Martian Meteorites Are Arriving

The eight SNC meteorites found on Earth are probably from Mars, most researchers now agree, but how they ever got off their home planet remains a question

It seems too good to be true. After spending $25 billion to obtain rocks from the nearby moon, rocks from Mars are falling out of the sky to be picked up by anyone that happens by. "We think [the existence of meteorites from Mars] is a very good working hypothesis," says geochemist Michael Drake of the University of Arizona, who was not that quick to warm to the idea. "It's probable, but not proven; it's not likely to be incorrect. But short of going to Mars, no one will be absolutely convinced."

An increasing number of reputable researchers are convinced enough of the reality of martian meteorites to begin inferring the nature of Mars from them, even though there is a lingering problem—no one is quite sure how the meteorites ever got off Mars. In this issue of *Science* (p. 738), Ann Vickery and Jay Melosh of the University of Arizona propose one way that it may have happened. The catch is that more needs to be known about Mars to show that their mechanism for interplanetary rock transport or any other is practical.

When the Apollo astronauts were picking up moon rocks, it seemed preposterous that even a planet-jolting impact by a small asteroid could blast a rock to high enough speeds to escape without first vaporizing the rock or at least pulverizing it. But then the chemical and isotopic evidence began to mount. The focus of attention was the SNC (pronounced snick) meteorites, a group of eight odd rocks collected around the world labeled with the names of three meteorites—Shergotty, Nakhla, and Chassigny—that typify three subgroups of the SNCs.

In appearance and composition, the SNCs resemble certain basaltic rocks commonly found on Earth. That was perplexingly odd for meteorites that were supposed to come from asteroids, where conditions are most unplanetlike. On the other hand, the SNCs have some distinctive characteristics, such as their oxygen isotope composition, that set them apart from Earth and from any other meteorite.

Several findings in the early 1980s eventually tipped the scales from the SNCs being intriguing oddities to probable samples of Mars. One was their relative youthfulness. All seem to be 1.3 billion years old or younger. That is a far cry from the 4.0-billion-year minimum age of all other meteorites, and it makes the SNCs too young to be from an asteroid, which would have long ago turned cold and volcanically dead. Another was the discovery in 1982 of four noble gases trapped in a shergottite in the same relative abundances, within analytical error, as found in the atmosphere of Mars by the Viking landers. Because these gases were trapped in bits of glass formed by the shock of an impact, the idea of a large impact on Mars that both sealed atmospheric gases in the rock and sent it flying off the planet achieved real respectability, if not total credibility.

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In the spring of 1983 a martian origin gained a psychological boost from the recognition of meteorites from another relatively large body, the moon. With Apollo samples in hand, the identification was simple. Explaining how they got here was not. By conventional wisdom, a rock could not reach the speed of 2.5 kilometers per second needed to escape the moon's gravitational pull and still remain intact.

Melosh got impact cratering dynamicists out of a tight spot by suggesting that the very shock thought to destroy any samples blasted off the moon could, under special circumstances, also protect them. Rock lying near the moon's surface would escape the crushing power of an impact's compressive shock wave, Melosh reasoned, because that wave reflects downward from the surface as a tensile wave, the superposition of the two waves greatly reducing the stress felt by the near-surface rock. Despite the near cancellation of the shock wave, the steep increase in pressure with depth would accelerate to lunar escape velocity rock fragments, called spalls, as large as tens of centimeters.

Even with the trapped gas analyses in hand and a psychological barrier removed, most meteorite specialists in 1983 viewed a martian origin for the SNCs as a promising possibility, but caution was the watchword. Some new evidence has appeared since. Most importantly, nitrogen-15 and carbon dioxide, the major components of the martian atmosphere, have been added to the list of gases trapped in shergottite glass.

There is still a note of caution from some quarters, but, perhaps more than anything, the passage of time has made a martian origin an acceptable hypothesis. "I think most people have come around to thinking this is a good idea," says Harry McSween of the University of Tennessee. Naturally enough, those working with the impressive geochemical data are most inclined to accept the idea, but support has broadened considerably. Most observers now characterize a martian origin as "reasonable," "likely," "almost certain," or "probable." "The problem is," notes McSween, "there is no way we can tell for sure without a martian sample."

Short of the return of rocks from Mars, the best news for SNC specialists would be the determination of a practical means of launching rocks from Mars to Earth. Dynamicists are not there yet, but they sound like they are a lot closer. In 1983 Vickery and Melosh built a case for multiple impacts on asteroids as a SNC source because the spallation mechanism that allowed impacts to splash rocks tens of centimeters in diameter off the moon yielded no rocks larger than 1 meter from Mars, whose escape velocity is a hefty 5 kilometers per second. One-meter rocks were too small to make a Mars source work, the SNC meteorites apparently having left the planet as 10- to 15-meter boulders.

In their *Science* article, Vickery and Melosh take note of the strong chemical evidence and take a hard look at Mars. They conclude that "the SNC meteorites were probably ejected from a very large [martian] crater (more than 100 kilometers in diameter) about 200 million years ago." The brighter prospects for meteorites from Mars

If Meteorites Come from Mars . . .

If the SNC meteorites come from Mars, which seems increasingly likely, the extensive analyses of the SNCs should reflect many of the properties of Mars as a whole. Harry McSween of the University of Tennessee has summarized some of the results so far:

■ The composition of the mantle of Mars as calculated from SNC compositions is more Earth-like than all but one of a half-dozen predictions made without SNC data. That would imply that the mantles of Earth and Mars had similar initial compositions and that they evolved in a similar fashion. The martian mantle seems to be as oxidized as Earth's.

■ The oxygen isotope composition of the SNCs is distinctly different from that of Earth and the moon. That would imply that the presolar nebula was isotopically heterogeneous even on the scale of the sweeping action of the early Earth-moon system. That would favor a close genetic link between Earth and the moon, such as formation of the moon from Earth by a large impact.

■ The core of Mars seems to have formed about 4.5 billion years ago on the basis of the SNC rubidium-strontium isotopic composition, which would considerably narrow the 3-billion-year uncertainty in the core's age. The depletion of sulfur-loving elements in SNCs suggests that the core is rich in sulfides, sulfur constituting about 14% of the mass of the core. The relatively small core would constitute about 22% of the mass of the planet, which is toward the higher end of the predicted range.

Analyses of the SNCs have excited researchers interested in how much of the volatile elements such as carbon, hydrogen, and nitrogen were originally allotted to Mars, but a clear picture has yet to emerge. One proposal, by Robert Pepin of the University of Minnesota, is that both the xenon content and the geochemical composition of SNCs imply a dominant contribution to the volatiles by nebular material having a carbonaceous chondrite composition. Carbonaceous chondrites are primitive meteorites rich in volatiles. Earth and Venus do not exhibit such a clear geochemical signature.

If the SNC meteorites are from Mars, they will allow Earth-bound researchers to do some martian geological fieldwork without going that far afield. A central question of martian geology is, if Mars enjoyed a thick atmosphere in earlier times, as implied by water-cut channels on the surface, where is that atmosphere now that the martian surface pressure is 1% of Earth's? Because the atmosphere is mostly carbon dioxide, a geologist would look for a storehouse of calcium carbonate. No sign of calcium carbonate has been found in Viking observations.

James Gooding of the Johnson Space Center and his colleagues believe that they have "very strong evidence" of martian calcium carbonate as well as calcium sulfate trapped in the same shergottite glass that yielded the Mars-like gases. That physical isolation and the same unique oxygen isotope composition of these compounds as determined for the SNCs have convinced these researchers that extraterrestrial weathering, presumably on Mars, produced these relict grains rather than weathering of the meteorite after it landed in the Antarctic ice.

Allan Treiman of Boston University reasoned that he might be able to understand better how the SNC rocks formed if he found similar rocks on Earth. So he tracked down an analog to the Nakhla meteorites in thick lava flows in the Abitibi greenstone belt of northern Ontario, which is more than 2.5 billion years old. These flows are 125 meters thick, far thicker than today's typical 30-meter-thick flows. The rock of the lower half of the flows and Nakhla "are indistinguishable except for a little terrestrial metamorphism," says Treiman. With more field study, he hopes to learn why terrestrial lava flows and martian flows look so much alike.

Ironically, the authenticity of the SNCs will remain in doubt until a verifiable sample is in hand, but then the subsequent usefulness of the SNCs will be greatly reduced. Unless the site of the SNC impact or impacts can be pinned down, their verification as martian will relegate them to the same uncertain status as lunar meteorites, whose scientific usefulness is limited by their still unknown point of origin on the moon. If the SNCs are shown to be from some body other than Mars, planetary scientists will have a challenging mystery indeed. ■ **R.A.K.**

result from the removal of an external constraint on the spallation mechanism. In earlier calculations, the largest allowable crater was 30 kilometers in diameter because that is the size of the largest martian crater on terrain that is clearly as young as the 1.3-billion-year-old SNCs. Vickery and Melosh have now extrapolated the spallation mechanism to ejection of 10- to 15-meter rocks at martian escape velocity and found that a 200-kilometer crater would be required. There is only one crater on Mars that size, and it is too old.

By assuming that they might be off by a factor of 2 in estimating crater size, Vickery and Melosh produced a list of about a dozen candidate craters 100 kilometers in diameter or larger. However, none of these is on the 10 to 15% of the surface taken to be as young as the SNCs. If spallation is to work, the impactor would have had to obliterate a young volcanic formation emplaced in old terrain while not launching much old material. That restriction could be eased, notes Vickery, if shergottites are actually old, as suggested by uranium-thorium-lead isotopic dating. Dating specialists have been debating the age of the shergottites, but the central question has been whether they are 1.3 billion years old or only a few hundred million years old. Most SNC researchers are assuming that consideration of all the types of isotopic dating still supports an age of 1.3 billion years or younger for all the SNCs.

If a single, large impact 200 million years ago is not a flawless option, Vickery and Melosh find the alternatives to be far less attractive. They ranked four scenarios involving different crater sizes, numbers, and ages according to the amount and size of rocks that would now be reaching Earth. In their calculations spallation ejected the rock, and its fate in space—fragmentation and destruction by collisions and eventual collision with Earth—was calculated by George Wetherill of the Carnegie Institution of Washington. The four scenarios, as constrained by isotopic dating and cosmic ray–determined residence times in space, ranged from the ejection of 15-meter blocks by the large impact 200 million years ago followed by recent fragmentation in space to ejection of small rocks by three small, recent impacts and no further fragmentation.

No alternative seemed as appealing as the large impact 200 million years ago. An impact ejecting all the SNCs 10 million years ago was several times less probable. Three impacts during the past 10 million years, a scenario favored by many SNC researchers, would deliver a mass of rock to Earth that is nearly 10,000 times smaller than required.

"This is not the end of the issue," says

Vickery. "This is a plausibility argument. Until there is a lot more information about the surface of Mars, this is about as well as we can do." Most helpful might be a reevaluation of crater ages.

Another alternative would be the evaluation of a different ejection mechanism in the same scenarios. The only other serious contender at the moment is the mechanism of vapor jetting. Recently, John D. O'Keefe and Thomas Ahrens of the California Institute of Technology have shown in a computer model supported by laboratory experiments that a martian impactor hitting the surface at an angle of anywhere from 25° to 60°, the most common sort, can blow rocks right off the planet. The force of the impact vaporizes parts of the impactor and planet. The resulting gases jet across the surface at upwards of 20 kilometers per second, scour the surface down to depths of at least 10 meters, and accelerate boulders as large as 1 to 10 meters to martian escape velocity, according to their model.

The jetting mechanism has the advantage of requiring a crater only about 50 kilometers in diameter, which might ease the problem of the lack of large craters on young martian terrain. On the other hand, O'Keefe and Ahrens have not estimated the amount of rock of the required size that jetting could launch or the probability of such a crater being created, so they have not tested the plausibility of the mechanism the way Vickery and Melosh have. Also, it is not obvious how the jetting mechanism would explain the Mars-moon conundrum—there are eight SNCs supposedly from the distant, more massive Mars but only four from the moon. Vickery and Melosh's large impact would be "a singular event in recent martian history," that is still sending a surge of rocks to Earth that is temporarily overshadowing the usual trickle of lunar meteorites.

The problem of transporting intact rocks from one planet to another is now being approached with a positive outlook, but its solution could take time. How far researchers are willing to go on the assumption that the SNCs are from Mars will depend on their attitude toward the sufficiency of the physical evidence. If recent trends are any indication, the temptation to work with exciting new data will more than balance second thoughts. ■ RICHARD A. KERR

ADDITIONAL READING

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Imaging Unaltered Cell Structures with X-rays

With the bright radiation from a synchrotron light source researchers are using a scanning x-ray microscope to make high-resolution images in a wet environment

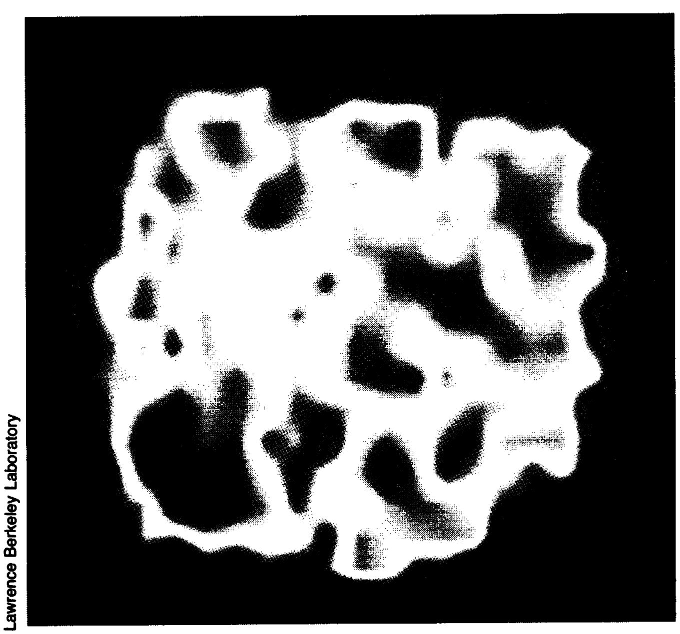
THERE has been no satisfactory method for high-resolution imaging of biological materials in their natural state. The resolution of optical microscopy is limited by the wavelength of light, whereas electron microscopy generally requires dehydrated, stained specimens. But a multi-institutional group working at the National Synchrotron Light Source (NSLS) has now shown that scanning x-ray microscopy can bridge the gap between the two older techniques. The investigators have made x-ray micrographs of zymogen granules extracted from the cells of the rat pancreas. The granules were in an aqueous environment. The microscope has a demonstrated resolution of 750 angstroms. With further development, including a hoped-for boost in the resolution to about 100 angstroms, the scanning x-ray microscope will eventually be made available to the general community on a routine basis.

X-ray microscopy is not a new idea. For several years, Ralph Feder and David Sayre of the IBM Yorktown Heights Laboratory and others have been doing so-called contact x-ray microscopy in which shadowgraphs of samples illuminated by an x-ray beam are recorded in a photosensitive polymer of the type used in the microelectronics industry. With a transmission electron microscope to magnify the image, a resolution of about 100 angstroms could be obtained. And there has been some work on the x-ray analog of an optical microscope. A group headed by Günter Schmahl of the University of Göttingen in West Germany has achieved a resolution of 500 angstroms with such an instrument.

In both cases, the use of an intense beam of "soft" or long wavelength x-rays from a synchrotron light source is the key. For example, x-rays in this wavelength range pass relatively unattenuated through water but are absorbed by carbon-containing substances, thereby allowing the imaging of organic material in a wet environment. The use of a scanning instrument opens additional possibilities, partly because the radiation dose is lower, which causes less damage to specimens and potentially allows researchers to follow changes within living cells as they occur. The disadvantage of scanning is that a very bright x-ray source is

Zymogen granule.

The digital image reconstructed by computer from the intensity of x-rays penetrating the specimen shows the nonuniform distribution of enzymes in a granule. Red represents opaque and blue transparent regions.



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