Experimental geologists are joining efforts to understand what it takes to form habitable planets.

THE RECIPE FOR OTHER EARTHS

Could super-Earths such as the one depicted here host geology similar to Earth's?

BY SHANNON HALL

Yingwei Fei and his colleagues had spent a month carefully crafting the three slivers of dense silicate — shiny and round, each sample was less than a millimetre thick. But in early November, it was time to say goodbye. Fei carefully packed the samples, plus a few back-ups, in foam and shipped them from Washington DC to Albuquerque, New Mexico. There, the Z Pulsed Power Facility at Sandia National Laboratories will soon send 26 million amps surging towards the slivers, zapping them, one by one, into dust.

The Z machine can replicate the extreme conditions inside detonating nuclear weapons. But Fei, a high-pressure experimental geologist at the Carnegie Institution for Science's Geophysical Laboratory in Washington DC, has a more otherworldly goal in mind: he hopes to explore how bridgmanite, a mineral found deep beneath Earth's surface, would behave at the higher temperatures and pressures found inside larger rocky planets beyond the Solar System.

The experiment is one small contribution to exogeology: a research area that is bringing astronomers, planetary scientists and geologists together to explore what exoplanets might look like, geologically speaking. For many scientists, exogeology is a natural extension of the quest to identify worlds that could support life. Already, astronomers have discovered thousands of exoplanets and collected some of their vital statistics, including their masses and radii. Those that orbit in the habitable, or 'Goldilocks', zone — a region around the host star that is temperate enough for water to exist in liquid form — are thought to be particularly life-friendly.

But Earth has a lot more going for it than its size, mass and favourable orbit, says Cayman Unterborn, an exogeologist at Arizona State University in Tempe. Its churning molten core, for example, creates and sustains a magnetic field that shields the planet's fragile atmosphere from the solar wind. And the motion of tectonic plates helps regulate global temperatures, by cycling carbon dioxide between rocks and the atmosphere. Exoplanet discoveries keep pouring in. But astronomers are "just now realizing, 'Well wait, we want to understand these systems a lot more than just stamp collecting'", Unterborn says. "Bringing geology into the mix is a natural factor."

Researchers are using simulations and experiments, such as Fei's at the Z machine, to learn what kinds of exoplanet might have Earth-like geology. The work could help researchers prioritize which exoplanets to study.

But the field faces several challenges, not least that mystery still surrounds much of Earth's geology — such as how and when tectonic activity first began. "It's a fundamental discovery that changed geology," says Richard Carlson, a geochemist at the Carnegie Institution. "But we still don't know why it works the way it does." What's more, confirming that an exoplanet actually boasts Earth-like geology could be difficult; astronomers rarely observe these planets directly, and if they do, the planet might be the size of a single pixel in their image.

Even indirect evidence — or the smallest suggestion — of geological activity could give researchers a more complete picture of these distant worlds, and which ones are the best candidates to search for indications of life. "It's like if you came across a giant crime scene with very little evidence," says Sara Seager, an astrophysicist at the Massachusetts Institute of Technology in Cambridge. "You work your hardest to take what little evidence there was and try to piece it together somehow."

TURNING OUTWARDS

One of the most exciting targets of exoplanetary science has been super-Earths. These rocky planets — with as many as ten times Earth's mass — have no parallel in the Solar System. But they are now known to be quite common in the Galaxy and, because many are fairly big, they could make easier targets for detailed observation than Earth-sized planets.

Early studies of super-Earth geology, published about ten years ago, examined what these planets would look like if they were simply scaled-up versions of Earth. But the scorching-hot planet 55 Cancri e, first spotted in 2004, underscored the idea that super-Earths could be quite different. Observations in 2011 revealed the planet to have roughly twice Earth's radius[1] and a little more than eight times its mass[2], yielding an average density only marginally higher than Earth's — and that presented a conundrum.

If 55 Cancri e had an iron core and silicate mantle, like Earth, it should be more massive given its size. An ocean wrapped around the whole planet would bring 55 Cancri e's density down to Earth-like levels. But the planet is too hot for water to survive for long; it orbits so close to its host star that the day-side temperature is roughly 2,500 kelvin.

A resolution came in 2012, when Nikku Madhusudhan, an astronomer then at Yale University in New Haven, Connecticut, and his colleagues decided to take a fresh approach. Previous research had suggested that the planet's host star has a much higher ratio of carbon to oxygen than the Sun. Stars and their planets are built from the same swirling disk of dust and gas, so it seemed fair to assume that 55 Cancri e would also be carbon-rich. When Madhusudhan accounted for this carbon in his model of the planet's interior, it produced a match with the mass and radius of the world[3]. "That was a revelation," says Madhusudhan, now at the University of Cambridge, UK. And such a world would be truly alien. Madhusudhan suspects that its crust could be dominated by graphite; inside the planet, the pressure would probably crush vast amounts of the element into diamond. "It would look pretty radical compared with what we see in the Solar System," he says.

A planet made of diamond would fire up the imagination, although 55 Cancri e's host star might not actually contain as much carbon as thought. Even if it did, astronomers caution against assuming that a planet's composition matches that of its host star. Seager notes that this idea wouldn't account well for the variety of planets in the Solar System. "At this point, it's a reasonable inference, but I think it's important to realize that it's not iron-clad," says Gregory Laughlin, an astronomer at Yale.

"I WOULD LIKE TO IDENTIFY THE COMPOSITIONAL GOLDILOCKS ZONE."

EXOPLANET-BUILDING

Exogeologists have embraced this uncertainty, and are trying their best to pin down how distant worlds form and evolve. To get from a list of starting elements to geology, scientists need to know what minerals form, when they melt and how their density changes with pressure and temperature. Those data can be used to simulate how a planet develops from an undifferentiated, molten ball into a layered structure, with minerals forming — and sinking or floating — as the planet cools. "We can build up a mineralogical, let's say, onion-skin model of what the planet would look like initially," says Wim van Westrenen, a geologist at the Free University of Amsterdam. Then, he says, researchers can use numerical models to predict how that planet will evolve and whether the migration of materials will be enough to drive plate tectonics.

To gather information to feed these models, geologists are starting to subject synthetic rocks to high temperatures and pressures to replicate an exoplanet's innards — as Fei and his colleagues are doing. Although the goal of these experiments is new, the approach is not. For decades, experimental petrologists have built instruments to simulate the conditions of Earth's interior, anywhere from a few centimetres below the surface to Earth's core. Many use a device called a diamond anvil cell. This apparatus squeezes materials by pushing the blunted tips of two gem-quality diamonds together. While a sample is under pressure, a laser can be used to heat it. At the same time, experimentalists can bombard the material with X-rays to investigate its crystalline structure and explore how the material changes as it is pushed to high temperatures and pressures.

Groups including Sang-Heon Dan Shim, a mineral physicist at

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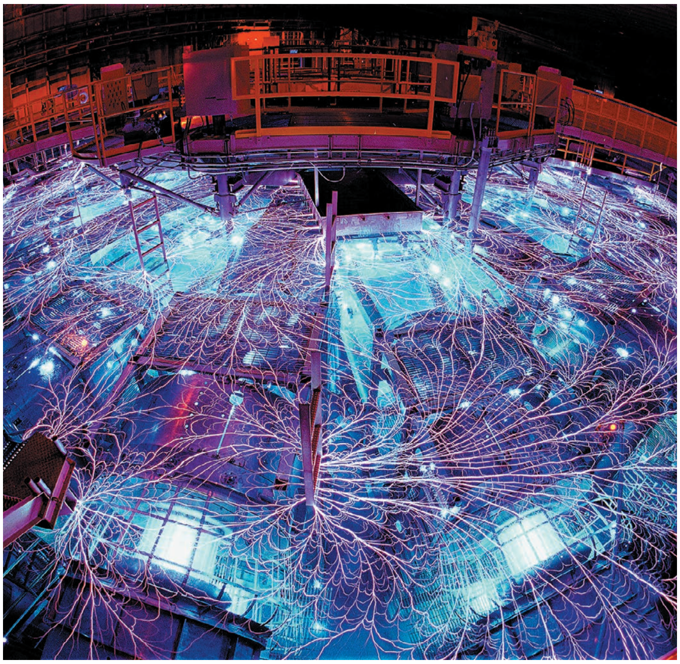

The Z Pulsed Power Facility can be used to investigate exoplanet compositions.

RANDY MONTOYA

Arizona State University, and his colleagues have used this process to squeeze carbon-rich samples that might reflect the composition of 55 Cancri e. The work has revealed[4] how planets dominated by carbon-containing compounds called carbides might transport heat, and how they might differ from planets that, like Earth, are dominated by silicates.

Carbon is not the only element of interest. Unterborn points to magnesium, silicon and iron as "the big three" that will affect a planet's bulk structure, influencing how heat flows in the mantle and the relative size of the planet's core — and so the presence of plate tectonics and a global magnetic field, respectively. Ratios of these elements vary widely in stars. The Sun has one magnesium atom for every silicon atom; in other stars, that ratio ranges from 0.5 to 2. The difference might seem small, but if the same ratios are present in planets, they could drastically affect geology.

Most textbooks argue that magnesium-rich rocks would be softer than those containing high concentrations of silicon — so much so that walking on a magnesium-rich world might feel like walking on mud. Shim's diamond-anvil-cell work on rocks with various magnesium-to-silicon ratios suggests these worlds could also boast deeper reservoirs of magma than a silicon-rich planet and, as a result, more catastrophic volcanoes. But Shim notes that other parameters, such as the concentration of water in minerals, must also be taken into account.

HIGH PRESSURE

With two diamonds, Shim can apply no more than 400 gigapascals of pressure, a little higher than the pressure in Earth's core. To probe the interiors of super-Earths, he has turned to the world's brightest X-ray laser: the Linac Coherent Light Source at SLAC National Accelerator Laboratory in Menlo Park, California. The instrument can generate shocks inside the sample, producing pressures as high as 600 gigapascals — enough to simulate the cores of planets twice as massive as Earth.

Geologists are also using other large facilities to probe potential exoplanet formulations. The Z machine can reach 1,000 gigapascals — the condition expected inside planets nearly three times Earth's mass. Laser facilities in Palaiseau, France, and Osaka, Japan, can reach a similar range. And some researchers have turned to the National Ignition Facility at Lawrence Livermore National Laboratory in California, which is used to study nuclear fusion and can subject samples to as much as 5,000 gigapascals, the pressure of Jupiter's deep interior. These experiments are still in their preliminary stages, as researchers compete for time at these facilities and slowly accumulate data on a variety of basic compounds.

At the end of the day, exogeologists hope to find the right combination of elements to build exoplanets with Earth-like geologies. "I would like to identify the compositional Goldilocks zone," says Wendy Panero, a geologist at the Ohio State University in Columbus. "What is the not-too-soft, not-too-stiff habitable zone for rock composition?"

The answer might not be clear-cut. Even perfect knowledge of composition might not tell exogeologists much about the state of a planet. Earth, for example, did not host plate tectonics in its early history, and it is not expected to do so forever. And its neighbour Venus shows how widely planetary evolution can diverge. The planet's mass, radius, composition and distance from the Sun are similar to those of Earth. But Earth supports life, whereas Venus, swaddled in a haze of carbon dioxide, is quite dead. Stephen Mojzsis, a geologist at the University of Colorado Boulder, suspects that the loss of plate tectonics on Earth will eventually cause it to resemble its super-heated sibling. "It's inevitable," he says. "We're just not sure when that will happen." So, although most early exoplanet models are focusing on composition, exogeologists might ultimately have to include additional factors such as billions of years of planetary evolution.

Some expect that this work will help astronomers determine which planets to target in the search for life. If scientists know the conditions needed to sustain a magnetic field for billions of years, or the proportions of elements required to drive convection in the mantle, they could advise their colleagues to scrutinize the worlds that meet those criteria. Then astronomers could turn powerful telescopes, such as NASA's James Webb Space Telescope, slated to launch in 2019, towards those planets to search their atmospheres for potential signatures of alien life.

It might also be possible to spot geological activity from a distance. A transient spike in atmospheric sulfur, for example, might be indirect evidence of the presence of an active volcano. Changes in reflectivity as a planet rotates might hint at the presence of continents and oceans, which could also suggest tectonic activity.

Already, there has been talk of a possible detection of volcanic activity — on 55 Cancri e. In 2016, Brice-Olivier Demory, an astronomer at the University of Bern, and his colleagues published[5] the first heat map of the planet, created using NASA's infrared Spitzer Space Telescope. The planet is tidally locked to its star, so one hemisphere is eternally bathed in sunlight and the other is dark. The planet should be hottest closest to the star, but Demory and his colleagues discovered that the hottest point seems to be offset. They posited that flowing lava is carrying heat away (although more recent work[6] has argued that winds might be responsible instead).

It's clear that 55 Cancri e is no place for life. But other worlds may be much more inviting. Earlier this year, Unterborn completed a study[7] that looked at more than 1,000 Sun-like stars. Using their compositions, he determined that one-third of those stars could host planets whose crust was dense enough to sink into the mantle — a process that might let plate tectonics thrive for billions of years.

Although researchers are just the beginning to explore the geology of exoplanets, Carlson notes that the study of these worlds has already yielded a number of surprises, not least evidence of planets that seem to have undergone dramatic migrations from their original orbits[8]. This discovery caused astronomers to rethink the Solar System's evolution, and theorize that similar movements could have helped carry materials, such as water ice, to Earth.

"I don't think humans are anywhere near as imaginative and creative as nature is," Carlson says. "So, understanding the diversity of what's out there will just open our eyes to other possibilities. And it's those other possibilities that will help us understand our situation better." ■

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