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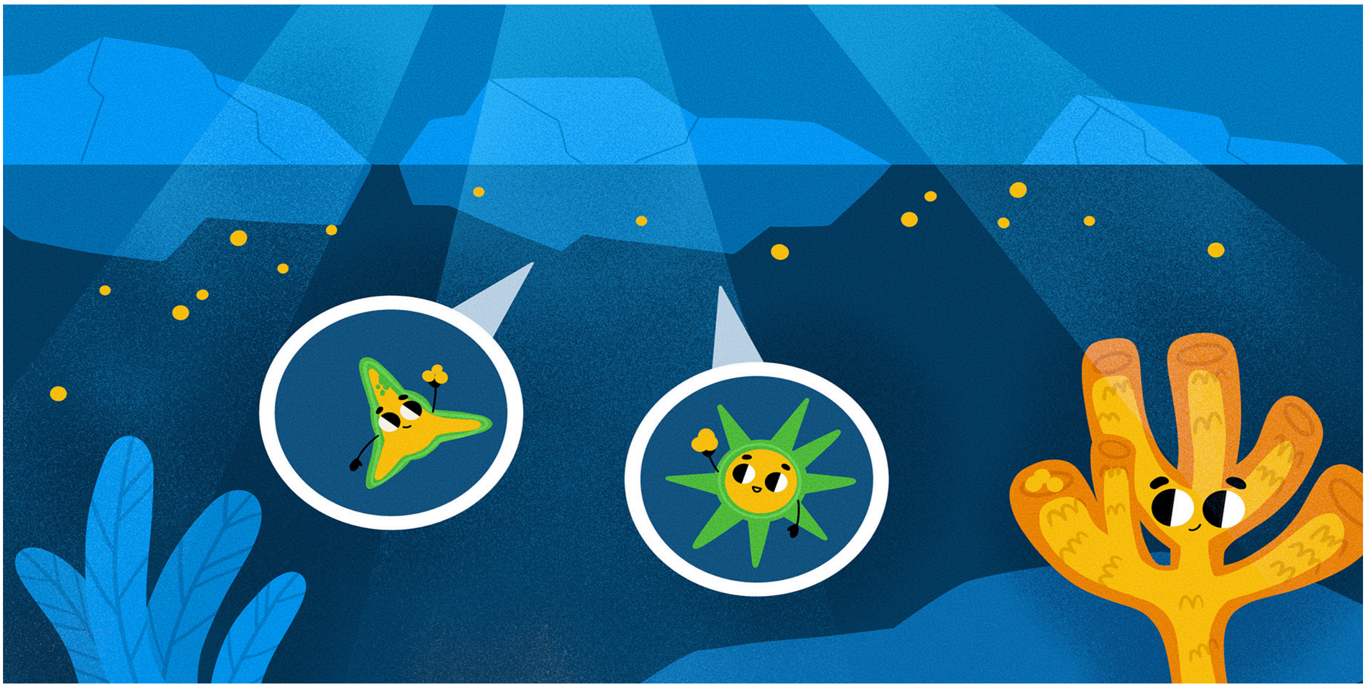

SILICIFIERS: THE GLASSY CREATURES OF THE OCEAN

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Silicon is one of the most abundant chemical elements in the universe. On Earth, it forms sediments, minerals, and rocks. In the ocean, silicon is found in a dissolved form that can be used by many organisms to grow. You probably know that humans use calcium to build their skeletons, but did you know that there are creatures capable of forming skeletons out of silicon? Organisms capable of capturing dissolved silicon from the environment and transforming it into glassy skeletons are called silicifiers. Silicifiers use a unique process called biosilicification to create their skeletons. In the marine ecosystem, silicifiers come in a surprising variety of shapes and sizes, and they include, among others, diatoms, rhizarians, and sponges.

These three groups, so diverse and yet so similar, are essential to the health of the oceans.

LIVING IN A GLASS HOUSE

Among the elements that you may have heard about in chemistry class, **silicon** is one of the most abundant on our planet. Did you know that silicon is the element that forms glass? In nature, glass, also known as **silica**, is part of what makes up the sand of the beaches that people love to walk on when they are on holidays. Humans use silicon for many purposes. For example, it is used to produce chips for computers and smartphones, medicines to improve skin healing and prevent bone damage, and lenses for eyeglasses, microscopes, and telescopes. However, when it comes to making things out of glass, humans are less efficient than certain other organisms. While the industrial glass-production process needs to reach very high temperatures, on the order of 1,000°C (1,800°F), some organisms can capture dissolved silicon from water and transform it into beautiful glassy structures, at regular temperatures!

Why would organisms want to have a silica skeleton? These walls of glass can protect organisms against predators and give them structural support, thanks to the hardness and elasticity of silicon. The ability to build glass houses is called **biosilicification**, and organisms that can do so are called **silicifiers**. Silicifiers are essential for the proper functioning of the ocean ecosystem. The processes carried out by these jewels of nature are full of mystery, and scientists are still striving to understand them, as they can serve as inspiration for the glass industry and for the production of new tiny structures thinner than a human hair called nanomaterials [1]. There are many silicifiers in the ocean, and we will introduce you to three of the most important ones.

DIATOMS—GLASS-COVERED ALGAE

When you think of algae, you probably imagine green leaves floating in the sea. The oceans are also home to a multitude of tiny organisms, called **microalgae**, which can only be observed with a microscope. Microalgae often have just a single cell, but sometimes they can form small, multicellular colonies. Like all plants, microalgae have tiny structures called **chloroplasts**, which help them to convert sunlight into energy through photosynthesis. Diatoms are the most abundant class of microalgae, and they are famous for their ability to capture silicon from seawater to build transparent glass skeletons (Figures 1A, D). This glass-containing cell wall, called the **frustule**, is decorated with a multitude of pores, forming regular patterns of exceptional delicacy and beauty. But why spend vital energy to build such a complex structure? This skeleton, which is hard but flexible, can protect diatoms

SILICON

Element 14 of the periodic table that conducts electricity very easily and is used to build computers and electronic devices.

SILICA

Compound formed by silicon and oxygen. It is very abundant in rocks and forms the sand of beaches.

BIOSILICIFICATION

Process made by living organisms that capture dissolved silicon in water and transform it into beautiful and robust glassy skeletons.

SILICIFIERS

Organisms that create silica skeletons, including diatoms, Rhizaria, and sponges, through the process called biosilicification.

MICROALGAE

A tiny plant-like living thing that floats in the water and makes food from sunlight.

CHLOROPLAST

A unique structure found in plant cells that can convert sunlight into energy, in a process called photosynthesis.

FRUSTULES

Glass walls covering the diatoms like a sandwich. The walls take many shapes and are highly decorated.

from the jaws of their predators: just as cows eat grass, there are tiny animals in the oceans that feed on diatoms. In addition, the glass skeletons can prevent attacks by viruses, improve nutrient absorption, and guide sunlight into the chloroplasts. Living surrounded by glass has allowed diatoms to thrive in all kinds of environments, from oceans to freshwater. Diatoms can live in seawater, in the sediments at the bottom of the ocean, and they can even survive in sea ice [2].

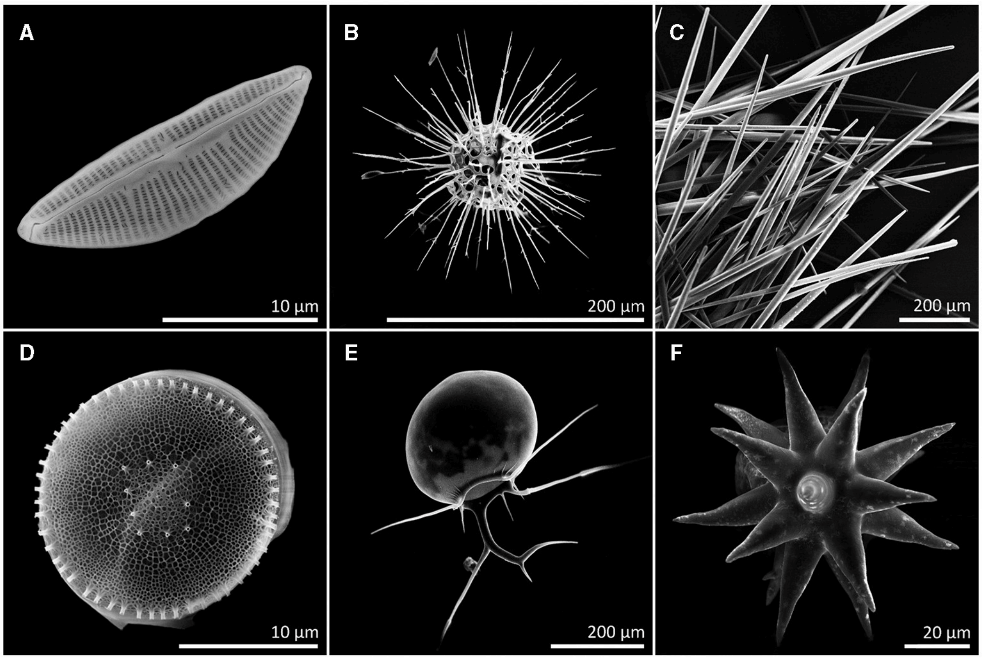

Figure 1

Figure 1

Images of silicifiers taken with a powerful microscope called a scanning electron microscope: **(A)** diatom; **(B)** rhizaria; **(C)** sponge spicules; **(D)** diatom; **(E)** rhizaria; and **(F)** sponge spicules.

RHIZARIA—BEYOND PHOTOSYNTHESIS

Marine rhizarians are unicellular organisms that range in size from several micrometers to a few millimeters (for those that form colonies) [3]. Many are larger than diatoms and can be seen with the naked eye. Rhizarians are fearless of extreme temperatures, which is why they can be found in all oceans, from tropical to polar climates. Unlike diatoms, which need light to exist, rhizarians can be found at all depths of the ocean. Those dwelling on the surface may even associate with microalgae for purposes of nourishment or protection, in an interaction called symbiosis.

Like diatoms, rhizarians can capture the silicon dissolved in seawater to form glassy skeletons with very diverse geometric shapes—such as pyramids, snowflakes, stars, spheres, and many others—which makes them true microscopic treasures (Figures 1B, E). Rhizarians can extend pseudopods, which are numerous arm-like projections, through their skeletons, using them to capture small prey—from bacteria and remnants of dead organisms to other planktonic organisms.

SPONGES—THE OLDEST ANIMALS ON EARTH

Silicon is not restricted to single-celled organisms. Sponges, which are multicellular aquatic animals, also use silicon to build their skeletons. Sponges are the oldest animals on Earth. They do not have organs like humans do. Instead, they have specialized cells for feeding, reproduction, or defense. Most sponges live in the ocean, but some live in rivers and lakes. They live fixed in one place, like plants, and do not move. Sponges capture their food by filtering large amounts of water and collecting tiny suspended particles, from bacteria and tiny remnants of dead organisms to small plankton.

Sponges come in many shapes and sizes: from tiny crusts measuring only a few millimeters, to sophisticated branched and cup-shaped forms measuring in meters. It is their skeletons that allow them to have such distinct shapes and enable them to resist strong currents caused by waves or tides. Most sponge species capture dissolved silicon from seawater and build a silica skeleton composed of millions of microscopic pieces called **spicules** (Figures 1C, F) [4]. However, there are some spicules that are large enough to be seen directly with the naked eye. Sponges are the only multicellular animals to have siliceous skeletons.

SPICULES

Each of the small glassy pieces that form the skeleton of a sponge. Spicules take forms varying from simple needle-shaped rods to highly ornamented star-shaped or hook-shaped pieces.

WHY ARE SILICIFIERS IMPORTANT IN THE OCEAN?

Silicifiers can live either floating on the surface, in the deep ocean waters, or attached to the seafloor, depending on the species. Partly because they can live almost everywhere, silicifiers are involved in many important ocean processes. One of their key roles is controlling the process of silicon reuse in ocean ecosystems. Silicifiers consume dissolved forms of silicon from the seawater to build their glassy skeletons. When silicifiers die, their skeletons sink toward the ocean floor, since they are heavy. As they sink, most of the glass skeletons dissolve and are recycled into the water, becoming dissolved silicon that can be used by other silicifiers. The fraction of the glass skeletons that resists dissolving reaches the seafloor, where it can either remain, covering the ocean floor with a silicon blanket, or dissolve and return to the upper layers of the ocean, carried by ocean currents. The skeletons of silicifiers like sponges, which already live on the ocean floor, also end up in the sediments where they undergo the same processes as the skeletons of diatoms and rhizarians—ultimately recycling their glassy spicules into dissolved silicon [5]. Despite the fragile appearance of the skeletons of silicifiers, some of them are very resistant over time. Their ancestors can be found in layers of sediment that are several million years old (Figure 2)! These fossils are studied by scientists called micropaleontologists, who try to find evidence telling them what the environmental conditions of the past were like.

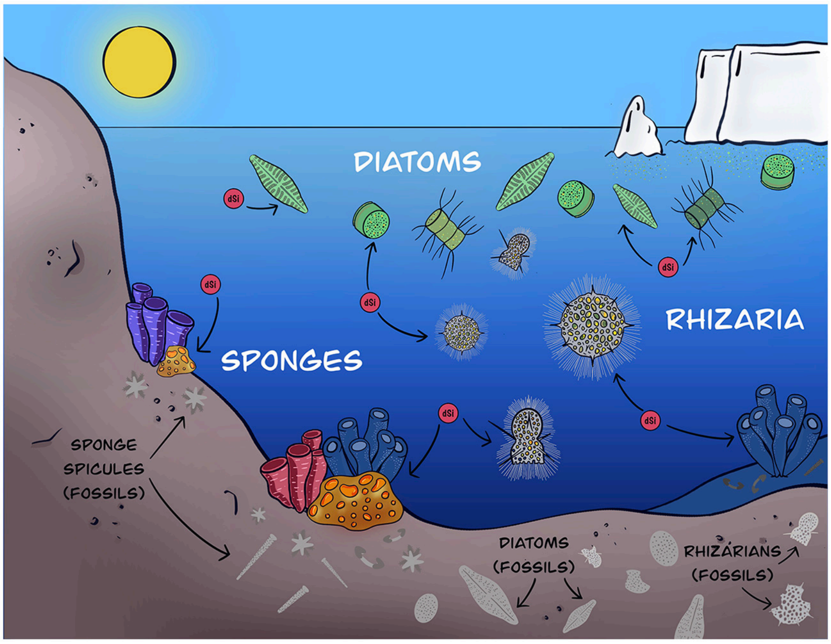

Figure 2

Figure 2

Silicifiers in the ocean. Dissolved silicon (dSi) in the ocean water is used by silicifiers to build their protective structures: the frustules of diatoms, the skeletons of rhizarians, and the spicules of sponges. When silicifiers die, their protective structures dissolve into the seawater, where the silicon can be reused by other organisms, or the skeletons can remain in the ocean sediments as fossils.

STUDY SILICIFIERS TO PROTECT THEM

Despite having impressive glassy armors, silicifiers are not immune to the effects of the ongoing climate change. In a changing ocean, the availability of silicon and other nutrients varies continuously, affecting the health of silicifiers. The study of these tiny and difficult-to-access organisms is a challenge for biologists and oceanographers. However, we need to figure out how silicifiers adapt to climate change. In the end, we can conserve only what we know and understand.

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MUHAMMAD, AGE: 14

The turning point in my curiosity came when I secured first place in my grade 3 science project. It was about photosynthesis, which I chose after knowing the fact that plants are universal food makers. The science textbook of every grade always familiarized me about the magical wonders behind my daily life's surroundings.

SEBASTIAN, AGE: 14
I like sports, reading, math, physics, and all things space!

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I am a marine biologist and my research interests focus on the biology of diatoms—an extraordinary group of unicellular photosynthetic organisms that are an abundant type of microalgae. During my Ph.D., I studied the structure, function, and evolution of the diatom frustule, particularly the way it helps diatoms to float and protect themselves against predators. Now I am working on the response of diatoms to climate change. *a.petrucciani@staff.univpm.it

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I am a marine ecologist and I am passionate about understanding the role of plankton in the ocean. I was fascinated by the beauty of plankton and decided to study the role of rhizarians in the ocean's silicon cycle. I was able to collect, observe, and study these planktonic jewels during four oceanographic voyages, in the Mediterranean, the Atlantic and Pacific Oceans, and the Ross Sea, Antarctica. I am now working to better understand the biosilicification process of these organisms. *natalia.llopis@sb-roscoff.fr

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I am a marine ecologist interested in the role of bottom-dwelling ocean organisms in ocean nutrient cycling, with a special interest in silicon. My model organisms are sponges, which I have been studying for more than a decade and still find as fascinating as the first day. I have studied sponges in shallow waters of the North Atlantic Ocean and Mediterranean Sea by diving, and in deep waters of the Norwegian Sea, Barents Sea, and North Atlantic Ocean using underwater robots. I am now studying the effects of human impacts on silicon recycling in sponges and other silicifiers. *lopezacosta@iim.csic.es