Catastrophes of Every Ilk at The Geophysics Fest

At the annual meeting of the American Geophysics Union (AGU) in San Francisco on 7-11 December, catastrophes came in all sizes. On the molecular level, atmospheric chemists had news about the manmade compounds destroying the ozone shield–and for once the news was good. More earthshaking were signs of long-distance connections among earthquakes. And from farther afield came reports of odd-shaped debris from mini-planet collisions.

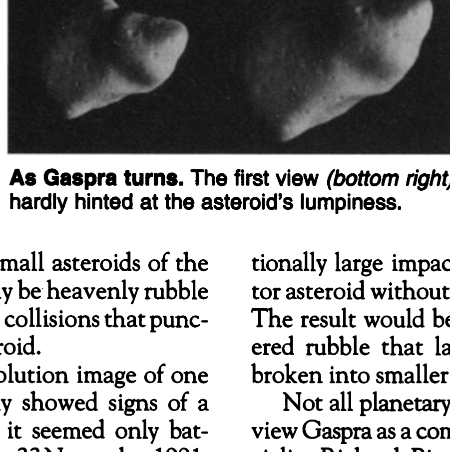
A Lumpy Gaspra Hints at a Shattering Secret

When astronomers got their first good look at the small asteroid Gaspra a year ago in an image from the Jupiter-bound Galileo probe, it looked much as they had imagined: a single slab of rock 17 kilometers long. But now that they've had a little more time to digest the image, along with additional views recently transmitted by Galileo, some planetary scientists are seeing a very different sort of asteroid, one they thought might be rare. Rather than a single rock, Galileo imaging team member Clark Chapman of the Planetary Science Institute in Tucson said at the meeting, he and his colleagues may be looking at two or more giant lumps of rock loosely held together by their own feeble gravity.

And Gaspra may be no exception. In another presentation at the meeting, Scott Hudson of Washington State University confirmed that the only other asteroid astronomers have studied up close, a 2-kilometer body that swung close to Earth in 1989, is clearly composed of two distinct lumps. At this rate, many of the small asteroids of the solar system may actually be heavenly rubble heaps, left over from the collisions that punctuate the life of an asteroid.

The initial high-resolution image of one side of Gaspra certainly showed signs of a collision-filled life, but it seemed only battered, not broken (*Science*, 22 November 1991, p. 1109). A sequence of images revealing most of Gaspra's surface as it rotated was not beamed back to Earth until just before Thanksgiving, however, because the failure of Galileo's main antenna to open has limited its transmitting power. "From almost any direction, it looks lumpy" in the new images, says Chapman, "kind of like you might have assembled two lumps of clay into a peanut shape."

It's not just the lumpiness of the new images that has planetary scientists thinking Gaspra may not be just one large mass; it's also the rounded, softened surface seen in the initial view. By conventional thinking, bodies this small—with only *1/2000th* the gravitational pull of Earth—can't hold onto debris kicked up by the steady rain of large and small meteorites. So, unlike the moon with its deep layer of "soil" or regolith, Gaspra should be bare, rough, and jagged. Far from it: Peter Thomas of Cornell University reported that the linear grooves visible on Gaspra's surface seem to be choked with debris. Chapman, among others, gets the impression from such analyses that Gaspra is blanketed by 100 meters of regolith, maybe much more.


NASA/JPL

As Gaspra turns. The first view *(bottom right)* hardly hinted at the asteroid's lumpiness.

That much regolith couldn't be the result of the impacts—it must have been on hand when Gaspra formed. And that suggests to Chapman that Gaspra might have had an earlier life as part of a much larger asteroid—one massive enough to hold onto the regolith formed by impacts. Then an exceptionally large impact shattered the progenitor asteroid without dispersing all the pieces. The result would be a heap of regolith-covered rubble that later impacts could have broken into smaller rubble piles like Gaspra.

Not all planetary scientists are inclined to view Gaspra as a composite. Says asteroid specialist Richard Binzel of the Massachusetts Institute of Technology, "I would tend to be cautious. I am surprised there are no jagged edges, but that's likely due to its being [sandblasted] by a large number of small objects. All in all, the evidence for a re-accumulated object is suggestive, but not overwhelming."

There was less debate, however, about the composite nature of the other closely inspected asteroid, Castalia. The clincher came when Hudson showed a three-dimensional image of the asteroid reconstructed from radar signals bounced off it during a 1989 experiment by Steven Ostro of the Jet Propulsion Laboratory and his colleagues. As they had already inferred from the raw data (*Science*, 24 November 1989, p. 999), Castalia looks like what Chapman describes as "one tennis ball stuck against a dimpled tennis ball." Presumably, the asteroid was formed when two chunks of rock blasted from the same parent asteroid remained so close that their feeble gravity bound them together. It's a tough life, being an asteroid.

Help Is on the Way for the Threatened Ozone Shield

Late last month the Montreal Protocol, which sets limits on the production of ozone-destroying halocarbons, was tightened a second time. It now requires the 92 signatory countries to phase out the worst offenders among the chemicals by 1996—4 years ahead of the earlier schedule. But have such controls actually made a difference yet? The atmosphere has given its answer: a definite yes.

At the meeting, researchers monitoring the halocarbons called chlorofluorocarbons (CFCs) reported that although CFCs continue to increase in the atmosphere, the rate of increase is slowing due to declining emissions around the world. That doesn't promise a near-term reprieve for the ozone layer; even after CFC levels begin to decline at the end of this decade, the stratosphere probably won't cleanse itself of most of these pollutants until sometime in the second half of the next century. But it does mean that industry is heeding—and sometimes even surpassing—the Montreal goals.

The good news came in a talk by atmospheric chemist Derek Cunnold of the Georgia Institute of Technology and his colleagues, who monitored CFCs from sites scattered from Ireland to Tasmania as part of the Atmospheric Lifetime Experiment and the Global Atmospheric Gases Experiment. They and other groups have found that the rate of increase in CFC-11 has fallen from the 9 parts per trillion (ppt) per year seen until 1988 to 5 ppt per year in 1990, the most recent year with complete data. The rate of increase of CFC-12 concentrations likewise peaked in 1988 at 17 ppt per year and dropped to 14 ppt per year in 1990.

To account for the slowing, say Cunnold and colleagues, releases in 1990 must have been down by about 20% from their peaks in 1988. At that rate, manufacturers were actually exceeding the goals of the existing Montreal Protocol by enough to anticipate the tightened standards. "People are seeing the case [against CFCs] as being settled," says

Daniel Albritton of the National Oceanic and Atmospheric Administration's Aeronomy Laboratory in Boulder, who has served as a scientific adviser during Montreal Protocol negotiations. "They see that there are opportunities in creating new markets" for CFC substitutes and halocarbon-free technologies, such as chlorine-free cleaning systems.

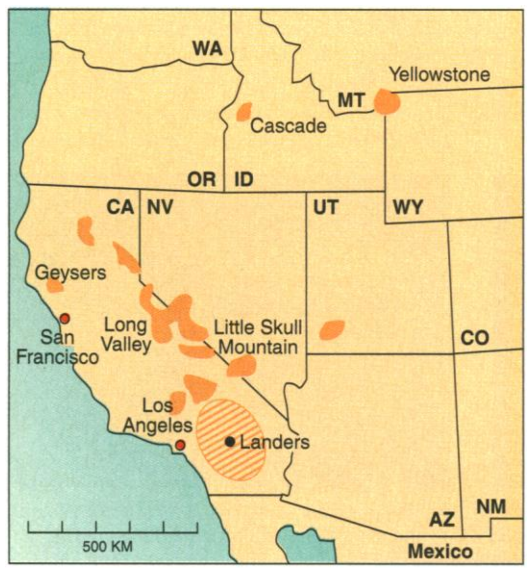
The companies embracing the Montreal goals may see a payoff before the ozone layer does, however. Under the old deadlines for CFC phase-out, the United Nations Environment Program and the World Meteorological Organization jointly estimated that stratospheric concentrations of CFC-derived chlorine would increase another 20% before peaking and beginning a decline around the end of the decade. It would take at least 60 years more for chlorine to drop to the level at which the Antarctic ozone hole first appeared in the late 1970s. The recent tightening of CFC limits will help—but only by years, not decades. The ozone-depletion die is cast, and no one can take it back.

Landers Quake's Long Reach Is Shaking Up Seismologists

As if a big earthquake weren't unsettling enough, it is inevitably followed by lots of smaller ones—just the thing to give victims the jitters for months after the big shake. True to form, the magnitude 7.5 quake that shook the Southern California town of Landers last June has been followed by a long, rumbling train of aftershocks. But this time, much to researchers' astonishment, the aftermath wasn't limited to the vicinity of the main quake—the Mojave Desert east of Los Angeles. Instead, they reported at the meeting, the temblor triggered surges of seismic activity up to 1250 kilometers away, in areas as distant as Northern California and Yellowstone National Park.

Those distant shocks have startled seismologists as well as ordinary residents. Conventional thinking, at least among U.S. researchers, holds that the stress generated when a fault slips in an earthquake peters out within a distance equal to a couple of times the length of the ruptured fault. For Landers, where about 70 kilometers of fault ruptured, that would amount to only about one-tenth of the observed reach. Researchers are now inventing mechanisms to explain the disparity, ranging from a domino effect of slipping faults to the geologic equivalent of shaking up a can of soda. And they are beginning to shed some of their traditional skepticism about such long-distance connections (*Science*, 15 March 1991, p. 1315) as they look for possible long-range links among earlier quakes.

In the case of Landers, it didn't take a lot of looking. "If I showed my mother" some of the data, Paul Reasenberg of the U.S. Geological Survey (USGS) in Menlo Park told an AGU session, "she'd have little trouble seeing" the connections. In records from Long Valley, east of Yosemite National Park and 450 kilometers north of the epicenter, for example, Andrew Michael of the USGS in Menlo Park found surges of magnitude 2 and smaller quakes beginning just 30 seconds after the first seismic shear waves arrived. One such coincidence would have been ignored, Reasenberg said. But other seismologists had little trouble finding abrupt increases in seismicity at 11 other sites strung out north of Landers (150 kilometers east of Los Angeles) along the eastern California border and into the northern part of the state, Idaho, and Wyoming. The most dramatic activity by far



SOURCE: P. REASENBERG ET AL. ILLUSTRATION: C. FABER SMITH

Shaking up the West. The Landers quake triggered activity well beyond the usual aftershock zone *(oval)*.

struck Little Skull Mountain in southern Nevada, where an immediate surge in microseismicity culminated in a magnitude 5.6 quake 22 hours later.

In the standard picture of how the crust transmits stress from a rupturing fault, there's no place for such distant effects. The crust, assumed to act like a uniform, perfectly elastic layer, should gobble up stress like a big block of foam rubber. But Joan Gomberg of the USGS in Denver and her colleagues suggested at the meeting that the real-world crust, which is riddled with innumerable faults, might act more like a mosaic of rigid blocks. When one fault slips in an earthquake, it might trigger silent slip on a cascade of increasingly distant faults culminating in a second, distant earthquake. Listeners were generally skeptical of this scenario, but they couldn't rule it out in the case of Little Skull Mountain, at 280 kilometers away among the nearest of the distant aftershocks. However, most researchers agree with Reasenberg's gut feeling that the most distant sites are beyond the reach of interconnected, silent faults.

What most seismologists are falling back on is not long-range stress transmission but shaking: the seismic waves that spread away from Landers. The most powerful prolonged shaking comes from surface waves, which are ocean wave-like undulations of the uppermost crust; their arrival at several sites coincided within seconds with the surge in seismicity. By working the crust back and forth, Reasenberg says, surface waves might generate enough local stress to trigger ruptures on faults already strained to near the breaking point—much like banging on a wall to free a stuck window.

Shaking alone, however, can't explain the duration of the seismic surges. The seismic waves from Landers were over in a few minutes, but the distant aftershocks kept rumbling away for hours or days. Some seismologists see a clue to what might have stretched out the activity: Many, but not all, of the triggered sites lie in volcanic regions, with magma or geothermal fluids beneath the surface. No one knows exactly how deep fluids would help, but it might have been as straightforward as shaking a soda bottle. The seismic waves might have driven dissolved gases out of the magma, which would have pressurized the rock around the magma and triggered quakes until the pressure leaked away.

Those same regions may be sensitive to other kinds of distant influences as well. At the meeting, seismologist Bernard Minster of Scripps Institution of Oceanography told how he had come across hints of a connection between some of the sites sensitive to Landers and the 1989 Loma Prieta earthquake—but in this case the distant rumbling preceded rather than followed the main event. Minster has been dissecting a computer program developed by Volodya Keilis-Borok of the Institute of Earthquake Prediction Theory and Mathematical Geophysics in Moscow and his colleagues that monitors huge areas for possible precursors of a large earthquake, such as swarms of small earthquakes triggered by deep-seated crustal strain. The algorithm predicted the Loma Prieta quake, but it is so complex that no one was sure whether its success wasn't just good luck (*Science*, 15 March 1991, p. 1314).

After hearing about the Landers triggering, Minster followed a hunch and found that the algorithm's prediction of Loma Prieta depended heavily on the earlier seismicity at four of the same volcanic areas sensitive to Landers—areas that lie hundreds of kilometers from Loma Prieta as well. "At this point it's only a suggestion" of another long-distance connection, says Minster, but "if true, the algorithm will have pointed us toward a [new] physical phenomenon. That is useful even if it doesn't predict earthquakes."

–Richard A. Kerr