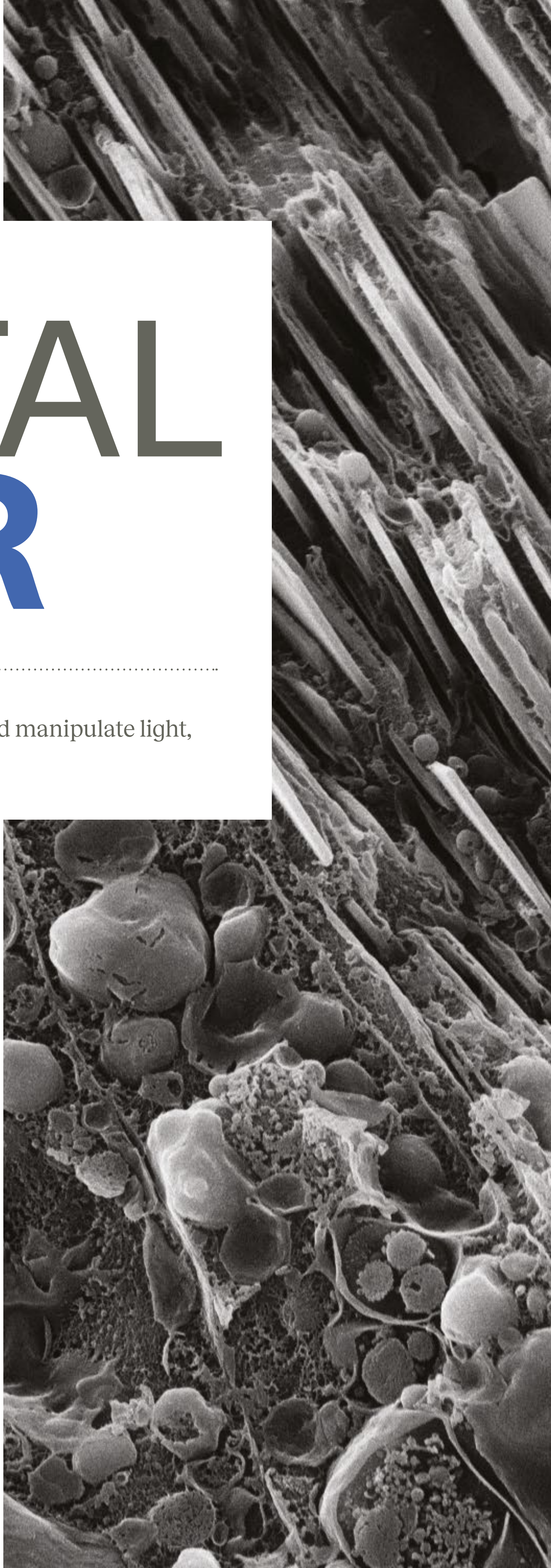
By Zac Unger
Photographs by Ariel van Straten

CRYSTAL CLEAR



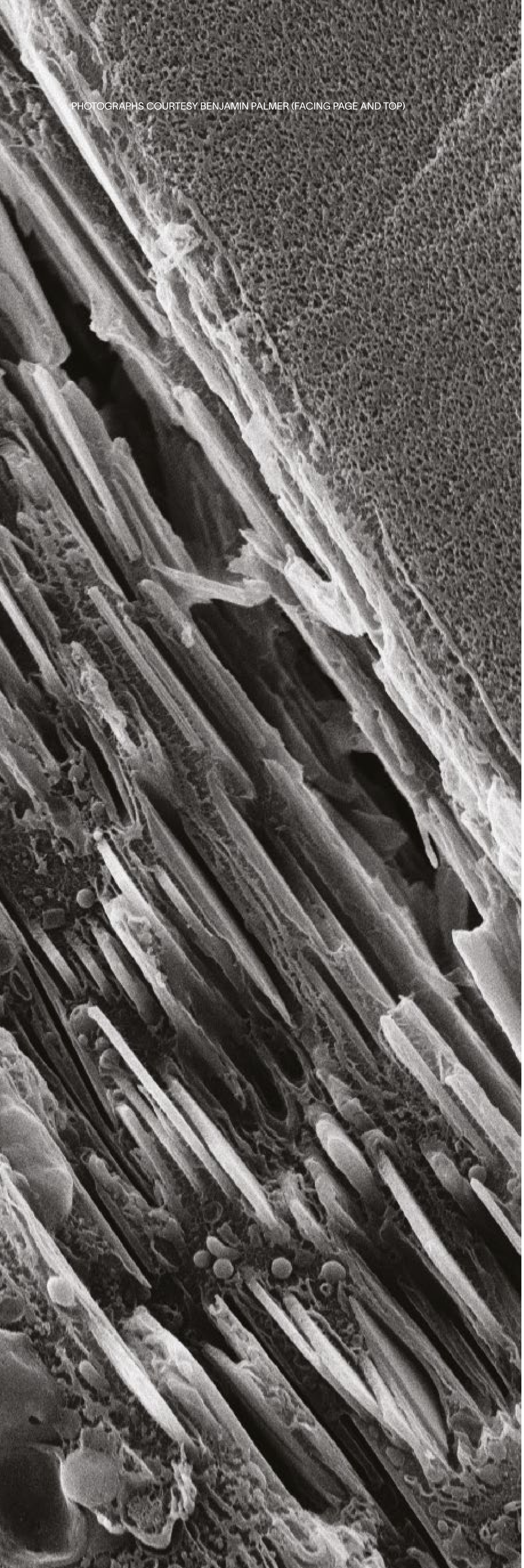
Benjamin Palmer explores how animals make crystals and manipulate light, with an eye toward creating novel organic materials

If you've never thought about how a scallop sees the world, you're probably not alone. Conjure a mental image of a scallop. Does it even have eyes? And even if you can picture where its eyes are, can you imagine a scallop seeing anything other than butter, garlic and the bottom of a sauté pan?

As it turns out, a scallop does have eyes. Up to 200, in fact, along the edge of the soft tissue that lines its shells. This allows the saltwater mollusc to see approximately 250 degrees around itself. Scallops use their eyes to help them escape from starfish and other predators — scallops aren't always permanently attached to rocks like their cousins the clam — and to determine which bits of floating material are food-worthy enough to risk opening their shells for.

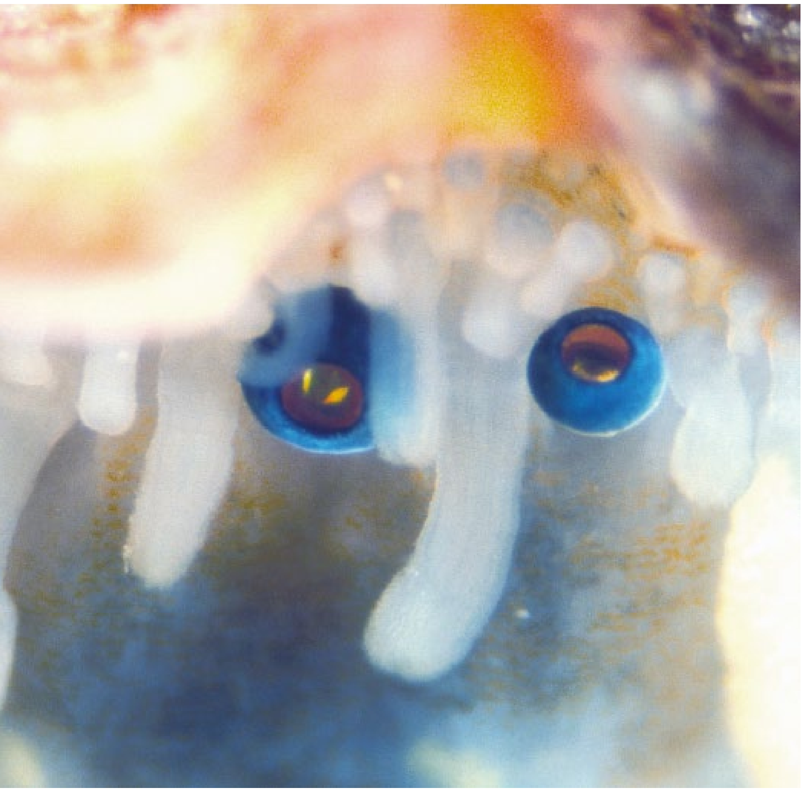
But all that is just a prelude to what's truly impressive about scallop eyes. They're nothing like human eyes. Scallop eyes are actually more akin to complicated telescopes, containing thousands of tiny, crystalline mirrors that allow scallops to see their environment.

Benjamin Palmer, a chemistry professor at Ben-Gurion University of the Negev and Azrieli Early Career Faculty Fellow, originally thought his academic career would focus on the pure, technical science of



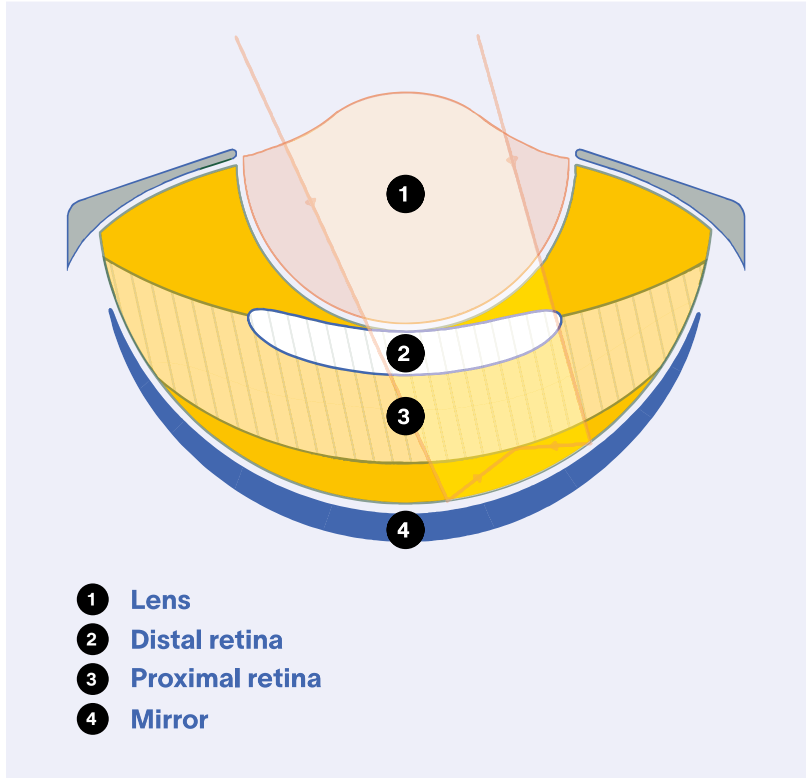
PHOTOGRAPHS COURTESY BENJAMIN PALMER (FACING PAGE AND TOP)

The tiny, crystalline mirrors inside a scallop's eye (facing page), as well as the eyes of shrimps (this image) and butterflies (below), illustrate the diverse range of Benjamin Palmer's research.



The eye of a scallop is an ancient evolutionary masterpiece that prefigured human engineering of telescopes by a few hundred million years.

PHOTOGRAPH COURTESY DAN-E NILSSON, LUND UNIVERSITY



Scallop eyes contain both a distal and proximal retina. The former is focused on detecting moving predators, while the latter receives light reflected from the mirrors at the rear of the eye for enhanced peripheral vision.

DIAGRAM BY DALBERT B. VILARINO; SOURCE: JOURNAL OF EXPERIMENTAL BIOLOGY

crystallography, or the arrangement of atoms in crystalline solids, a field that can help us understand the atomic structure of almost anything. That goal lasted until he encountered scallop eyes, an ancient evolutionary masterpiece that prefigured human engineering of telescopes by a few hundred million years.

"For whatever reason, I was always interested in crystals," says Palmer, who joined Ben-Gurion in 2019 after a postdoctoral fellowship at the Weizmann Institute of Science. "I guess the symmetry appealed to me. There was something very aesthetic about it. Then I read a couple of articles from two professors at Weizmann on animal crystallization and compared what I was doing in the lab with what these animals were doing." He remembers thinking, "Well, there's no point in me carrying on doing my chemistry stuff. I should go and learn what animals are doing because they clearly do it much better." After "blowing through" the articles and sending his CV to the authors, Lia Addadi and Steve Weiner, Palmer flew to Israel from his native Wales and decided immediately that he wanted to stay.

Most animal eyes work by allowing light to pass through a lens at the front of the eye. That light is then projected and focused onto the retina, which lies at the rear of the eye, creating an image that is collected by tiny nerves and then sent to the brain for interpretation. But scallop eyes work quite differently. First of all, the light passes through not one but two retinas, distal and proximal. And, crucially, the retinas are not located at the back of the eye as with humans and other animals, but float in the middle. Light passes all the way through the retinas until it encounters mirrors at the rear of the eye. It's the job of the mirrors, working in a perfectly coordinated array, to bounce the light up to the retinas, where it is finally focused for use. The unusual shape of the mirrors reflects incoming light to different points on the retinas, allowing them to perform two separate functions. The upper retina is specialized for imaging well-focused on-axis light for detecting moving predators, while the lower retina is specialized for imaging off-axis light and providing relatively high-quality peripheral vision.

And if all that isn't remarkable enough — remember, we're talking about scallops here, nobody's idea of the most sophisticated animal on Earth — the structure of the mirrors, made of layered crystals, is another marvel of evolution. "The general theme of our lab is to figure out how animals use crystalline materials to manipulate light," says Palmer. Broadly speaking, this area of study is a subset of the field of biomineralization, or the processes animals use to make hard structures like bones, shells and teeth. The big question in that field is how do organisms take ions that they find naturally — in sea water, mother's milk and so forth — and concentrate them into a functional material like bone? "But there is another class of materials that form in animals," Palmer explains, "and these crystalline materials are

Scallop eyes are nothing like human eyes. They're actually more akin to complicated telescopes, containing thousands of tiny, crystalline mirrors that allow scallops to see their environment.

After being drawn to crystallography by its symmetry and aesthetic, Palmer was struck by the ability of animals to manipulate light more intricately than people. "I should go and learn what animals are doing," he thought, "because they clearly do it much better."

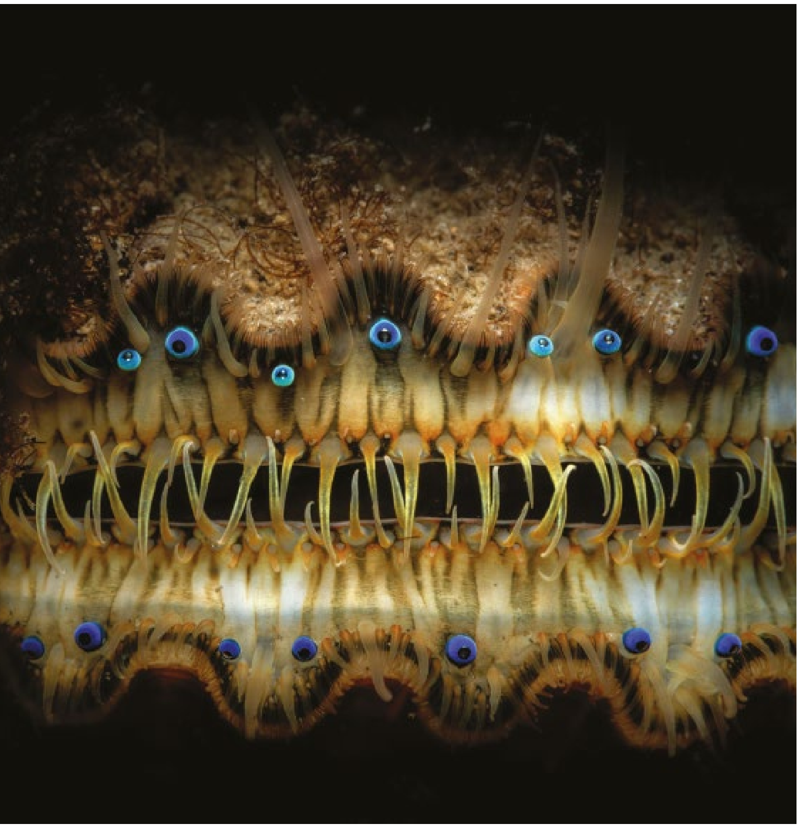
made by the cells themselves." Instead of being formed using ions found in the surrounding environment, these organic crystals are synthesized internally by specialized cells. A particularly useful building block employed by scallops is guanine, one of the four essential bases that make up the structure of DNA.

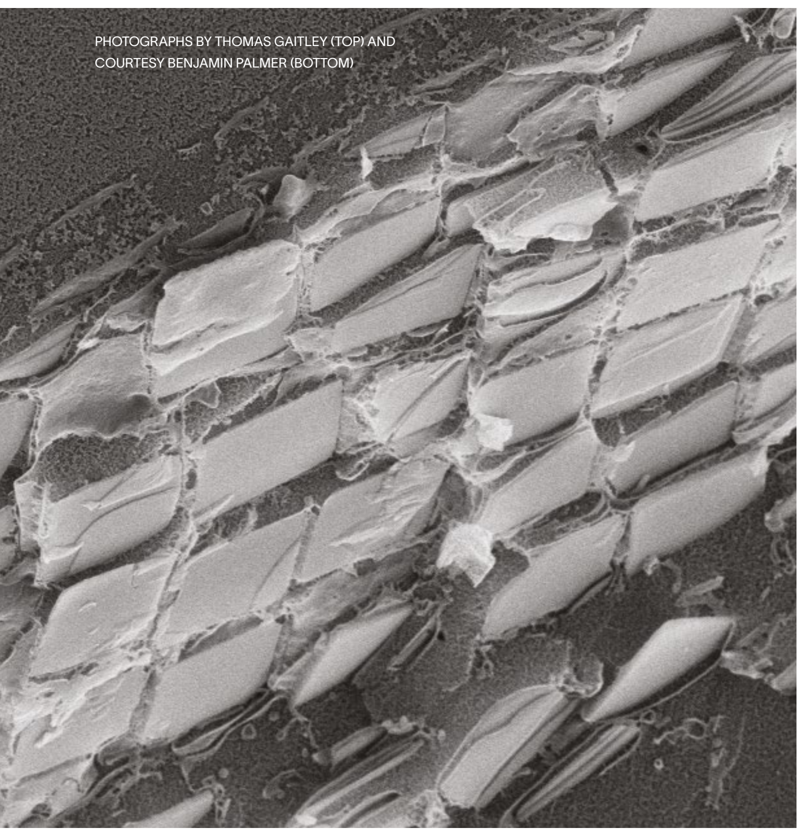
"These guanine crystals are very beautiful, and they also happen to be extremely good at reflecting light," says Palmer. One of the key factors and limitations in optics is the refractive index, a measurement of how quickly light travels through a substance. To see clearly, an animal needs to make a material with a higher refractive index than the medium that surrounds it. "The refractive index of water is 1.3," Palmer says, "and the refractive index of air is one. But these molecular crystals have some of the highest refractive indices of any biological materials." This makes the mirror crystals perfect for the low-light conditions that scallops live in. This critical property, combined with guanine's easy cellular availability, has allowed the scallop to evolve the concave mirrored eye structure that is best suited not only for the murkiness of seawater, but also for the specific spectra of light that penetrate below the surface.

When viewed under a scanning electron microscope, these crystals appear as perfect rows of squares, a tiled mosaic structure that wouldn't look out of place on the floor of the grand entranceway to a luxurious mansion. But what the scallop has created is even more complicated than that — the concave mirror has a structure that isn't flat but is actually three-dimensional. The full structure consists of several dozen layers of crystals, separated by cytoplasm. These layers are perfectly aligned so that each individual tile of crystal directly underlies the one above it, creating a vertical stack. This closely coordinated tiling minimizes defects, which could scatter the light and result in less effective vision.

Palmer gets visibly excited when talking about the wonder of a system this beautiful and well-organized. "If chemists knew how to precisely control crystal form and morphology, it would be a dream for material science," he says, noting that the shape and properties of crystals affect what a structure made with these materials could accomplish. "Animals somehow do this in these specialized cells, and we don't even know the underlying rules behind the formation yet. So that's half of our research, trying to uncover the rules and the crystallization tricks that the animals employ to control crystal morphology."

The lab work itself is no easy task; scallop eyes are incredibly tiny, about one millimetre each, after all. "We have a three-pronged approach to the imaging, basically chemical, physical and biological methods," Palmer says. "But in truth, we're throwing the kitchen sink at it." One critical technique is cryogenic scanning electron microscopy, which utilizes a freezing mechanism to trap the cells





PHOTOGRAPHS BY THOMAS GAITLEY (TOP) AND COURTESY BENJAMIN PALMER (BOTTOM)

The eyes of a scallop (top) are nothing like human eyes. They're more akin to complicated telescopes, with perfectly coordinated arrays of mirrors (bottom).

of the eye in a close-to-life state so that they can be studied and manipulated before they disintegrate as they normally do at room temperature. Palmer and his colleagues also use synchrotron particle accelerators and then "interrogate the structural properties with X-rays." An exciting new avenue of study involves watching how animals create these crystals during different stages of embryonic development, capturing different morphological moments as they occur.

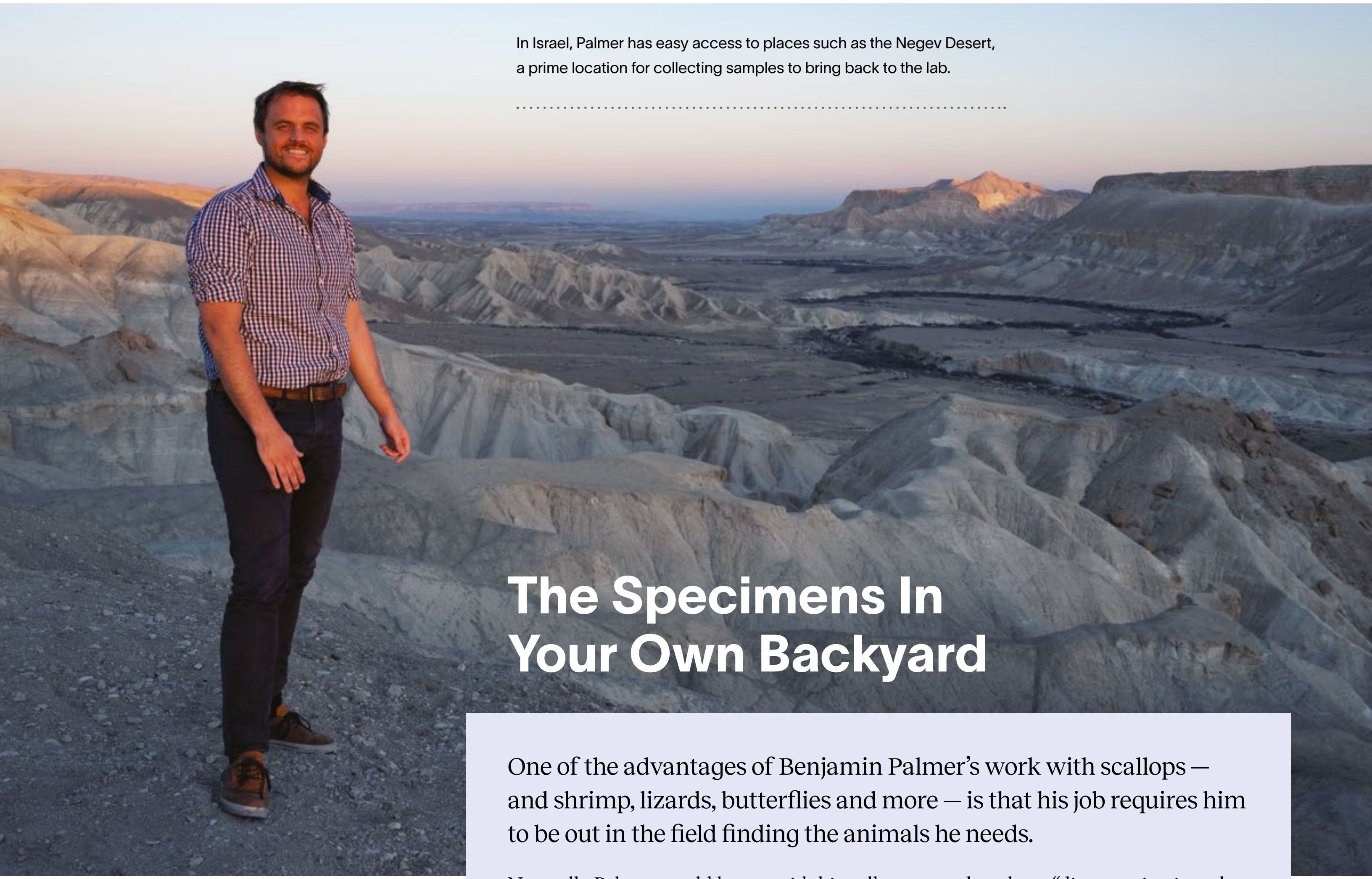
Although guanine crystals are found in seven different animal phyla, Palmer is quick to note that guanine isn't the only biomineral capable of forming complex crystalline structures. "This is a very new field," he says, "and it's just bubbling right now. Guanine has been known and studied for years, but I've been asking 'What else is there?' Because nobody thought to look! In the last couple of years we've found a new class of crystals which have similar structures, but which are based on a different family of crystals."

Additionally, it isn't just scallops that have evolved this remarkable strategy for seeing the world around them. "We have many animal models that we work on," says Palmer. "A lot of them are aquatic, like scallops, shrimp and fish. But we also work on lizards, snakes, butterflies. Maybe ten or so animals right now. So many that I've almost lost track."

Palmer's passions primarily lean toward understanding the basic science of how such a system functions. "If my students go to an electron microscope I always say, 'Call me if you find anything exciting.' And then I run down to the microscope because you never tire of seeing a crystal in an animal cell. Because often it just doesn't make sense, this perfectly geometrical thing that you think of as synthetic and manufactured, yet it finds itself inside a biological cell."

Although the pure science of discovery provides Palmer all the thrills he needs, there is great potential for practical applications to emerge from his research. "This is almost like sci-fi," he says. Knowing which genes are responsible for the size and shape of the crystals allows us to potentially manipulate the process and build new crystals. "If we understand the rules these organisms use to make these materials," Palmer says, "we can apply the principles that animals have taught us to make new optical or electrical materials in a more sophisticated, controlled way."

Palmer's long-term vision is to understand how organisms control crystallization processes and uncover new bio-inspired crystallization techniques for the synthesis of novel organic material, and his enthusiasm for this field is infectious. "The next frontiers are finding out what crystals are out there and then understanding the underlying mechanisms," he says. "But it doesn't just take me; it will take biologists and chemists and physicists to collaborate on everything." The humble scallop has perfected this system over hundreds of millions of years of evolution, but our understanding of how it all works is in its infancy. "Honestly," Palmer says, "I don't understand why everyone in the world isn't working in this area. Even if I didn't get paid, I'd still turn up at the lab every morning." ▲●■



In Israel, Palmer has easy access to places such as the Negev Desert, a prime location for collecting samples to bring back to the lab.

The Specimens In Your Own Backyard

One of the advantages of Benjamin Palmer's work with scallops — and shrimp, lizards, butterflies and more — is that his job requires him to be out in the field finding the animals he needs.

'Israel facilitates serendipitous opportunities because people are so inquisitive and curious that there's no limit to what you can end up doing.'

Normally Palmer would be out with his colleagues and students "disappearing into the desert," he says. "We're off-road trying to get spiders, we're floating in the Jordan with nets, we've got head torches in the middle of the night, searching for shrimp with shiny eyes." Unfortunately, he is currently stuck in his office at Ben-Gurion University putting the finishing touches on multiple papers, and he has to settle for staring at the Negev through the window instead.

Because this is such a new field, opportunity abounds. "Serendipity and opening your mind as much as possible has started half of these projects," Palmer says. His signature project on scallops began with a chance encounter in Wales with a friend of his father's, a scalloper who dives for scallops at night and described scallop eyes as thousands of undersea "diamonds" reflecting back in his torchlight. "I asked him if maybe he could grab one for us," Palmer recalls. "He said, 'Sure, sure.' I took it back to Israel and within a week we had it under the microscope." Another of Palmer's projects started from overhearing a Negev ranger talk about a lizard that can change its pale colour. Sure enough, when Palmer and his students studied it in the lab, they found precisely the kind of crystal morphology they'd been working on. "Things like this happen all the time," Palmer says. "Israel facilitates this stuff because people are so inquisitive and so curious that there's no limit to what you can end up doing."

Palmer adds that, before he moved to Israel, he didn't expect the country's geography to play such a crucial role in his research. "We have a huge advantage in that we can go to Eilat or the Negev any time of year to collect specimens, whereas other people in Britain or America might have to make one special trip to Australia a year. But we have these animals that do funky things with crystals on our doorstep pretty much all the time."