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times that have been assigned to it (based on fossil calibration and evolutionary rate estimates) tell us that the major lineages of complex animals diverged much earlier — we're talking hundreds of millions of years here, or a dozen or so Manhattan blocks — than we can detect their traces in the fossil record.

The cloud becomes even thicker once we climb out of our animalcentric vantage point and realize that the animal tree of life is really only the tiniest twig on the overall behemoth. Most of the diversity of life on earth sits within the Bacteria, Archaea and single-celled eukaryotes — the stuff that diverged above 59th St, essentially. And here, molecular comparisons have revealed that the tree is not a useful heuristic device at all anymore. This is largely due to the fact that these critters swap around DNA not only with their own kind but promiscuously with everyone and anyone. It's as if you were to constantly swap books and clothes and furniture with your neighbours. You would still live in 8R, but would it really still be the same apartment? In this vast domain of life, the concept of the tree as a reflection of the real unfolding of evolution becomes practically meaningless. You can of course still trace the bifurcations of individual genes and cells, but it doesn't tell you much about the evolutionary history of an organism as a whole.

So, is the tree — as a metaphor and a means of understanding of the unity and diversity of life on Earth — obsolete? Other, less evocative concepts have been proposed, ranging from bushes and shrubs to the inevitably bland 'networks'. And do we really need one image to capture all of evolution's greatness? Maybe not. Maybe it is enough to know that "we're related to the grass". But mankind's inability to fathom much more concrete facts — like climate change — doesn't inspire confidence. Maybe it doesn't matter. Maybe it's just something that makes for geeky conversations. But maybe, if we all had fully internalized that all the creatures that we're exploiting, killing, chopping down and depriving of their livelihood are truly and fundamentally one with us, we would indeed start to treat them differently.

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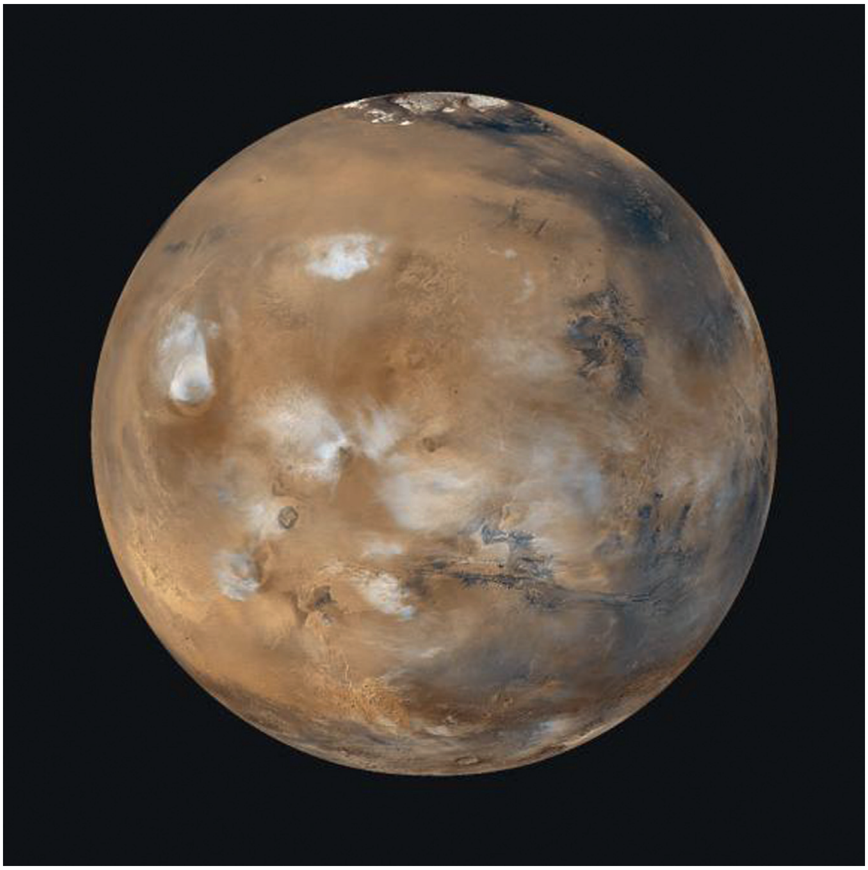
Feature

How life shaped Earth

Earth is much more complex than all the other solar system objects that we know. Thanks to its rich and diverse geology, our planet can offer habitats to a wide range of living species. Emerging insights suggest that this is not just a happy coincidence, but that life itself has in many ways helped to shape the planet. **Michael Gross** reports.

On July 14th, NASA's New Horizons mission flew past the dwarf planet Pluto at a distance of just 12,472 kilometres and sent back images that intrigued many of the inhabitants of its home planet. Images of Pluto's ice mountains as high as 3,500 metres and surprisingly smooth patches that suggest a surface being remodelled by geological processes, as well as at least five moons, will keep scientists busy for months to come, while New Horizons speeds on to its provisional next target, the Kuiper Belt Object 2014MU69.

Crowning a mission that had been in preparation since 2000 and in flight since January 2006, the flyby also continued a long string of successful solar system missions in this century. Other notable achievements include orbiting of and deposition of a lander on comet 67P/Churyumov–Gerasimenko as well as the multiple missions currently active on Mars. Most spectacularly perhaps, the Mars rover Opportunity is still going strong in its 12th year of exploration, while the Curiosity rover, with its advanced



Dead planet: While the intensive exploration of our neighbour may yet discover traces of past life, it is clear that planet Mars is much simpler in terms of mineral composition and has not been shaped by life as our planet has been for billions of years. (Photo: NASA/JPL-Caltech/MSSS.)

uninhabitable. Thus life is, in a mosaic pattern created by its many different influences, keeping our planet broadly habitable, even if occasionally a rogue species like ours comes along and triggers a mass extinction. How far back can we trace the ability of life to build its own habitat in the geological record?

Hollowed out: Limestone caves are caused by bacteria oxidising hydrogen sulphide to produce sulphuric acid. The image shows researchers from Penn State University at work in such a cave. (Photo: Jennifer Macalady, Penn State.)

laboratory equipment, beams back detailed information about Mars' geology and chemistry.

These missions have revealed fascinating details of the materials that our planetary system is made of. All the uninhabited planets and moons appear to be much simpler in their composition than our living planet. But is a geologically rich and complex planet a prerequisite for life, or does life itself convert a basic ball of rock into something much more interesting?

Ecosystem engineers

It is undeniable that life on Earth is currently remodelling the planet. Our species in particular has added land surface to continents, redirected rivers, linked oceans, and dug holes that are large enough to be seen from space. Our most far-reaching influence, however, may be in those aspects that aren't visible to the naked eye, including the change to the composition of the atmosphere, acidification of the oceans, and global distribution of novel materials.

Humanity's impact on the Earth systems is so significant and pervasive that geologists are now officially considering the definition of a new epoch, the Anthropocene, in order to include this phenomenon in the geological timeline (Curr. Biol. (2015) *25*, R131–R134). While our species may be unique in producing massive global change in a very short time, we are not the only ecosystem engineers. In fact, the natural world around us has been shaped by living organisms in many ways that don't immediately meet the eye.

Science writer Bob Holmes from Edmonton, Canada, has explored a speculative scenario of the future of Earth if life were to become extinct (New Scientist (2013) *2936*, 38–41). With the end of photosynthesis, the atmosphere would accumulate CO_2 and deplete in oxygen fairly quickly, which would not only see temperatures rising and ice caps melting, but would also affect weathering and thus the structures of mountains. Rivers would meander differently if their banks weren't stabilised by plant roots. Soil would wash off into the seas leaving a surface of bare rock and sand, much like the one the rovers are exploring on Mars.

On longer timescales of some tens of millions of years, Holmes speculates, positive feedback loops could subject Earth to a runaway greenhouse effect creating conditions similar to those on Venus, and make it permanently uninhabitable.

Layer upon layer

Much of what we see as Earth around us is of course the product or the mortal coil of some past life form. The rivers and coastlines that define our maps are all shaped by life — the very shapes our geography is built from would have looked different before life conquered land. The white cliffs of Dover — much like their continental counterparts in Denmark, Germany and France — are sediments made of the skeletal remains of coccolithophores (single-celled planktonic algae) that accumulated during the Cretaceous, between 145 and 66 million years ago.

Below ground, the fossil fuels that our civilisation burns so enthusiastically are the remnants of plants that mostly died several hundred million years ago and were then anaerobically processed under pressure and in part with the help of bacteria. None of these geological layers would exist if our planet had remained lifeless.

Beyond the layering of dead organisms, microbes can also shape our world in three dimensions. Bacteria converting hydrogen sulphide into sulphuric acid are responsible for vast caves in rocks such as limestone. A recent analysis by Jennifer Macalady and colleagues from Penn State University, USA, suggests that in a typical hydrogen sulphide-rich limestone cave the bacteria living above water are responsible for producing the sulphuric acid that dissolves the rock, while those below the water line only produce elemental sulphur (Chem. Geol. (2015) *410*, 21–27).

The fossils that help geologists to identify the layers of the Earth's crust and biologists to make sense of the evolution of life remind us that we are walking on many layers of past life. When animals started building hard shells or internal skeletons some 540 million years ago, they made the fossil record more diverse and interesting — and they may have wiped out much of the previous biodiversity.

Simon Darroch from Vanderbilt University at Nashville, Tennessee, USA, recently analysed Ediacaran fossils dated to 545 million years ago from a site in Namibia to test the competing hypotheses concerning the causes of the mass extinction that ended the Ediacaran period. The authors concluded from their quantitative palaeoecological evidence “that evolutionary innovation, ecosystem engineering and biological interactions may have ultimately caused the first mass extinction of complex life” (Proc. R. Soc. B. (2015) *282*, 20151003). Although previous organisms were much more primitive, the history of life shaping Earth reaches back even further.

Ground work: Roots of plants help to shape and stabilise the ground they grow in, preventing erosion and influencing the course of rivers. (Photo: Richard Bardgett.)

Oxygen boosts mineral evolution

A major turning point in the history of life on Earth was the ‘Great Oxygenation Event’ around 2.4 billion years ago, when photosynthetic microbes related to today’s cyanobacteria converted an anaerobic biosphere into a largely aerobic one. The change to the atmosphere by itself is already one of the biggest Earth-shaping changes that life has made, but its knock-on effects also reached into other parts of the Earth system, including minerals.

Robert Hazen from the Carnegie Institution in Washington DC, USA, has developed a step-wise model of the evolution of the diversity of minerals that we see on Earth today (Elements (2010) *6*, 9–12). This diversity needs explaining, as meteorites and other planets harbour much smaller numbers of different minerals, and in the detailed model proposed by Hazen, the oxygenation event represents the biggest jump.

Essentially, the number of minerals increased with every additional process that could convert their structure or chemical composition. The star dust from which our solar system formed contained only around a dozen different minerals. Upon ignition of the Sun, around 50 were added, as the energy released made star dust melt and recondense. The accretion of our planet and the acquisition of water (most likely from comet impacts) enabled the number to grow to around 250, which form the repertoire that Earth shares with other rocky planets and with meteorites. In the second era of the mineral evolution, the differentiation of Earth into core, mantle and crust, along with the availability of water as a solvent for recrystallisation, drove further diversification of minerals to around 1,500 kinds — three times as many as are likely to be present on a simpler planet like Mars, which lacks plate tectonics.

From this level of diversity caused principally by inorganic processes, the availability of free oxygen in the atmosphere, caused or at least helped by microbes, catapulted the mineral diversity to a much higher level of just over 4,000 different kinds of minerals. “For decades we’ve realized that minerals probably played key roles in life’s origins; now we’re coming to realize that life played equally essential roles in the origins of most mineral species,” Hazen concludes.

Today, the official count by the International Mineralogical Association (IMA) stands at 5,046 (http://rruff.info/ima/). A recent statistical analysis conducted by Hazen and colleagues has shown that our current knowledge is bound to be incomplete — there are more than 1,500 minerals likely to be present but as yet undiscovered (Math. Geosci. (2015) *47*, 647–661).

The IMA count also ignores all man-made materials by default. Jan Zalasiewicz and colleagues have argued that man-made mineral materials that are likely to persist in the environment on geologically relevant timescales — such as the tungsten carbide that forms the ball in a ballpoint pen — should now be added to the count (Geol. Soc. Sp. (2014) *395*, 109–117). This is one of the ways in which life shapes Earth, and, as Zalasiewicz argues, just another piece of evidence showing that the Anthropocene is upon us.

Early days

Before the oxygenation event, there were only anaerobic microbes, and we have only very little evidence regarding what they did to the young planet. They built up finely layered ‘living rocks’ — stromatolites — that can now be found in some ancient limestones, and they were probably involved in a kind of photosynthesis that did not produce molecular oxygen (anoxygenic photosynthesis) that began to precipitate iron out of the early oceans. Overall, though, they may have been too sparse to have a profound global effect, but then again they were lacking the checks and balances of a complex biosphere, so it is conceivable that a bloom of bacteria all running the same chemical reaction may have tipped geology one way or the other. This

Layer cake: Banded iron formations are an early sign of life in as much as they were produced between three and two billion years ago when the anoxic oceans rich in the highly soluble ferrous iron (Fe^{2+}) became oxidised, leading to the precipitation of ferrous iron (Fe^{3+}), the version familiar from all things that rust. The white layers typically consist of the silicate mineral chert. (Photo: Graeme Churchard.)

would also be consistent with the very dramatic changes in the deep climate history of our planet.

Oxygen sent Earth's climate on a roller-coaster ride. "If a new breed of bacteria begins to introduce that novel and very reactive chemical compound, free oxygen, into the atmosphere, then that could have consequence for a planet over and above creating a raft of new minerals," Jan Zalasiewicz explains. "That oxygen could oxidise and therefore destroy something that might have been an important constituent of the atmosphere, namely methane — which happens to be a greenhouse gas many times more powerful than carbon dioxide. It is probably not a coincidence that the 'Great Oxygenation Event' was shortly followed by the first of the 'Snowball Earth' episodes, when the Earth went into a deep freeze, and became enveloped in ice. That's quite a trick for a single-celled organism to pull off."

Then there is the question of how the deeper layers of the ocean became oxygenated during the Neoproterozoic era, between one billion and 540 million years ago. The dramatic change in the oxidation state of the oceans was a key requirement for the evolution of complex animals, including our first vertebrate ancestors.

Many have assumed that a rise in atmospheric oxygen led to the oxygenation of the waters. However, as the oxygen-producing phytoplankton organisms sink to the seafloor and use up oxygen as they decompose, a simple equilibration may not hold the answer.

Tim Lenton from the University of Exeter and others have recently suggested that life, again, had an additional role in this crucial event of global change enabling our own evolution. Lenton and colleagues argue that as eukaryotes grew larger and sank faster, the oxygen consumption in surface waters would have been reduced. First filter-feeding animals, such as sponges, might also have cleaned up the water and thereby reduced the oxygen demand — earlier research from Lenton and colleagues had shown that the sponges only consumed very little oxygen themselves. In a further layer of geochemical complexity, the researchers argue, the penetration of oxygen to the sea floor would have reduced the release of phosphorus from the sediment, which in turn could have reduced primary productivity in the oceans and thereby oxygen demand.

As for the solid foundation of our continents, there have been suggestions that oxygen-producing photosynthesis evolved much earlier than most people think and that it may have played a role in turning basalt into granite, a key reaction in the origin of the continents. The movement of continents due to plate tectonics on our planet is another key difference between Earth and other rocky planets in our neighbourhood and a mystery waiting to be solved. Water may have lubricated the movement of the plates, although a role for life is less likely in this case. However, it is very hard to find conclusive evidence for anything that happened in the early days of our planet, if only because most of the crust that was present then has since been recycled by the very same process of plate tectonics that we are seeking to understand.

Further back in time, the origin of life is yet another unsolved mystery, but it was clearly dependent on what chemicals the geological context made available. As soon as life acquired the ability to spread and multiply, it also carried the potential to change the environmental chemistry from which it had emerged.

A fragile Gaia

The idea of life shaping its own habitat evokes James Lovelock's famous Gaia hypothesis, of the living planet Earth as a super-organism evolving to perpetuate habitability.

We may today be slightly less optimistic than Lovelock was when he wrote his first book about Gaia, published in 1979. Yes, life has changed our planet and made it a more complex, diverse, and life-friendly place, but on the other hand it is no stranger to positive feedback loops that lead to mass extinctions and could in principle wipe out all life. Even after the end of all life on Earth, and even if the surface became more inhospitable and Mars-like, geological formations would persist for many millions of years as evidence from which any alien visitors could conclude that this rocky planet was once shaped by life.

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