Unchartered underground

Taking the rigour of physics to the netherworld, a handful of scientists are combining their favourite hobby with their day job, exploring how underground caves form, evolve and move water from one place to another. **Stephen Ornes** reports on the emerging field of "speleophysics"

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Matt Covington didn't sleep much the night before his big swim. Who could blame him? For two days, the wiry caver had, with the help of ropes and ladders, been making his way down through J2, a deep cave in the mountainous Mexican province of Oaxaca. Marcin Gala, an experienced caver from Poland, joined him on the descent, just as he had on multiple previous adventures.

The entrance to J2 is dramatic: it's an enormous 100 m wide sinkhole, lined with stubborn plants and surrounded by tall trees. A small hole – about as tall as a person – leads from the bottom of the sinkhole deeper into the cave. Cables and ladders lead to a series of tight turns and drops. Because of the quick descent, once a caver enters J2, the Sun virtually vanishes. No-one knows how far down J2 goes.

The year was 2009 and Covington and Gala were in Mexico as part of a caving expedition dedicated to finding and exploring the untouched netherworld of the world's deepest caves. "In mountaineering, you have Everest. In caving, there's this push to find the deepest caves in the world," says Covington, a physicist at the University of Arkansas. "The weird thing is, you never really know when you've found it."

For this part of the mission, he and Gala were on their own. Already, they'd made their way through a tight spot called the Barbie Squeeze and rappelled down a series of striated cliffs known as the Jungle Series. By the third day, the duo were 1200 m below the cave entrance and putting on scuba suits outfitted with heavy oxygen tanks. They were preparing to swim through a sump – a dark underground passage filled with water – which was the only way to keep searching for J2's secrets.

Gala was getting cold, so he plunged first into the clear water. Covington followed, weighed down by their supply bags and air tanks. They carefully made their submerged way along the floor of the sump, the bags snagging on jagged pillars of rock. About seven minutes into the dive, however, Covington became short of breath. Worrying that his air tank had malfunctioned, he reached for his back-up air – but again, his attempts to inhale were met with resistance. Panic lurked at the periphery. His wife was scheduled to arrive for a visit the next day. It was common knowledge among the team that there were no good rescue options in that sump or beyond, and the chances of being rescued alive from the bottom of J2 were slim to none. The key was not to let panic win.

Caving isn't for everyone, but among cavers Covington is something of an exception. He's both an explorer and a physicist, which means his research lands him in a small and curious area of endeavour that merges physics, chemistry and mathematics to quantify how karst forms, evolves and moves water from one place to another. (Karst is the general term for landforms that have been sculpted by dissolution of soluble rocks such as limestone. It may include caves, sinkholes, cliffs and fissures.) He's part of a small group – including maybe two dozen, maybe only a handful, depending on whom you ask – that is taking the rigour of physics to the netherworld. He light-heartedly refers to the field as "speleophysics".

A quest for karst

Cavers and scientists alike see caves as a sort of last frontier. "Caves are the last parts of Earth which are not yet explored," says Franci Gabrovšek, a physicist at the Karst Research Institute in Postojna, Slovenia. "They are full of surprises, and when you progress to the next step, you never know what your next challenge will be. Of course, that's general in science, not just in our field." He thinks the field is growing. "There are still so many open questions in speleogenesis," or cave formation, says Gabrovšek. "What are the dynamics of growth? How do cave channels self-organize to form the geometry that we observe in nature?" Scientists have a good understanding of the dissolution process, but "we don't know the exact circumstances that govern it", he says. Gabrovšek adds that he and others also want to get a better understanding of the relative roles of chemical and mechanical processes both at the beginning of a cave's formation and during its later growth.

There's also a practical concern at stake in speleophysics: karst and caves play a critical role in the water cycle. Roughly 20% of the fresh water supply in the US – and about half of that in Europe – comes from karst aquifers, where water can flow rapidly through labyrinthine networks of channels like water pipes through a city. The water's movement can be fickle, changing by the season or during times of flood. Understanding how aquifers shuttle water from one point to another deepens our understanding of the water cycle, and may suggest solutions should something go wrong. Right now, "you put a pollutant in somewhere, and you don't know where that pollutant will come out", says Gabrovšek. "The caves control where the water's going to go and how quickly it will get from one place to another," Covington adds.

Wolfgang Dreybrodt, a pioneer in the field and now an emeritus professor of experimental physics at the University of Bremen, Germany, thinks that applying the laws of physics to caves can bring together an

interdisciplinary understanding of a complex natural phenomenon. "Caves are usually described by geologists or geographers who don't have a mathematical education," he says. Rigorous models have the potential to stitch descriptive theories from other disciplines into a coherent whole. But he also says the field calls for geologists who have better training in physics – and physicists with a more thorough knowledge of geology.

"Engineers, physicists and chemists involved in karst must be ready to learn about geology to at least the extent which enables them to have a good idea of what they are dealing with," he said in a 2011 interview with the journal *Acta Carsologica* (**40** 225). In a way, his advice mirrors the approach needed to tackle a cave like J2 – co-operation is the only way forwards.

Dark data
Matt Covington – pictured here in the J2 cave system in Mexico – ventures to some of the most remote spots in the world to study the physics of cave formation.

Secrets of the caves

Caves, by their very nature, are always hiding something. What that something is, however, depends largely on time and place.

Thousands of years ago, caves were believed to harbour dragons or other beasts, gods and goddesses, or passages to the underworld. In Indonesia, caves are the canvasses for the oldest known art in the world.

Matt Covington

Weathered and worn This Alpine karst landscape conceals a deep network of caves.

Seers from ancient Greek cults immersed themselves in caves to commune with the immortals and emerge with prophecies. The wonder has changed flavour in more recent times but it remains intact. Now, cavers search for unknown and unmapped subterranean chambers. Millions of tourists annually flock to show caves such as Mammoth Cave in Kentucky – the largest known cave system in the world – for the experience of simply being somewhere deep, somewhere dark, surrounded by a strange wonderland of natural sculpture.

People have been describing caves and cave features for centuries. By the 1830s scientists began hammering out the basic recipe for karstification. It's deceptively simple. Flowing water absorbs carbon dioxide from soil air and becomes carbonic acid, which Dreybrodt calls "the motor of erosion". Carbonic acid is weak, but strong enough to dissolve limestone. As small channels grow wider, more water flows and more limestone dissolves, thanks to a feedback loop that allows more water through, which dissolves more limestone, and so on. The channels open up, the cave grows.

Scientists began to quantify that characterization of speleogenesis in equations in the mid-20th century. But new problems quickly emerged. A 1958 quantitative model published by Peter K Weyl of the Shell Development Company, for example, accounted for how water absorbs carbon dioxide and erodes limestone. On the one hand, that model was a welcome step forwards in the field, moving previous descriptive models into the realm of physics. On the other, that rigorous treatment led to a paradox.

According to the model, water flowing over limestone becomes saturated with calcium ions, which means it can't dissolve any more limestone, which means deep caves shouldn't exist at all. Scientists remained in the dark about explaining the existence of caves until the 1980s, when Dreybrodt and other researchers created 1D models showing how the evolution of caves depends on a nonlinear erosion behaviour that arises in the interaction between the water and the limestone. (But even that solution has been challenged: in 2010, speleophysicists in Poland and the US used a 2D model and avoided nonlinearity altogether.)

Researchers are now developing 3D models of speleogenesis and more powerful tools to collect data. Postojna in Slovenia hosts a giant show cave – complete with a mile-long "cave train" that whisks tourists into the belly of the karst – in which Gabrovšek has recently set up sensors to monitor air flow, temperature, humidity and carbon-dioxide levels, to build a cave climate model. Covington has similarly set up sensors in a cave in Arkansas more than a mile long, creating a field laboratory where he can keep tabs on the cave climate and send his students for research projects.

He's also something of a hacker. "We've been doing 3D scans inside of caves that get reconstructed in real time," he says, equipped with only an XBox Kinect and a laptop. "The XBox Kinect is basically a video game controller, but in reality it's a very inexpensive 3D scanner."

From hobby to research

Not surprisingly, "most of us who are doing this somehow started caving as a hobby", says Gabrovšek. "You try to join your hobby with your profession, and I think speleophysics is one of those areas where you can do this." Figuring out how to merge the two, like finding the next clear passage in an uncharted cave, isn't always easy.

Dreybrodt, who explored abandoned mines and canyons during his childhood in the German Democratic Republic, trained as an experimental physicist and in 1974 he joined the faculty at the newly founded University of Bremen. But Dreybrodt's mood quickly soured due to the educational climate, which was wracked by student protests and even bullying in his lectures, which he says was supported by the Social Democratic Party, the leading political establishment in Bremen. In his 2011 interview, he described the university at that time as "an incredible realm of ignorance and intolerance". As a means of escape from the hostile intellectual environment, he turned to the caves in Germany's Harz mountains and began reading up on speleogenesis.

Those excursions gave him solace – and a rising curiosity. Dreybrodt describes his time in caves with reverence and awe. "I was fascinated by the realm of darkness in caves from which fantastic shapes emerge in the faint light on the helmet. How could such a variety of structures arise by dissolution of limestone and later by precipitation of calcite?" he said. More recently, Dreybrodt told *Physics World* "Going to caves for some people is a deep, spiritual thing, which is not easy to explain…If you go in there and see all those caves, then you want to understand why. It has to do with pure inspiration and something emotional and spiritual and philosophical."

He tackled research projects aimed at understanding what he'd witnessed first-hand in the caves. Those included a mathematical explanation for the growth of stalagmites (the ones that point up), as well as that 1D model that uses nonlinearity to show how deep caves can evolve. In 2011, in the *Journal of Hydrology* (**409** 20), he and Gabrovšek published a model of how pollution can spread through a karst aquifer.

Marcin Gala

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Danger physics Matt Covington during his 2009 descent of the J2 cave system in Mexico. Left: still wearing his scuba gear after diving through the sump.

Gabrovšek says that when he began looking at graduate schools, nearly 20 years ago, there were only a few physicists studying caves in earnest. "The Internet had just started," he says, "and I had a hard time finding a supervisor who could guide me to a doctoral thesis." He'd just finished an undergraduate degree in physics and was spending almost every weekend in caves, which helped inspire the questions he wanted to answer in his research. His quest led him to Dreybrodt, who agreed to take him on as a student – and the two went on to become close collaborators.

Covington, too, travelled a circuitous route before he arrived at speleophysics. He was finishing his PhD in astrophysics at the University of California, Santa Cruz, when he attended a lecture that helped send him on a different path. The speaker began describing how the statistical technique of Markov Chain Monte Carlo can be applied to theories of galaxy formation. But Covington began to wonder if physics equations could be applied to caves – and discovered an entire body of research. After he finished his PhD, he secured a fellowship from the National Science Foundation in the US to study with Gabrovšek in Slovenia. Another collaboration was born.

"I felt like when I first started working in this field, there was almost a whole playground of things to work with," he says. And he kept caving, of course. He's noticed that the experience of mapping or studying a cave differs noticeably from the experience of pure exploration. "When you're mapping, you move through a cave in a different way," he says. "If you're the one who's sketching, drawing the features of the cave, you experience the cave at a slow pace and absorb a lot of information about the cave that you wouldn't necessarily observe if you were just going through."

He also knows the benefits of slowing down. That night in 2009, finding it hard to breathe in a flooded channel 1200 m beneath J2's entrance, Covington remembered to open a valve on his rescue air. The air flowed, and he was relieved. He paused there, at the bottom of the lake, buried deep in the cave, to gather his wits. Down there, in such an extremely wild environment, panic was the enemy. Then he picked his way again, and two minutes later emerged at the other side. He didn't know whether the mishap was due to faulty equipment or stress, but in some ways it didn't matter. He knew that on the way back, staying calm would be his top priority.

In July this year Covington returned to Slovenia to investigate a cave he'd begun to explore on a previous visit, but he couldn't say whether his trip was more research- or exploration-related. As he explains, "It's not always 100% clear which one I'm doing at any given time." ■