence of events at Wabar.

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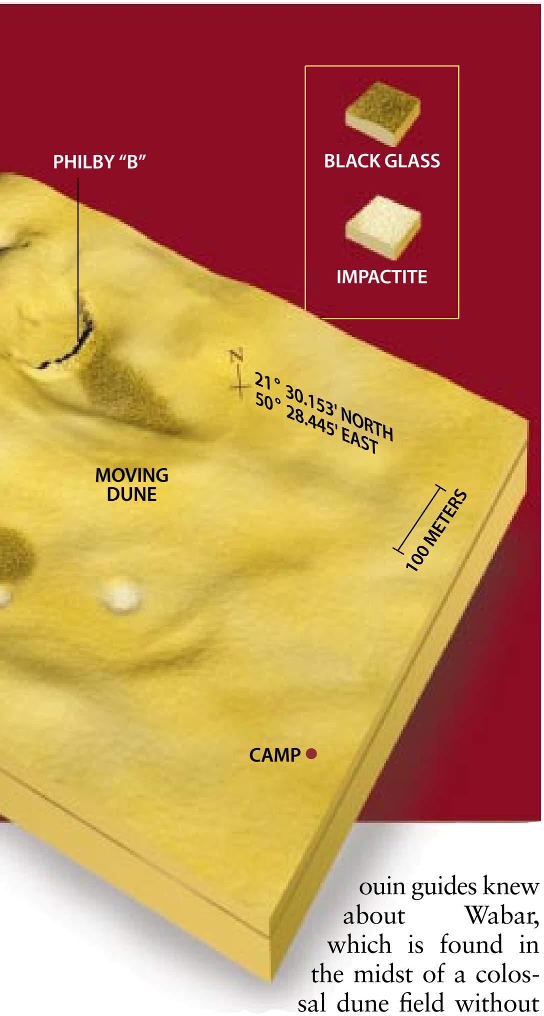
The impact was an episode much repeated throughout the earth's geologic and biological history. And the solar system has not ceased to be a shooting gallery. Although the biggest meteors get most of the attention, at least from Hollywood, the more tangible threat to our cities comes from smaller objects, such as the one that produced Wabar. By studying Wabar and similarly unfortunate places, researchers can estimate how often such projectiles strike the earth. If we are being shot at, there is some consolation in knowing how often we are being shot at.

One has to wonder how Philby's Bed-



LAURIE GRACE (*map*); SLIM FILMS (*illustration*)

ouin guides knew about Wabar, which is found in the midst of a colossal dune field without any landmarks, in a landscape that changes almost daily. Even the famously tough desert trackers shy away from the dead core of the Empty Quarter. It took Philby almost a month to get there. Several camels died en route, and the rest were pushed to their limits. "They were a sorry sight indeed on arrival at Mecca on the ninetieth day, thin and humpless and mangy," Philby told a meeting of the Royal Geographical Society on his return to London in 1932.

Otherworldly

When he first laid eyes on the site, he had become only the second Westerner (after British explorer Bertram Thomas) to cross the Empty Quarter. He searched for human artifacts, for the remains of broken walls. His guides showed him black pearls littering the ground, which they said were the jewelry of the women of the destroyed city. But Philby was confused and disappointed. He saw only black slag, chunks of white sandstone and two partially buried circular depressions that suggested to him a volcano. One of his guides brought him a piece of iron the size of a rabbit. The work of the Old People? It slowly dawned on Philby that this rusty metal fragment was not from this world. Laboratory examination later showed that it was more than 90 percent iron, 3.5 to 5 percent nickel and four to six parts per million iridium—a so-called sidereal element only rarely found on the earth but common in meteorites.

The actual site of the city of Ubar, in southern Oman about 400 kilometers (250 miles) south of Philby's Wabar, was uncovered in 1992 with the help of satellite images [see "Space Age Archaeology," by Farouk El-Baz; Scientific American, August 1997]. Wabar, meanwhile, remained largely unexplored until our expeditions in May 1994, December 1994 and March 1995. The site had been visited at least twice since 1932 but never carefully surveyed.

It was not until our first trip that we realized why. One of us (Wynn) had tagged along on an excursion organized by Zahid Tractor Corporation, a Saudi dealer of the Hummer vehicle, the civilian version of the military Humvee. To promote sales of the vehicle, a group of Zahid managers, including Bill Chasteen and Wafa Zawawi, vowed to cross the Empty Quarter and invited the U.S. Geological Survey mission in Jeddah to send a scientist along. This was no weekend drive through the countryside; it was a major effort requiring special equipment and two months of planning. No one had ever crossed the Empty Quarter in the summer. If something went wrong, if a vehicle broke down, the caravan would be on its own: the long distance, high temperatures and irregular dunes preclude the use of rescue helicopters or fixed-wing aircraft.

An ordinary four-wheel-drive vehicle would take three to five days to navigate the 750 kilometers from Riyadh to Wabar [*see map on opposite page*]. It would bog down in the sand every 10 minutes or so, requiring the use of sand ladders and winches. A Hummer has the advantage of being able to change its tire pressure while running. Even so, the expedition drivers needed several days to learn how to get over dunes. With experience, the journey to Wabar takes a long 17 hours. The last several hours are spent crossing the dunes and must be driven in the dark, so that bumper-mounted halogen beams can scan for the unpredictable 15-meter sand cliffs.

Our first expedition stayed at the site for a scant four hours before moving on. By that time, only four of the six vehicles still had working air conditioners. Outside, the temperature was 61


JEFFREY C. WYNN

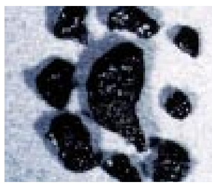
SAND-FILLED CRATER, 11 meters (36 feet) in diameter, was discovered by the authors on their expedition to Wabar in December 1994. Under the sand the crater is lined with a bizarre kind of rock—impactite—thought to have formed when immense pressures glued sand grains together. Around the crater rim are centimeter-size chips of iron and nickel. From the size of the crater geologists estimate that it formed when a dense metallic meteorite just one meter across smacked into the sand. This meteorite had split off from the larger bodies responsible for the other two craters at Wabar.

Identifying Impact Craters

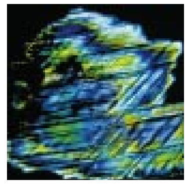
How would you recognize an impact crater if you fell into one? It isn't easy. Although the moon is covered with craters, it has no water, no weather, no continental drift—so the craters just stay where they formed, barely changed over the aeons. On the earth, however, all these factors have erased what would otherwise have been an equally pockmarked surface. To confuse matters further, more familiar processes—such as volcanism and erosion—also leave circular holes. Not until early this century did geologists first confirm that some craters are caused by meteorites. Even today there are only about 160 known impact structures.

Only about 2 percent of the asteroids floating around in the inner solar system are made of iron and nickel, whose fragments are fairly easy to recognize as foreign. But other types of meteorites blend in with the rest of the stones on the ground. The easiest place to pick them out is in Antarctica, because few other rocks find their way to the middle of an ice field. Elsewhere, recognizing a meteorite crater requires careful mapping and laboratory work. Geologists look for several distinctive features, which result from the enormous velocities and pressures involved in an impact. Even a volcanic eruption does not subject rocks to quite the same conditions. —*J.C.W.*

• **Shatter cones.** These impressions, found in the rocks around a crater, look like cookie-cutter cones or chevrons. Occasionally, you can see them in rock outcroppings if the cones have fractured lengthwise. No shatter cones appear at Wabar because the site formed in loose sand.



• **High-temperature rock types.** Laminated and welded blocks of sand have been seen at Wabar and at nuclear test sites. In addition, tektites—glassy rocks thought to form when molten rock is splattered into orbit and then solidifies on the way back down—appear around many large impact sites.



• **Microscopic rock deformation.** The crystal structure of some minerals is transformed by the shock waves during an impact. Quartz, for example, develops striations that are oriented in more than one direction. It can also recrystallize into new minerals, such as coesite and stishovite, detectable only in x-ray diffraction experiments.

CAROLYN SHOEMAKER

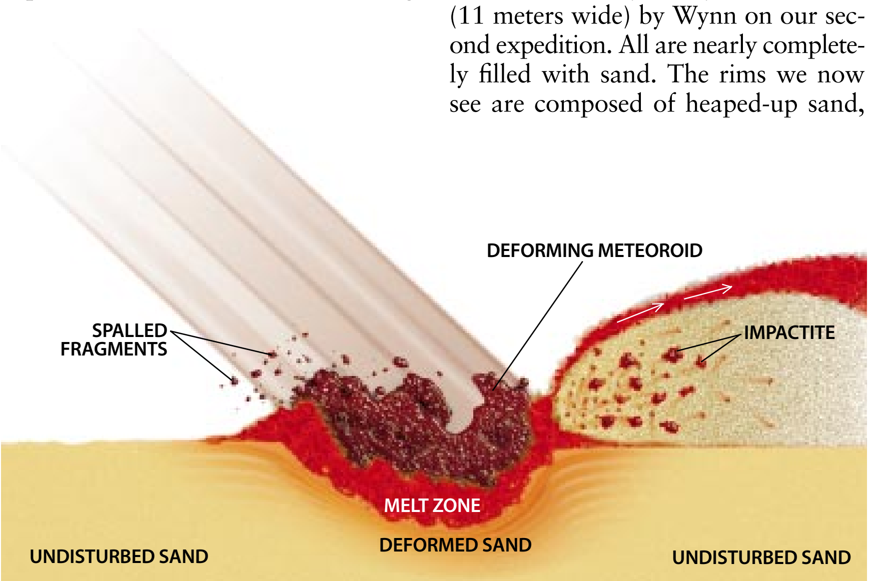
degrees C (142 degrees Fahrenheit)—in the shade under a tarp—and the humidity was 2 percent, a tenth of what the rest of the world calls dry. Wynn went out to do a geomagnetic survey, and by the time he returned he was staggering and speaking an incoherent mixture of Arabic and English. Only some time later, after water was poured on his head and cool air was blasted in his face, did his mind clear.

Zahid financed the second and third expeditions as well. On our weeklong third expedition, furious sandstorms destroyed our camp twice, and the temperature never dropped below 40 degrees C, even at night. We each kept a two-liter thermos by our beds; the burning in our throats awoke us every hour or so.

Shocking Rock

The Wabar site is about 500 by 1,000 meters in size. There are at least three craters, two (116 and 64 meters wide) recorded by Philby and the other (11 meters wide) by Wynn on our second expedition. All are nearly completely filled with sand. The rims we now see are composed of heaped-up sand, anchored in place both by "impactite" rock—a bleached, coarse sandstone—and by large quantities of black-glass slag and pellets. These sandy crater rims are easily damaged by tire tracks. There are also occasional iron-nickel fragments.

Geologists can deduce that a crater was produced by meteorite impact—rather than by other processes such as erosion or volcanism—by looking for signs that shock waves have passed through rocks [*see box above*]. The impactite rocks at the Wabar site pass the test. They are coarsely laminated, like other sandstones, but these laminations consist of welded sand interspersed with ribbonlike voids. Sometimes the



SLIM FILMS

CROSS SECTION of meteorite impact, as reconstructed by computer simulations, shows how the Wabar craters were created within a matter of seconds. The meteorite flattened as it hit the ground; a shock wave traveled backward through the body, causing part of it to spall off with little damage; the rest of the meteorite melted and amalgamated with sand directly underneath; surrounding sand was compressed into impactite. The whole mess was then thrust into the air. Deeper layers of sand were relatively unaffected.

layers all bend and twist in unison, unlike those in any other sandstone we have ever seen. The laminations are probably perpendicular to the path taken by a shock wave. Moreover, the impactite contains coesite, a form of shocked quartz found only at nuclear blast zones and meteorite sites. X-ray diffraction experiments show that coesite has an unusual crystal structure, symptomatic of having experienced enormous pressures.

*At the point of impact, **a conelike curtain of hot fluid** erupted into the air. The incandescent curtain of molten rock expanded rapidly as more and more of the meteorite made contact with the ground.*

The impactite is concentrated on the southeastern rims and is almost entirely absent on the north and west sides of the craters. This asymmetry suggests that the impact was oblique, with the incoming objects arriving from the northwest at an angle between 22 and 45 degrees from the horizontal.

The two other types of rock found at Wabar are also telltale signs of an impact. Iron-nickel fragments are practically unknown elsewhere in the desert, so they are probably remnants of the meteorite itself. The fragments come in two forms. When found beneath the sand, they are rusty, cracked balls up to 10 centimeters in diameter that crumble in the hand. Daniel M. Barringer, an American mining engineer who drilled for iron at Meteor Crater in Arizona early this century, called such fragments, which occur at several iron-meteor sites, "shale balls."

When the iron fragments are found at the surface, they are generally smooth, covered with a thin patina of black desert varnish. The largest piece of iron and nickel is the so-called Camel's Hump, recovered in a 1965 expedition and now displayed at King Saud University in Riyadh. This flattened, cone-shaped chunk, weighing 2,200 kilograms (2.43 tons), is probably a fragment that broke off the main meteoroid before impact. Because the surface area of an object is proportional to its radius squared, whereas mass is proportional to the radius cubed, a smaller object undergoes proportionately more air drag. Therefore, a splinter from the projectile slows down more than the main body; when it lands, it may bounce rather than blast out a crater.

The other distinctive type of rock at Wabar is the strange black glass. Glassy rock is often found at impact sites, where it is thought to form from molten blobs of material splattered out from the crater. Near the rims of the Wabar craters, the black glass looks superficially like Hawaiian pahoehoe, a ropy, wrinkled rock that develops as thickly flowing lava cools. Farther away, the glass pellets become smaller and more droplike. At a distance of 850 meters northwest of the nearest crater, the pellets are only a few millimeters across; if there are any pellets beyond this distance, sand dunes have covered them. When chemically analyzed, the glass is uniform in content: about 90 percent local sand and 10 percent iron and nickel. The iron and nickel appear as microscopic globules in a matrix of melted sand. Some of the glass is remarkably fine. We have found filigree glass-splatter so fragile that it does not survive transport from the site, no matter how well packaged.

The glass distribution indicates that the wind was blowing from the southeast at the time of impact. The wind direction in the northern Empty Quarter is seasonal. It blows from the north for 10 months of the year, sculpting the huge, horned barchan sand dunes. But during the early spring, the wind switches direction to come from the southeast. Spring is the desert sandstorm season that worried military planners during the Gulf War; it coincides with the monsoon season in the Arabian Sea. All year long, the air is dead still when the sun rises, but it picks up in the early afternoon. By sunset it is blowing so hard that sand stings your face as you walk about; on our expeditions, we needed swim goggles to see well enough to set up our tents. Around midnight the wind drops off again.

Curtains

Black material and white—the Wabar site offers little else. This dichotomy suggests that a very uniform process created the rocks. The entire impact apparently took place in sand; there is no evidence that it penetrated down to bedrock. In fact, our reconnaissance found no evidence of outcropping rock (bedrock that reaches the surface) anywhere within 30 kilometers.

From the evidence we accumulated

JEFFREY C. WYNN

SECOND-LARGEST CRATER at the Wabar site, Philby "A," has been nearly buried by a creeping seif ("sword," in Arabic) dune. Only its southeastern rim, preserved by a gravelly mix of rock formed during impact, still pokes up above the sand. The 64-meter (210-foot) crater marks the impact site of a five-meter meteorite, one of several pieces of the original Wabar meteoroid (which broke apart in midair). The chunks hit the ground at speeds of up to 25,000 kilometers per hour—20 times as fast as a .45-caliber pistol bullet.

during our expeditions, as well as from the modeling of impacts by H. Jay Melosh and Elisabetta Pierazzo of the University of Arizona, we have pieced together the following sequence of events at Wabar.

The incoming object came from the northwest at a fairly shallow angle. It may have arrived in the late afternoon or early evening, probably during the early spring. Like most other meteoroids, it entered the atmosphere at 11 to 17 kilometers per second (24,600 to 38,000 miles per hour). Because of the oblique angle of its path, the body took longer to pass through the atmosphere than if it had come straight down. Consequently, air resistance had a greater effect on it. This drag force built up as the projectile descended into ever denser air. For most meteoroids, the drag overwhelms the rock strength by eight to 12 kilometers' altitude, and the object explodes in midair. The Wabar impactor, made of iron, held together longer. Nevertheless, it eventually broke up into at least four pieces and slowed to half its initial speed. Calculations suggest a touchdown velocity of between five and seven kilometers per second, about 20 times faster than a speeding .45-caliber pistol bullet.

The general relation among meteorite size, crater size and impact velocity is known from theoretical models, ballistics experiments and observations of nuclear blasts. As a rule of thumb, craters in rock are 20 times as large as the objects that caused them; in sand, which absorbs the impact energy more efficiently, the factor is closer to 12. Therefore, the largest object that hit Wabar was between 8.0 and 9.5 meters in diameter, assuming that the impact velocity was seven or five kilometers per second, respectively. The aggregate mass of the original meteoroid was at least 3,500 tons. Its original kinetic energy amounted to about 100 kilotons of exploding TNT. After the air braking, the largest piece hit with an energy of between nine and 13 kilotons. Although the Hiroshima bomb released a comparable amount of energy, it destroyed a larger area, mainly because it was an airburst rather than an explosion at ground level.

At the point of impact, a conelike curtain of hot fluid—a mixture of the incoming projectile and local sand—erupted into the air. This fluid became the black glass. The incandescent curtain of molten rock expanded rapidly as more and more of the meteorite made contact with the ground. The projectile itself was compressed and flattened during these first few milliseconds. A shock wave swept back through the body; when it reached the rear, small pieces were kicked off—spalled off, in geologic parlance—at gentle speeds. Some of these pieces were engulfed by the curtain, but most escaped and plopped down in the surrounding sand as far as 200 meters away. They are pristine remains of the original meteorite. (Spalling can also throw off pieces of the planet's surface without subjecting them to intense heat and pressure. The famous Martian meteorites, for example, preserved their delicate microstructures despite being blasted into space.)

A shock wave also moved downward, heating and mixing nearby sand. The ratio of iron to sand in the glass pellets suggests that the volume of sand melted was 10 times the size of the meteorite—implying a hemisphere of sand about 27 meters in diameter. Outside this volume, the shock wave, weakened by its progress, did not melt the sand but instead compacted it into "insta-rock": impactite.

The shock wave then caused an eruption of the surface. Some of the impactite was thrown up into the molten glass and was shocked again. In rock samples this mixture appears as thick black paint splattered on the impactite. Other chunks of impactite were completely immersed in glass at temperatures of 10,000 to 20,000 degrees C. When this happened, the sandstone underwent a second transition into bubbly glass.

The largest crater formed in a little over two seconds, the smallest one in only four fifths of a second. At first the craters had a larger, transient shape, but within a few minutes material fell back out of the sky, slumped down the sides of the craters and reduced their volume. The largest transient crater was probably 120 meters in diameter. All the sand that had been there was swept up in a mushroom cloud that rose thousands of meters, perhaps reaching the stratosphere. The evening breeze did not have to be very strong to distribute molten glass 850 meters away.

JOE POLIMENI AND BILL CHASTEEN *Zahid Tractor Corporation and A.M. General Corporation*

EJECTA BLANKET at the edge of the Philby "A" crater consists of three types of debris from the impact: white impactite (a sandstonelike rock formed from compressed sand), black glass (a lavalike rock formed from melted sand) and meteorite fragments (nearly pure iron, with a little nickel). The authors, dressed in special jumpsuits to protect them from the harsh climate, are using magnetometers to search for the meteorite pieces. The tall antenna on the white Hummer vehicle is for Global Positioning System tracking—essential in the middle of the desert, where it is easy to get lost in the protean landscape.

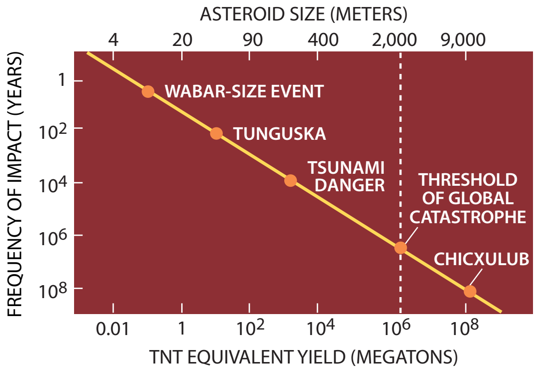
Fading Away

And when did all this take place? That has long been one of the greatest questions about Wabar. The first date assigned to the event, based on fission-track analysis in the early 1970s of glass samples that found their way to the British Museum and the Smithsonian Institution, placed it about 6,400 years ago. Field evidence, however, hints at a more recent event. The largest crater was 12 meters deep in 1932, eight meters deep in 1961 and nearly filled with sand by 1982. The southeastern rim was only about three meters high during our visits in 1994 and 1995. Dune experts believe it would be impossible to empty a crater once filled.

The Wabar site might have already disappeared if impactite and glass had not anchored the sand. At least two of the craters are underlaid by impactite rocks, which represent the original bowl surface before infilling by sand. We were able to collect several samples of sand beneath this impactite lining for thermoluminescence dating. The results, prepared by John Prescott and Gillian Robertson of the University of Adelaide, suggest that the event took place less than 450 years ago.

The most tantalizing evidence for a recent date is the Nejd meteorites, which were recovered after a fireball passed over Riyadh in either 1863 or 1891, depending on which report you believe. The fireball was said to be headed in the direction of Wabar, and the Nejd meteorites are identical in composition to samples from Wabar. So it is likely that the Wabar calamity happened only 135 years ago. Perhaps the grandfathers of Philby's guides saw the explosion from a long way off.

The date is of more than passing interest. It gives us an idea of how often such events occur. The rate of meteorite hits is fairly straightforward to understand: the bigger they come, the less frequently they fall [*see illustration above*]. The most recently published estimates suggest that something the size of the Wabar impactor strikes the earth about once a decade.



AVERAGE FREQUENCY OF IMPACTS on the earth can be estimated from the amount of scrap material zipping around the solar system and the observed distribution of craters on the moon. A two-kilometer rock, capable of wreaking damage worldwide, falls once every million years on average. (In relating size to explosive energy, this graph assumes a stony asteroid at 20 kilometers per second.)

DAVID MORRISON *NASA Ames Research Center*; LAURIE GRACE

There are similar iron-meteorite craters in Odessa, Tex.; Henbury, Australia; Sikhote-Alin, Siberia; and elsewhere. But 98 percent of Wabar-size events do not leave a crater, even a temporary one. They are caused by stony meteoroids, which lack the structural integrity of metal and break up in the atmosphere. On the one hand, disintegration has the happy consequence of protecting the ground from direct hits. The earth has relatively few craters less than about five kilometers in diameter; it seems that stony asteroids smaller than 100 to 200 meters are blocked by the atmosphere.

On the other hand, this shielding is not as benevolent as it may seem. When objects detonate in the air, they spread their devastation over a wider area. The Tunguska explosion over Siberia in 1908 is thought to have been caused by a stony meteoroid. Although very little of the original object was found on the ground, the airburst leveled 2,200 square kilometers of forest and set much of it on fire. It is only a matter of time before another Hiroshima-size blast from space knocks out a city [see "Collisions with Comets and Asteroids," by Tom Gehrels; SCIENTIFIC AMERICAN, March 1996].

By the standards of known impacts, Wabar and Tunguska are mere dents. Many of the other collision sites around the world, including the Manicouagan ring structure in Quebec, and the Chicxulub site in Mexico's northern Yucatán, are far larger. But such apocalypses happen only every 100 million years on average. The 10-kilometer asteroid that gouged out Chicxulub and snuffed the dinosaurs hit 65 million years ago, and although at least two comparable objects (1627 Ivar and the recently discovered 1998 QS52) are already in earth-crossing orbits, no impact is predicted anytime soon. Wabar-size meteoroids are much more common—and harder for astronomers to spot—than the big monsters. Ironically, until the Wabar expeditions, we knew the least about the most frequent events. The slag and shocked rock in the deserts of Arabia have shown us in remarkable detail what the smaller beasts can do. SA

The Authors

JEFFREY C. WYNN and EUGENE M. SHOEMAKER worked together at the U.S. Geological Survey (USGS) until Shoemaker's death in a car accident in July 1997. Both geoscientists have something of an Indiana Jones reputation. Wynn, based in Reston, Va., has mapped the seafloor using electrical, gravitational, seismic and remote sensing; has analyzed mineral resources on land; and has studied aquifers and archaeological sites around the world. He served as the USGS resident mission chief in Venezuela from 1987 to 1990 and in Saudi Arabia from 1991 to 1995. His car has broken down in the remote deserts of the southwestern U.S., in the western Sahara and in the deep forest in Amazonas, Venezuela; he has come face-to-snout with rattlesnakes, pit vipers and camel spiders. Shoemaker, considered the father of astrogeology, was among the first scientists to recognize the geologic importance of impacts. He founded the Flagstaff, Ariz., facility of the USGS, which trained the Apollo astronauts; searched for earth-orbit-crossing asteroids and comets at Palomar Observatory, north of San Diego; and was a part-time professor at the California Institute of Technology. At the time of his death, he was mapping impact structures in the Australian outback with his wife and scientific partner, Carolyn Shoemaker.

Further Reading

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Additional information on impact structures can be found at http://bang.lanl.gov/solarsys/eng/tercrate.htm on the World Wide Web.