From sea shells to sea change

An introduction to biomineralization by Gerald Langer and Charlotte Walker.

On first inspection it would be hard to unite the bones of a whale, the shell of a barnacle, the Egyptian pyramids and the White Cliffs of Dover. However, all these marvels are connected by biomineralization, a natural process that has been occurring for millennia. Biomineralization is the production of inorganic substances, in this case minerals, by living organisms. Biominerals are found within the hard parts of organisms—the bones, shells and teeth—where they perform many crucial functions. Moreover, the process of bio-mineralization can greatly influence the environment in which they are produced.

In most cases biomineralization is controlled by the organism. By directing the composition, location, orientation, size, and shape of the minerals it produces, the organism creates functional biomineral structures. Controlled precipitation of minerals often involves organic materials, for example, limpet shells are dominated by the minerals calcite and aragonite but they also contain various organic components such as proteins and polysaccharides.

Another, less common, mode is biologically induced biomineralization. This refers to processes initiated by an organism which lead to the precipitation of a mineral, but the organism exerts no control over the form, and sometimes even the particular mineral produced. For instance, some cyanobacteria (marine photosynthetic bacteria) alter the seawater chemistry in their vicinity in a way that causes calcium magnesium carbonate minerals such as aragonite to precipitate. This type of biomineralization can result in large structures known as stromatolites.

The role of biominerals

Biominerals fulfil many different roles within organisms, the most obvious of which are structural and mechanical, for example skeletons which provide support and enable movement. Endoskeletons (internal to an organism) are composed mainly of the protein collagen and the mineral hydroxyapatite—a substance more commonly known as bone. The bones of a turtle are an interesting curiosity because they form both an endo- and an exoskeleton (external to an organism). The endoskeleton provides the structure and mobility while the exoskeleton provides protection.

Protection is also an important function of biomineralized structures, for example, the hard shells of crustaceans which protect their soft bodies from physical damage and predation. The biomineralization process in crustaceans occurs by precipitating calcium carbonate within an organic matrix of chitin protein fibres. This process is energetically expensive and has associated risks—for example, crustaceans are exposed to predators when they moult—but the benefit provided by the long-term protection outweighs the cost.

Figure 1. *Amphistegina lessonii*, a tropical benthic foraminifer. The picture shows an electron micrograph of the shell, and a light micrograph of the so-called pseudopodia (© University of Cambridge, UK), which are a part of the amoeboid cell. Images: Gerald Langer.

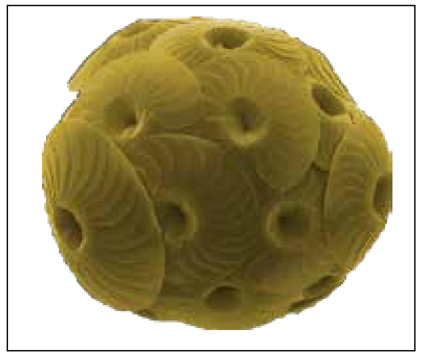

Figure 2. *Calcidiscus leptoporus*, a coccolithophore. The picture shows an electron micrograph of the shell, the so-called coccosphere. © Gerald Langer.

Biominerals fulfil other functions in animals. Interesting examples are the statoliths and otoliths which are components of gravity-sensing mechanisms. Statoliths are found in a broad range of marine invertebrates including bivalves, cnidarians and cephalopods. The statolith is a mineralized mass within a statocyst, a sac-like structure containing many inverted sensory hairs. The statolith shifts as the animal moves, brushing the hairs which provide the information to correct the organism's balance. Otoliths are tiny particles of calcium carbonate found in the inner ear of vertebrates.

The impact of biomineralization

The production of biominerals greatly influences the environment. This is particularly true in the case of calcite, largely because of the chemistry behind its creation and the density it gives to organisms that produce it. In this context we refer not to the skeletons of large animals but to the shells of microscopic single-celled plankton, the most important groups of which are the foraminifera and coccolithophores (Figs 1 and 2). The foraminifera are amoeboid protozoa that produce a multi-chamber calcite shell of up to several millimetres in size. The coccolithophores are characterized by calcite platelets, termed coccoliths, which are extruded to the cell surface and form a shell-like covering called a coccosphere. These coccospheres are only 5–25 micrometres across, but owing to their abundance they substantially influence the global carbon cycle on very different timescales. In the short-term, the production of calcium carbonate in sea surface waters changes the carbon chemistry of the water most significantly by increasing the carbon dioxide (CO_2) concentration which affects gas exchange between the ocean and atmosphere. An analogy of this effect is opening a bottle of sparkling water. The bubbles are gaseous CO_2 which was previously dissolved in the water. In the ocean this effect acts on short timescales of approximately one year. By contrast, the sinking of these shells to the deep sea and their eventual burial and subduction removes carbon from the system for hundreds of millions of years, thereby affecting the carbon cycle over geological timescales (see Fig 3).

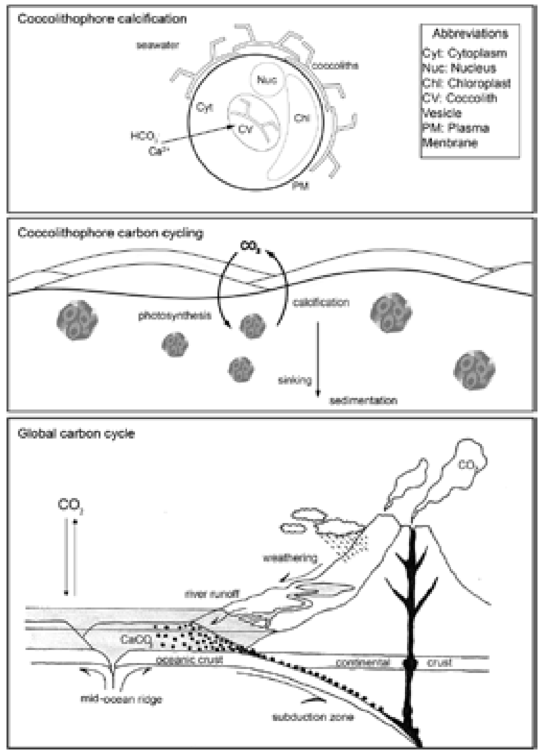

Figure 3. Top: Calcification by microalgae captures atmospheric carbon over short (annual) timescales. Middle: Sinking of coccoliths removes carbon over geological timescales. Bottom: The global carbon cycle (Global carbon cycle sketch © Karina Kaczmarek).

Striking examples of mass sedimentation of these microscopic organisms are the White Cliffs of Dover, which are mainly composed of coccoliths and foraminifera shells. These huge deposits were formed in the age of the dinosaurs, approximately 70 million years ago. Extremely large (frequently several centimetres across) disc-shaped foraminifera called Nummulites accumulated on the more recent Eocene seabed, and gave their name to nummulitic limestones—famous as the stone used to build the pyramids.

Applying the science of biomineralization

Extracted from sediments millions of years old, the shells of planktonic foraminifera have played a crucial role as a 'climate archive' for reconstructing past climates. The foraminifera calcite not only contains calcium and carbonate, but a suite of other trace elements and their isotopes. An element is defined by the number of protons in its nucleus. Most elements also have neutrons in their nucleus, but the number of neutrons can vary, making the element more or less heavy. We speak of heavy and light isotopes of an element. Oxygen, for example, has different isotopes; the most common ones are the heavier ^{18}O and the lighter ^{16}O. Since isotopes have different masses they react slightly differently in many chemical reactions, leading to different isotopic compositions of the product. The isotopic compositions are influenced by physico-chemical parameters and can therefore be used to get information about these parameters. For instance, the oxygen isotopic composition and the magnesium/calcium ratio are used to reconstruct temperature. The boron isotopic composition is related to seawater pH, an important parameter of the seawater carbon system. The reconstruction of temperature and seawater carbon chemistry over geological timescales can inform our predictions of present and future climate change and its anthropogenic component.

Another group of phytoplankton that have inspired remarkable biomineralization applications are the diatoms. Diatom silica frustules (Fig. 4) are thought to have evolved to protect the cell body beneath. They produce intricate, lightweight silica structures at various scales that may have applications as templates for drug delivery carriers, optical devices, tools, and lightweight parts for cars, ships and spacecraft.

Figure 4. ***Asterionellopsis***, a chain-forming diatom. Image: © Charlotte E. Walker /Marine Biological Association.

The study of biomineralization is exciting and rapidly evolving. It spans areas of research from biochemical and cell physiological mechanisms to geological processes. Today, research is not confined to fundamental bioscience, but is central to applications such as construction of lightweight materials and past climate reconstructions.

Gerald Langer (gerlan@mba.ac.uk) is an MBA Research Associate.
Charlotte Walker (chawal@mba.ac.uk) is an MBA and University of Southampton PhD Student.