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## POINTS OF ORIGIN

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# THEY CAME FROM OUTER SPACE

by Katie Neith

Down in the basement of Arms Laboratory, in a room covered in acoustic paneling, staff scientist Chi Ma has spent the past eight years looking for clues that will help uncover the secrets of the early solar system. But Ma is neither an astronomer nor a physicist, rather he is a nanomineralogist—a term he has coined for the kind of scientist who peers into the smallest of nooks and the most minute of crannies in rock and mineral samples from meteorites, looking for clues to the evolution of the interstellar gas and dust cloud left over from the sun's formation.

While more than 4,900 minerals have been identified on Earth, at present only about 60 such substances have been identified that are believed to have first existed in the cloud, called the solar nebula, from which the planets of our solar system were formed.

"As our solar system started to develop about 4.6 billion years ago, high-temperature minerals arose when condensation processes turned some gasses into solids," explains Ma. "These refractory minerals—meaning they are the first solar solids and formed at high temperatures—along with presolar grains mark the very beginning of mineral evolution at the very beginning of our solar system and also mark my proudest contribution to science."

That's because, out of the 50 or so refractory minerals identified to date, Ma has found and characterized 20 using an electron microscope and analytical tools in the Division of Geological and Planetary Sciences Analytical Facility, where he has worked since 1998.

But Ma wasn't always a meteorite guy. The child of a mineralogist and a petrologist, Ma grew up tagging along on field trips and wondering how the things he saw around him right here on Earth came to be.

"For as long as I can remember, I wanted to know the basics of what makes something, down to its atoms," he says. And so, for many years, he studied increasingly smaller bits of terrestrial minerals, finding inclusions—embedded chunks of other materials—at the micro- and nanoscale that gave new insights into minerals that had been thought to be well known. For example, in 1997, then-postdoc Ma and Caltech mineralogist George Rossman examined samples of rose quartz and discovered the tiny borosilicate fiber inclusions that give the stone its pink hue, upending previous theories that suggested the color comes from manganese or titanium.

Additional experiments revealed similar insights about other minerals, like obsidian and rainbow hematite, finding crystals, films, and other inclusions at a very small scale that explain why some minerals look the way they do. (See "The Secret Lives of Minerals," *E&S* 2007, no. 1.)

"By taking the analysis of minerals down to nanoscales, we find all sorts of new things, like inclusions, thin coatings, and tiny pores, all of which tell us something about what was happening when it was formed or when the sample was altered," Ma says. "Sometimes those tiny features help us answer big questions. Because of these clues, we are solving some questions that already had textbook answers . . . and finding that those answers were not correct."

In the mid-2000s, Ma was studying benitoite—a bright blue crystal that is the state gemstone of California—when he found and characterized a new mineral for the first time, a natural occurrence of $BaTiO_3$ he named barioperovskite. $BaTiO_3$ had already been synthesized by materials scientists, and it was reported in one paper to exist in the Allende meteorite, a giant space rock that fell in Mexico in 1969 and is often described as the world's best-studied meteorite. (This is in part because the Allende meteorite fell at a time when U.S. labs were preparing to analyze lunar rock samples about to be returned from the moon by the Apollo program. So researchers used Allende samples to test their state-of-the-art, newly developed instruments.)

But when Ma started to look at samples from Allende, he saw nothing of the kind. "That was in early 2007," he says. "And I still haven't found it!"

Still, that exposure to the study of meteorites—and to the enduring hunt for barioperovskite—hooked Ma, and it has been his focus ever since. "I call my research curiosity-based science," Ma says. "I let my inquisitiveness lead the way in what I study next."

His nanomineralogy approach has paid off: he's identified 15 new minerals with his colleagues in the Allende meteorite alone. "Allende is where scientists first found those refractory inclusions, the first solids to form from the gasses in the solar nebula," says Ma. "The meteorite is very primitive—our current understanding about early solar evolution is heavily based on intense studies of this rock. It's that important."

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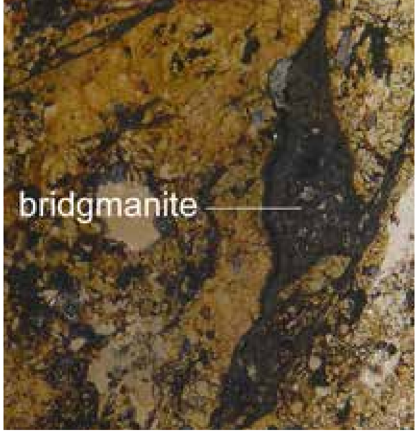
Today, Ma looks far beyond the Allende meteorite, using a suite of fine-tuned instruments to peer into the deepest recesses of various far-flung minerals. In the GPS Analytical Facility, where he serves as director, he has both a high-resolution analytical scanning electron microscope (SEM) and an electron probe microanalyzer (EPMA). The SEM can be found in a room with acoustic panels that are meant to dampen sound vibrations, since merely talking in the lab can cause tiny tremors that would impact the images created by the machine.

An SEM, which is typically used for geological, biological, and materials science purposes, produces images by scanning a focused beam of electrons over a sample and detecting signals that reveal information about the sample's topography and composition. The microscope is perfect for Ma's purposes, he explains, because it can image samples down to nanoscales and analyze the composition and structure of any areas in which he thinks he may have spotted something new.

Once he comes across an interesting mineral using the SEM, Ma uses the EPMA to further measure its composition. This helps him identify whether or not it is, in fact, a new mineral.

For some new minerals, where the SEM alone cannot unlock the crystal structure, the last step requires a trip beyond Caltech's boundaries to a synchrotron facility—there are only eight such facilities in the United States—where he joins his colleague Oliver Tschauner (a former visiting associate at Caltech who is now at the University of Nevada, Las Vegas) to use the synchrotron's high-flux X-ray to determine the crystalline structure of particular minerals through X-ray diffraction. (For more on X-ray diffraction and crystallography, see *X-ray Vision*, p. 24.)

Once Ma or one of his colleagues has determined the composition and structure of a new mineral, the International Mineralogical Association (IMA) Commission on New Minerals, Nomenclature and Classification has to officially approve the minerals, as well as their suggested names, for inclusion on the commission's list.



*Bridgmanite, above left, is shown in a shock melt vein in the Tenham meteorite. Ahrensite, above right with a bluish green color, is seen in the Tissint meteorite. On page 19, the top photo is a back-scatter electron image showing tissintite—the dark material in the center region—in a shock melt pocket. The bottom photo shows a piece of the Allende meteorite in the GPS Mineral and Meteorite Collection room, also featured on page 16 with Ma and other meteorites from the collection.*

Naming, Ma says, is the easy part. When Ma first identified a new mineral in the Allende meteorite in 2007, he appropriately named it allendeite. A more recent Ma find, panguite, is a new variation of titanium oxide named after Pan Gu, the giant from ancient Chinese mythology who established the world by separating yin from yang to create the earth and the sky. Panguite is one of the oldest refractory minerals formed in the solar system, but Ma thinks it is more than just a curiosity; he thinks it could be useful for materials science. His colleague, John Beckett, a senior research scientist in geochemistry, has been able to synthesize it in the lab.

"To our surprise, panguite has a complex chemical composition in a relatively simple structure, and we'd like to see if it could be something that engineers could use," Ma says. "People look at the periodic table to dream up combinations when they want to make new engineering materials, but now we know this new material already exists in nature. It's pretty exciting."

Not every mineral that Ma names is a reference to mythology or the meteorite in which they were found: some of his appellations simply call out the mineral's structure and composition, so that—as Ma explains—when people hear it, they can get a good idea what it looks like or is made of. Take hexamolybdenum, for example—it is hexagonal in its crystal symmetry and rich in molybdenum, a chemical element.

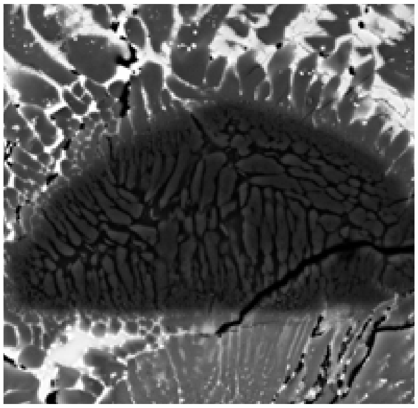
Other mineral monikers have a more personal meaning behind them, one example being bridgmanite. It was made an official mineral in the summer of 2014 and was named by Tschauner and Ma in honor of Percy Bridgman, who won the 1946 Nobel Prize in Physics for his fundamental contributions to high-pressure physics. Scientists have long believed that something like bridgmanite makes up about 38 percent of our planet's volume and sits from 400 to 1,600 miles below Earth's surface in a thick layer called the lower mantle. But even though scientists have been able to create synthetic examples of this mantle mineral since the 1970s—and study its supposed compositions—no naturally occurring samples had ever been confirmed in a rock on Earth's surface.

Ma, along with Tschauner, had a hunch they might be able to find a naturally occurring specimen of the elusive bridgmanite in a meteorite. In particular, they had their eyes on the Tenham meteorite, a space rock that fell in Australia in 1879. It was a good candidate, because at 4.5 billion years of age, apparently the recipient of high-impact shocks, the meteorite had undoubtedly survived high-energy collisions with asteroids in space; this meant that parts of it were believed to have experienced the high-pressure, high-temperature conditions seen in Earth's mantle.

When Ma and Tschauner used their trio of machines to deeply probe a sample, lo and behold, they uncovered bits and pieces of bridgmanite, the discovery of which Ma says is their biggest accomplishment to date.

"The finding not only provides new information about shock conditions and impact processes on small bodies in the solar system, but the tiny amount of bridgmanite found in a meteorite could also help investigations of the deep Earth," says Ma.

In addition to naming bridgmanite after Bridgman, Ma and his colleagues dubbed another new high-pressure, shock-induced mineral found in a meteorite ahrensite, after the late Caltech geophysicist Thomas J. Ahrens. They wanted to honor Ahrens's pioneering and fundamental contributions to high-pressure mineral physics. Two additional minerals in Allende have been named to honor Caltech cosmochemists for their contributions to meteorite research: burnettite for Donald Burnett, professor of nuclear geochemistry, emeritus; and paqueite, for associate research scientist Julie Paque.



Ahrensite also marks something of a new branch of study for Ma: the examination of martian meteorites. Two years ago, Yang Liu, a colleague from JPL, brought Ma a sample from a meteorite called Tissint, which fell near a Moroccan town of the same name in 2011. Scientists determined the meteorite to be martian based on its chemical compositions. During a nanomineralogy investigation of this martian rock, Ma and his colleagues uncovered two new minerals from the sample: ahrensite and a mineral Ma is calling tissintite, which is brand new to science and has neither been observed before in nature nor made in a lab. The two discoveries were reported at the Eighth International Conference on Mars held at Caltech in July 2014.

Both are high-pressure minerals most likely formed by a shock process during the impact event on Mars that excavated the Tissint meteorite and ejected it from the Red Planet. The investigation by Ma and his colleagues of ahrensite—which had been previously described—provided the full set of chemical and structural information needed to officially establish it as a new mineral.

Ahrensite and tissintite are among the first IMA-approved new minerals from Mars. Since tissintite is brand new to researchers, the next step is to try to determine the conditions under which it formed, says Ma.

It is this kind of work—and these kinds of discoveries—that keeps Ma constantly engaged in the study of the minerals both on Earth and beyond.

"We already have a story about the solar system's evolution, but adding these new details gives a clearer picture," he says. "They are pieces of the big-picture puzzle. Some people call the rare new minerals we find bizarre, but I just think they all are beautiful." e&s

*Chi Ma is a member of the professional staff and the director of the GPS Analytical Facility, which is supported, in part, by National Science Foundation grants.*