which Donald Clayton of Clemson University in Clemson, South Carolina, has shown must have formed in the flurry of nuclear reactions in a supernova. Some of the graphite grains that Bernatowicz and his colleagues have studied contain unusually large amounts of silicon-28 and high ratios of carbon-12 to carbon-13—two other signs of a supernova origin. Others carry the anomalously low carbon ratios characteristic of winds from the old, bloated, low-mass stars called asymptotic giant-branch (AGB) stars.

Bernatowicz, who organized the conference along with stardust pioneers Robert Walker and Ernst Zinner of the McDonnell Center for the Space Sciences at Washington University, is going beyond identifying stars to probing conditions inside them. By cutting the grains with a microtome and examining the slices with an electron microscope, he discovered even smaller particles at their center—crystals of titanium carbide, for example, that looked like they were engulfed by the graphite as it condensed, layer by layer. Says Bernatowicz, "You're pretty safe in the assumption that the titanium carbide was there first" when the graphite condensed, like dust particles caught in growing hailstones. The team realized that this sequence of formation—along with the near absence of silicon carbide, even though silicon is abundant in AGB stars—was a clue to conditions in the stellar atmosphere.

Graphite condenses at about the same temperature regardless of pressure, for example, but titanium carbide condenses more readily as the pressure goes up. Calculations by team member Katharina Lodders and others showed that for the titanium carbide to have formed first, the density of the stellar atmosphere had to be extraordinarily high—at least 100 times higher than astronomers had estimated. At those densities, AGB stars would shed mass far too quickly in the high-speed winds that astronomers have clocked blowing outward from them, unless the high densities are limited to narrow jets or knots of turbulence.

Bernatowicz says that the grains bearing the isotopic signature of supernovas are flecked with such inclusions as well, implying that supernova atmospheres also have pockets of high density. "It's really a beautiful result," says Arizona's Arnett. Recent computer models of supernovas did imply lumpy atmospheres, but "now we have a way to test [such predictions] in the laboratory."

Washington University's Larry Nittler and Caltech's Wasserburg and Gary Huss, meanwhile, are finding that another kind of grain may offer a deeper look into stars. Examining particles of aluminum oxide that seem to come from red giant stars, the researchers found that one oxygen isotope, oxygen-18, was unexpectedly scarce. The depletion suggested that before the grains condensed, the gases that formed them had been churned deep into the stars, through layers hot enough to "cook" that isotope into heavier elements. The same process would also deplete the surface gases of helium-3—an isotope that traces element-forming processes in the big bang. Such stellar churning, if it's common enough, could explain why the cosmos as a whole seems to contain less helium-3 than some scenarios of element formation predict (*Science*, 7 June, p. 1429).

Another set of oxide grains might help settle a different cosmic conundrum: the age of the universe. Various measures of cosmic age point to wildly different figures—anywhere between 8 billion and 15 billion years—so astronomers would welcome an extra indicator. The first step in extracting an age from the oxide grains is to add the 4.6-billion-year age of the solar system to the likely age—just short of 6 billion years—of the red giant stars that contributed the grains to the presolar nebula. The next is to determine how old the galaxy was when the stars formed, and a complex comparison of three different oxygen isotopes in the grains points to an answer: slightly under 4 billion years. The rough total is 14 billion years. Because the universe as a whole has to be at least that old, the result—although uncertain—is squarely on the side of an old universe.

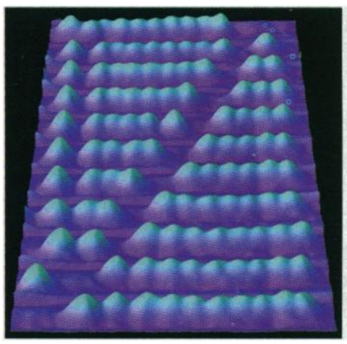
The grains have plenty of other secrets to reveal, participants at the conference emphasized. Besides offering glimpses of their stellar birthplaces, they may also hold clues to conditions in the primordial solar nebula. Patrick Cassen of the NASA Ames Research Center, for example, presented model calculations he did with his colleague Kenneth Chick showing that meteorites formed in different parts of the nebula might contain different amounts of stardust, depending on the amount of heating and mixing their ingredients had undergone. As a result, stardust counts might be used to map out the workings of the primordial Cuisinart. For astronomers facing the blizzard of data from such studies, said Zinner in summing up the conference, it all adds up to "a much harder life, but I hope a much more enjoyable life."

–**James Glanz**

DATA STORAGE

Tiny Abacus Points to New Devices

Talk about coming full circle. This week, a team of researchers at IBM's Zurich Research Laboratory reported crafting the first nanoscale abacus, some 2000 years after its macroscopic cousin first came into widespread use. Unlike a traditional abacus, a counting device consisting of sets of beads threaded on parallel wires, the IBM version is composed of spherical carbon molecules, called buckyballs, lined up along a steplike edge on a copper surface. Although the new abacus may not have quite the impact of its predecessor, it could lead to data-storage devices capable of holding vastly greater amounts of information than today's computer chips and disk drives can hold.



IBM ZURICH RESEARCH LABORATORY

Back to the future. Buckyballs lined up on a copper surface.

"The work is certainly a landmark experiment," says Stephen Minne, an electrical engineer at Stanford University in Palo Alto, California. Indeed, it represents the first time researchers have succeeded in using individual molecules at room temperature to store numerical information. The IBM group used their abacus to store numbers from 1 to 10 by sliding the buckyballs along the edge one by one, with an ultrasharp tip of a scanning tunneling microscope (STM). Still, the scientists have a long way to go before their work can be applied to real-world computing, say Minne and others. For starters, an STM tip can only move one buckyball at a time; for the technique to be useful for reading and writing huge amounts of data, researchers would need to figure out how to manipulate thousands or millions of the buckyballs in concert.

The new work, which is described in the 11 November issue of *Applied Physics Letters*, builds on plenty of previous research. Another team of IBMers, led by physicist Donald Eigler at the Almaden Research Center in California, was the first to push atoms around on a metal surface with an STM tip. But in that experiment, conducted in 1990, the researchers had to chill their sample down to just a few degrees above absolute zero to keep the surface atoms from skittering around. Earlier this year, the Zurich-based IBM team—led by physicist James Gimzewski—constructed a new member of a class of organic molecules known as porphyrins that readily adhered to metal surfaces at room temperature. But these molecules were difficult to control when pushed by an STM tip, so the researchers couldn't use them to represent numerical information (*Science*, 12 January, p. 181).

For the current experiment, Gimzewski and his colleagues Maria Teresa Cuberes and Reto Schlittler tried soccerball-shaped buckyballs on copper. Researchers have known for some time that metal surfaces are rarely perfectly flat; rather they resemble a series of flat terraces separated by atomic-scale steps. Researchers have also noted that buckyballs cling to metal surfaces, and they preferentially line up along the steps, where they share the most attractive electronic interactions with neighboring metal atoms. The team decided to try to use one of these steps to keep the buckyballs in line, much as an abacus's wires hold the beads in place.

And it worked. After depositing buckyballs on a copper sample, the researchers used the STM to take a look at the surface. As they had hoped, they found a row of buckyballs lined up along the step between two terraces. Then they pushed the buckyballs along the step with the STM tip, one at a time, much like one would push abacus beads. After moving each buckyball, they used the atomic-imaging tip to take a new picture of the surface. Finally, they pieced together the 10 images into one composite image (previous page).

While the current demonstration doesn't store numbers as computer-friendly binary 1s and 0s, it's easy to imagine how to change the setup to make binary data storage possible, says Cuberes. One approach would be to create tiny grooves in the copper surface, just wide enough for one buckyball to fit inside and only long enough for it to move back and forth when pushed by an STM tip. One side of the groove would be the 0 position; the other side, the 1. The researchers are nowhere near accomplishing this, Cuberes acknowledges. But if they can pull it off, this nanoscale device, like the original abacus, could create a bit of history of its own.

–Robert F. Service

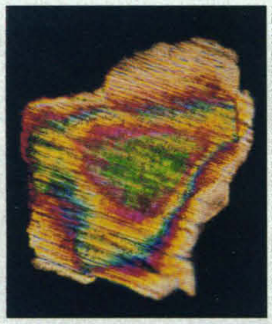
EXTINCTIONS

A Shocking View of the Permo-Triassic

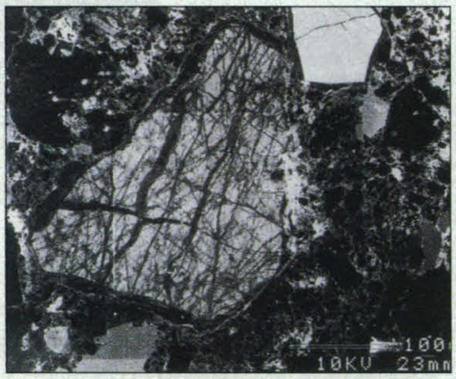
DENVER—The great whodunit of the dinosaur extinctions has a likely suspect—an asteroid impact. But what of the largest mass extinction of all time, 250 million years ago at the Permo-Triassic boundary? This great dying marked the end of the 300-million-year reign of the "old life" of the Paleozoic era—typified by the last of the trilobites—and made way for more diverse and predatory life, including the dinosaurs. Its cause has long been a mystery, with theories ranging from anoxia in the oceans to massive volcanic eruptions on land (*Science*, 1 December 1995, p. 1441).

Now, at the annual meeting here of the Geological Society of America, paleontologist Gregory Retallack of the University of Oregon has presented pictures of microscopic quartz grains that he claims are the "first unequivocal evidence of an impact," implicating a comet or asteroid in this extinction too. The hallways buzzed with paleontologists and geologists exchanging opinions on Retallack's photos, which purportedly showed faint bands of glass-filled fractures within the grains. Retallack thinks the fractures formed in the shock of a massive impact and notes that similar grains have been linked to the Cretaceous-Tertiary extinction. The hallway buzz was more cautious. "There may be something there," says petrologist Glen Izett of The College of William and Mary in Williamsburg, Virginia, "but photographs don't show what your eye does through a microscope."

If Retallack and his Oregon colleagues Abbas Seyedolali and David Krinsley are right, then the Permo-Triassic extinction will have not only a new cause but also a new time scale. Most paleontologists have seen the crisis as a protracted "event" or even as two separate pulses of extinction. But an impact extinction would have happened in a geologic instant. It is a crucial question, notes paleontologist Douglas Erwin of the National Museum of Natural History, because "if the Permo-Triassic extinction hadn't happened the way it did, you would find a whole different bunch of beasts" alive today.



GLEN IZETT/COLLEGE OF WILLIAM AND MARY



G. RETALLACK, A. SEYEDOLALI, D. KRINSLEY/U. OF OREGON, EUGENE

Shock effect? Permo-Triassic quartz grain *(above)* is fractured, but the banding characteristic of an impact doesn't show as clearly as in a truly shocked grain *(top)*.

Although intrigued, many of Retallack's colleagues are not yet convinced. The quartz grains are old and fractured by more recent, mundane stresses, notes Philippe Claeys of Berlin's Museum of Natural History, making it difficult to see the faint traces that might have been left by an impact. Truly shocked quartz is riddled with thin, straight, parallel planar structures called planar deformation features (PDFs), which form sets that intersect at predictable angles depending on the crystal structure of the quartz. Photomicrographs of the Oregon group's grains, which come from the Permo-Triassic boundary near Sydney, Australia, and from the Transantarctic Mountains in Antarctica, reveal one set of possible PDFs, says Claeys. But he argues that several sets intersecting at the correct angles would be required for conclusive proof.

Retallack counters that Claeys and others haven't yet seen all there is to see. Under the microscope, where the full depth of a quartz grain can be viewed by changing the depth of focus, all the grains can be seen to have at least three sets of PDFs, he says; one has seven.

If other claims of shocked quartz are any guide, it may take a while to convince the community. Researchers have searched the rock record from one end of geologic time to the other for signs of impacts coinciding with biological crises, and the only success so far has been at the end of the Cretaceous. Some claims of shocked quartz have been summarily rejected, while others, such as possible shocked quartz from the Jurassic-Triassic boundary 202 million years ago, have interested but not yet persuaded researchers (*Science*, 11 January 1991, p. 161).

Ideally, experts would like their own three-dimensional look at Retallack's grains. Barring that, they want numbers: more quantitative data, such as the refractive index of the grains, which is altered by shock, as well as the orientations of PDFs. The Oregon group says they are gathering those data in cooperation with colleagues. They are also examining their samples for iridium—another telltale sign of an impact, abundant at the Cretaceous-Tertiary boundary. Better pictures, specifically transmission electron microscopic (TEM) images that can identify the shock-generated glass unique to PDFs, would help too. Retallack "has got a fairly good chance," says Claeys, "but he's got to do the TEM." Otherwise, his data may not be so shocking after all.

–Richard A. Kerr