

# The chemistry of fossilization on Earth and Mars

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The story of our world is written in the rocks. Turning over the stony pages, a trained geologist can read about mountains that rose and fell in the distant past, oceans that dried out in the sun, and continents that came together and drifted apart. The ground beneath us was shaped by processes like these over millions of years, and perhaps it is unsurprising that these epic shifts in the landscape should have left traces behind. But here and there, to our immense good fortune, the rocks yield something else: remains or traces of ancient life. If a good rock can be read like a good book, then a well-preserved fossil is like a finely wrought illustration, a vivid depiction of a fleeting moment in the life of the world. Fossils, whether on the scale of dinosaurs or individual molecules, provide our most decisive evidence for testing hypotheses about the abundance, diversity and evolution of life on Earth over the past three-and-a-half billion years. They are also our best hope for answering one of the most compelling questions in science: was there ever life on Mars?

## How do fossils form?

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There are many ways to make a fossil, but very few organisms fossilize; most simply rot away. Decay is driven by physical, chemical and biological agents, including the digestive and autolytic enzymes of the decaying organism itself. Aerobic bacteria rapidly destroy organic remains that are exposed to air, so burial under mud, silt or sand is a prerequisite for most styles of fossilization. After burial, new minerals can precipitate from groundwater inside and around the remaining structures, welding the sediment grains into a mould and filling any cavities left behind by decay. (Paradoxically, decay is often necessary for preservation to occur: the breakdown of organic matter favours mineral precipitation by changing chemical conditions and supplying mineral ions like sulphide and phosphate.) Finally, with deeper burial, compaction and further cementation by new minerals, soft sediment turns into hard rock, and the ephemeral stuff of life is converted into fossils that can last for millions or even billions of years.

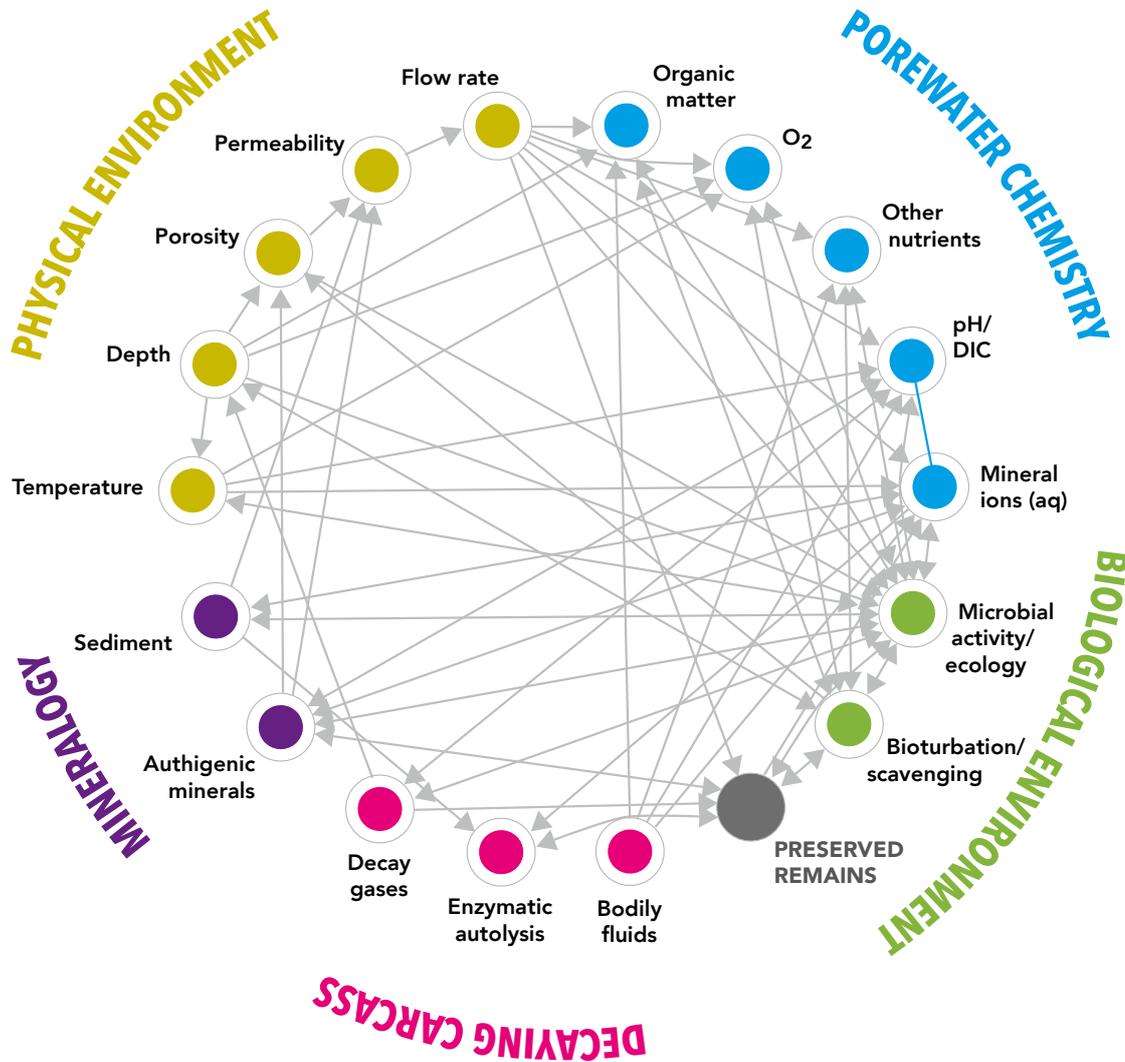
Fossils vary enormously in their composition and level of detail, reflecting the complex and unpredictable play of biogeochemical interactions around decaying organic remains (Figure 1). There is a whole subdiscipline of palaeontology (*taphonomy*) dedicated to understanding the diverse ways in which fossils can form. Taphonomists often conceptualize fossilization as a contest or race between processes that tend to destroy biological information (decay) and processes that tend to secure it for posterity (preservation). Decay usually wins hands

down. Admittedly, some biological materials are more resilient than others. Bones, teeth and shells lose their organic matrix long before their inorganic, crystalline components, which typically recrystallize after burial, forming more stable minerals while maintaining their original shape. Organic macromolecules vary widely in their resistance to decay. Nucleic acids break down fast, but lipids can be extraordinarily resilient, surviving for billions of years (as 'molecular fossils') as long as they are not exposed to high temperatures. Structural polymers like lignin, cellulose, collagen, keratin and chitin outlast other proteins and carbohydrates, but skin, muscles and other such 'soft parts' are still extremely rare as fossils. To preserve them, conditions must conspire to suppress decay for longer than usual, or minerals must precipitate unusually early and pervasively around the organism after (or even before) death. Even then, organic carbon preserved within fossils is typically altered by heat and pressure over time, gradually transforming into kerogen, petroleum, natural gas and graphite.

## Why care about how fossils form?

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There are at least four reasons why taphonomy matters to palaeontologists. First, the fossil record is not perfect. It tells an incomplete story, systematically biased in favour of certain biological materials, chemical conditions and physical environments. To fill in the gaps in the evolutionary timeline, we need to know what is likely to be missing from the fossil record and why. Second, to reconstruct the anatomy and physiology of ancient



**Figure 1.** Schematic overview showing some of the interactions governing fossil preservation. Arrows indicate directions of influence. A carcass or microbial cell buried in sediment is a complex biogeochemical reactor that can behave unpredictably. Figure designed with help from Victoria E. McCoy (University of Bonn)

organisms accurately from their fossils, we need to be able to compensate for the distortions and omissions produced during decay and mineral growth. Third, understanding what conditions are most favourable for fossil preservation allows us to optimize the search for the best-preserved fossils, which can provide unique insights into the physiology and ecology of extinct organisms. Fourth, understanding these conditions allows us to predict whether and how fossils would form in radically different environments — like those existing billions of years ago on Mars.

## Why look for fossils on Mars?

Humans have speculated about life on Mars for hundreds of years, but the robotic missions of the last few decades have revealed the red planet to be a brutally inhospitable place. The low temperatures and pressures make water

unstable on the Martian surface except where its freezing point is suppressed by toxically high concentrations of salts. Any organic matter lying around would soon be destroyed by a combination of oxidizing soil chemistry (including Fenton reactions) and intense ionizing radiation from space and the Sun, against which Mars' weak magnetic field and thin atmosphere offer very little protection. If there is life (as we know it) on Mars today, it would have to be restricted to deep sheltering niches underground, where geothermal heat could maintain a supply of liquid water. To find these hypothetical organisms would require drilling deep into the Martian subsurface, an impossible task with the technology (and budgets) currently available.

Between about four and three billion years ago, however, the surface of Mars was a much more hospitable environment. Ancient valley networks, exposed shorelines and sedimentary rocks — all preserved in

excellent condition because Mars lacks plate tectonics or forceful erosion — testify to the existence of an active water cycle on early Mars, which in turn implies higher temperatures and a thicker atmosphere. Intriguingly, conditions on Mars seem to have been most suitable for life at around the same time that life began on Earth. In my judgment, Earth's oldest convincing fossils are about 3.4 billion years old. Reports of fossil bacteria in meteorites from Mars have not stood up to scientific scrutiny, but there is experimental evidence to suggest that debris from asteroid impacts could have transported viable microorganisms from one planet to the other. Even if life originated only on Earth, it could still have spread to Mars, or *vice versa*.

Both NASA (the National Aeronautics and Space Administration) and ESA (the European Space Agency) have now committed billions of dollars to robotic rover missions that will search for physical or chemical remnants of life — fossils — in ancient Martian rocks. The long-term aspiration of both space agencies is to put these rocks into the hands of palaeontologists and geochemists back on Earth. To this end, NASA's Mars 2020 rover will collect its most promising finds and gather them together in one place. If these samples are deemed interesting enough to warrant the expense, they will be scooped up and returned to Earth by a purpose-built follow-on mission.

Clearly, understanding how and where fossils could have formed on Mars is critical to the success of these missions. Insights from taphonomy therefore have the

potential to determine which landing sites are chosen, which routes the rovers take over the Martian surface, and which rocks they sample or collect for return to Earth.

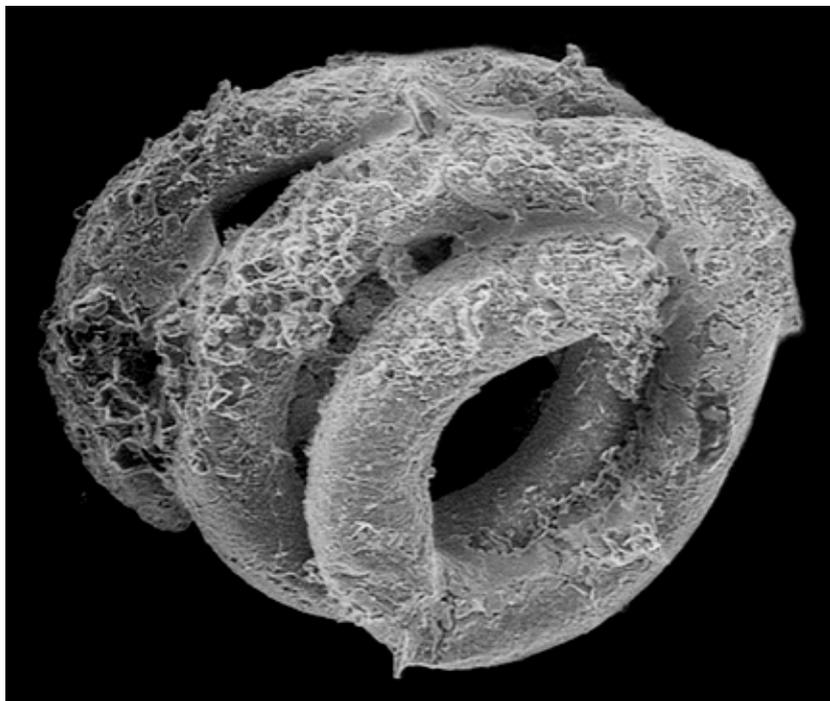
## Fossil microorganisms on Earth and Mars

By the time animals and plants arose on Earth, the surface of Mars had already been an icy wasteland for two or three billion years. Nobody, therefore, is looking for Martian dinosaur bones (sorry, Hollywood!). Instead, microbes like bacteria and archaea provide our best analogues for the kind of fossils we might hope to find on Mars. Such microorganisms dominated the Earth for most of its history—in many ways, they still do—and could have made a living in the anaerobic conditions on early Mars using photosynthesis or by catalysing redox reactions involving iron, sulphur and hydrogen. Fossil microbes are not especially rare on Earth, although most cannot be seen without scanning electron microscopes or polished slides for high-magnification optical microscopy. These techniques will not be available to rovers on Mars, so we won't know for sure if they've found fossil bacteria until we can get the samples back to Earth. We would be reasonably optimistic, however, if rovers on Mars found the macroscopic features that we associate with bacterial activity in ancient sediments on Earth, like fossilized gas bubbles or large convex-upward protrusions composed of fine laminations.

Cyanobacteria, the most important bacterial photosynthesizers on Earth, have a cellular fossil record stretching back over a billion years (Figure 2). These relatively large microorganisms are extremely abundant and commonly produce extracellular sheaths made of polysaccharides, which in some strains are highly resistant to decay. Under certain conditions, cyanobacterial sheaths have also been shown to facilitate the precipitation of minerals including carbonates and clays, which can encrust and preserve the cyanobacteria as fossils. Many other groups of bacteria share this ability to deposit minerals outside their cells for homeostatic purposes, making this is an important pathway by which bacteria can enter the fossil record — effectively fossilizing themselves.

Ultimately, however, most microbial fossils result from speedy entombment in minerals delivered by the environment. For example, geysers and hot springs can rapidly dump vast amounts of silica, a mineral which dissolves into hot water underground and precipitates as an amorphous mass in cooler conditions at the surface, trapping any organic remains within it (Figure 3). Amorphous silica is an excellent medium for preserving

**Figure 2.** A spring-shaped phosphatic fossil cyanobacterium, *Obruchevella* (about 0.2 mm across), from 0.6 billion-year-old rocks in Mongolia.





fossil cells at sub-micron resolution. It's also very common on Mars, mostly as a weathering product of ancient lava flows. NASA's Opportunity rover found a lot of silica in Gusev Crater, where its distribution and textural features are consistent with deposition in a geyser-like environment. At the time of writing, this locality is being considered as a possible landing site for NASA's Mars 2020 mission precisely because it could be a fossiliferous deposit. Other, less exciting interpretations of the silica haven't been fully ruled out, however, which makes this site a somewhat risky prospect.

## Glorious mud

In my view, the most palaeontologically promising rocks on Mars are the lakebed mudstones — fine-grained, clay-rich, thinly layered rocks like those explored by NASA's Curiosity rover in Gale Crater (Figure 4; these rocks also turned out to be surprisingly rich in amorphous or very finely crystalline silica). By their very nature as the products of long-lived lakes, we know that these rocks formed in habitable environments. On Earth, many mudstones contain wonderfully preserved animals and plants, whose soft tissues appear to have been fortified by adsorptive interactions with clay particles and retained as

thin carbonaceous films. Mudstones rarely contain fossil bacteria except for those with unusually robust cell walls or resistant sheaths, like cyanobacteria, although pervasive, early precipitation of silica would substantially improve the odds of preserving other kinds of microorganisms. More importantly, however, mudstones can preserve large amounts of ancient biological organic matter, even where structures like cells have broken down beyond recognition. The biological origin of this organic matter is revealed by the presence of molecular fossils: organic biomarkers, mostly derived from lipids like sterols or hopanoids.

As I remarked above, organic molecules would not fare well if exposed to the harsh conditions at the Martian surface. If entombed inside rocks, however, organic matter formed on early Mars could have survived for billions of years down to the present day. Indeed, using a miniaturized pyrolysis GC-MS instrument, the Curiosity rover has already been able to identify ancient organic matter within the four-billion-year-old mudstones in Gale Crater. Low yields and reactions with perchlorate inside the pyrolysis chamber have obscured the original composition of this organic matter, which may or may not have been biological. If future rovers visit similar rocks, they may settle the issue using more sensitive techniques. It could be a day to remember!

**Figure 3.** El Tatio geyser field in Chile. The hot springs at this site discharge silica-laden water, forming fossiliferous rocks texturally similar to controversial deposits observed on Mars.



**Figure 4.** Four-billion-year-old lakebed mudstones on Mars, found by the Curiosity rover to contain organic matter

## What can we do on Earth?

Our understanding of how fossils form on Earth — including much of the detail mentioned in this article — has been refined in recent decades by an experimental approach to the study of taphonomy. When it comes to soft tissues or microbes, the race between decay and preservation is often won in a matter of hours or days, not millions of years. This makes it possible to study these processes in the laboratory. A few workers, like Frances Westall and her colleagues at CNRS Orleans, have conducted taphonomic experiments using bacteria and archaea, artificially

## Further reading

- McMahon, S., Bosak, T., Grotzinger, J. et al. (2018) A field guide to finding fossils on Mars. *Journal of Geophysical Research: Planets* **153**, 1012–1040 (open access)
- Eigenbrode, J.L., Summons, R.E., Steele, A. et al. (2018) Organic matter preserved in 3-billion-year-old mudstones at Gale Crater, Mars. *Science* **360**, 1096–1101
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entombing them in silica, for example, to understand what controls the quality of silicified microfossils. In future, experiments like these will need to be adapted to take better account of the physical and chemical environments encountered on Mars over the past few billion years, such as anoxic CO<sub>2</sub>-rich atmospheres, acidic brines, oxychlorine compounds and low temperatures. Future work addressing these conditions may provide further insights that can be used to guide us towards the first fossil to be identified on Mars. That long-anticipated discovery could be bacterial or even molecular in scale — but it would be another giant leap for humankind. ■



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