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## A dynamic planet

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Processes within the Earth shape and influence the surface environment and the emergence and evolution of life. Our Editorial board members outline recent advances and future directions in our attempt to understand the history of our planet and its environment.

The geological and geochemical records stored in rocks hold the keys to investigating our planet's past, including internal processes, environmental changes, and the evolution of life. Here, to celebrate one year since the launch of *Communications Earth & Environment*, our Editorial Board members give their views on the greatest questions surrounding Earth's history and how we are starting to address them. Even as we learn more about our own planet's workings, we are expanding our capability to investigate the dynamics of other worlds in the solar system and the possibilities for those further afield.

### Claire Nichols: An inner core conundrum

Life on Earth is shielded by the planet's stable magnetic field. This field arises from convection driven by compositional gradients in Earth's liquid outer core during crystallization of the solid inner core, a phenomenon known as the geodynamo. The geomagnetic field appears to have been active for at least 3.5 billion years, but age estimates for the onset of inner core nucleation are very imprecise and span almost the entire history of the Earth. Without crystallization of the inner core, it is unclear how the Earth's magnetic field could have been generated and maintained. An old inner core, with a low thermal conductivity, would imply that the geodynamo may have been driven by both thermal and chemical convection for billions of years. In contrast, a young inner core with a high thermal conductivity would suggest the current dynamo mechanism has only been in operation for a fraction of the time over which Earth has generated a stable magnetic field. Furthermore, thermal convection is inhibited at high conductivities, leaving the dynamo mechanism prior to solidification open to debate.

High core thermal conductivity and a young inner core, between about 1.3 and 0.5 billion years old, have been inferred from state-of-the-art diamond anvil cell experiments coupled with first-principles calculations, and from single-crystal paleointensity studies. If the inner core is as young as that, a different mode of dynamo must have been in operation to generate the preceding stable paleomagnetic field. One proposed mechanism is a precipitation of light elements at the core-mantle boundary and convection driven by compositional buoyancy. However, the plausibility of this mode of dynamo operation depends upon thermal conductivity estimates from high-pressure-temperature experiments, which focus on pure iron, rather than on Fe–Ni–light element alloys which are more representative of core compositions. The addition or extraction of light elements across the core-mantle boundary could also trigger solidification, suggesting that thermal conductivity and secular cooling are not the only factors at play.

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Dynamo models have predicted increases, decreases, and no change in intensity when the inner core begins to solidify. Future progress will therefore depend on improving the ancient record of Earth's magnetic field strength. Paleointensity measurements continue to advance, and recent studies have benefited from well-defined reliability criteria and increasingly rigorous analytical approaches such as single-crystal paleointensity methods, and the direct identification of magnetic carriers using the quantum diamond microscope. Nonetheless, much of Earth's history is under-represented in the paleointensity record, and significantly more data will be required to identify robust statistical trends in field strength over the last 4 billion years. We can also look to other terrestrial bodies to aid our understanding of dynamo mechanisms. Key questions include how the lunar dynamo operated for nearly 2 billion years despite the small size of the Moon's core, and why the Martian dynamo was short-lived whereas the geodynamo has been sustained for billions of years. Answering these questions will require a collaborative approach to improve the resolution of the paleomagnetic record, in tandem with dynamo models underpinned by experimental data gathered on realistic core compositions.

### Derya Gürer: Where oceans start to sink

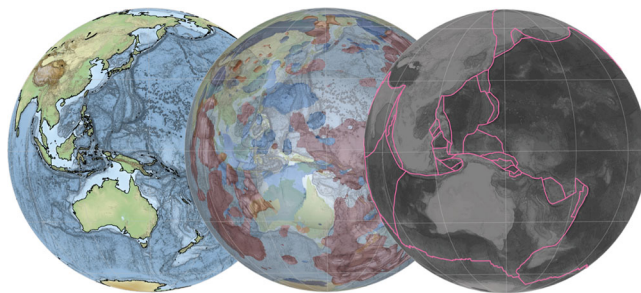
Earth is the only planet that we know of with active plate tectonics, manifested in the motion and deformation of continents and the formation and destruction of ocean basins. The sites at which oceanic lithosphere sinks into the mantle, subduction zones, are considered the primary engine of plate tectonics on Earth. In driving plate tectonics, they enable unique environmental conditions, making Earth the only known habitable planet. At the same time, subduction zones cause some of the most devastating earthquakes, tsunamis, and the majority of volcanic eruptions. Despite numerous advances since the theory of plate tectonics was established, the mechanisms controlling the formation and stability of subduction zones today, and back in deep geologic time, remain enigmatic.

This is because Earth's oceanic lithosphere is continually being recycled through subduction and our constraints on this fundamental process are progressively lost with time. There are many potential explanations for subduction initiation. Subduction zones could initiate from a spontaneous gravitational collapse of the aging oceanic lithosphere; or form due to sudden stress changes in response to the arrival of buoyant features such as continents, oceanic plateaus, or volcanic arcs in trenches. Mantle plumes and regional to global changes in mantle flow have also been suggested as drivers of subduction initiation<sup>1</sup>. The most fundamental result of the last decade of tectonic research is that almost all large onshore exposures of oceanic lithosphere that escaped recycling into the Earth's mantle by subduction—ophiolites—form when subduction zones initiated<sup>2</sup>.

Geologic constraints from these unique sequences of rock reveal that horizontally forced subduction zone initiation, where plates are pushed against each other, has been the dominant mode over the last 100 million years, and that most initiation events are close to previously existing subduction zones<sup>3</sup>. In addition, plate-boundary-wide subduction zone initiation events may be tied in a chain of events to global plate reorganizations<sup>4</sup>. As well as ancient subduction zone plate boundaries, studies are starting to focus on potential locations for young and future subduction initiation events, such as the Puysegur Trench off New Zealand<sup>5</sup>. To advance our understanding of subduction zone initiation, it is crucial to approach this enigma from a multitude of different angles and study modern and ancient examples using a variety of approaches:

geological and geochemical observations, plate reconstructions, seismic tomography, and geodynamic modelling.

There is no unique tectonic setting in which oceans start to sink; however, preferential sites for subduction zone initiation will be regions with weak lithosphere, for example along old plate boundaries, fracture zones, transform faults, failed rifts, and ocean-continent boundaries. The role of structural inheritance, and particularly the higher-resolution study of heterogeneous oceanic plate interiors, represents an exciting avenue for resolving this long-standing question. In this context, the global effort to map the entirety of the seafloor by 2030 may provide the key to unlocking the process of subduction zone initiation.



Credit: Grace Shephard/Fabio Cramer

### João C. Duarte: Plate tectonics goes planetary

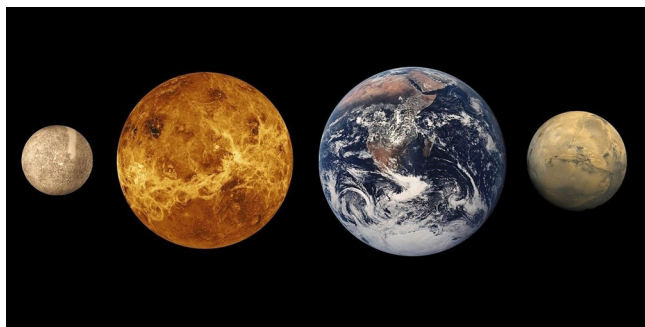
The surface of our planet is divided into coherent plates that move in relation to each other. The continental portions of plates float at the surface, but their oceanic counterparts continuously acquire new material at mid-ocean ridges and are recycled back into the Earth's mantle at subduction zones. Over time, the study of plate tectonics has evolved from investigating how plates move, towards asking why they move, in a concept that unifies mantle convection and plate motion: sinking plates drag the remainder of the plate along and in turn induce mantle convection.

As such, plate tectonics is the surficial expression of a partially top-driven convective system. However, periods of subduction quiescence characterized by large supercontinents may have generated strong mantle upwelling and made bottom-driven convection at least temporarily dominant. If so, then the balance between the driving forces of plate tectonics has changed over time.

High-performance computation now makes it possible to simulate plate tectonics and mantle convection at the scale of the entire planet. And thanks to high-resolution three-dimensional seismic imaging, we can compare these simulations with detailed observations of the Earth's interior structure. This approach has revealed that Earth's mantle is organized into two large upwelling regions, below Africa and below the Pacific, encircled by a girdle of downgoing slabs. However, this might not always have been the case and it is hard to come up with a full understanding of planetary dynamics with only one planet to observe.

This is about to change. We now have rovers, a drone, and even a seismometer on Mars and we will soon send three probes to Venus. What is more, both Mars and Venus may represent different stages on the path of terrestrial planet evolution. Our two neighbours might even have had liquid water in the past. Water is not only a lubricant for plate tectonics but also a prerequisite for life as we know it. Remarkably, life emerged on Earth in the Archean when the planet would have probably looked more like Venus. We now think that Venus may in fact be an

analogue for the Early Earth, distant in time but astronomically right next door.



Credit: Pixabay

Understanding how our neighbours work will be helpful when looking for potentially habitable exoplanets. They will give us a more complete library of what these planets may look like. However, for the time being, we are only on the verge of glimpsing what the composition of exoplanet atmospheres might be. Could we tell something about their internal workings with this information? Maybe, if we do our homework in understanding how geodynamics and atmospheres interact. We may even be able to tell if there is life out there. And that would be the greatest discovery of all time!

#### Mojtaba Fakhraee: History of oxygen and life

The fundamental question of how and why life formed on the early Earth has engaged a wide range of scientific communities, from geologists and biologists to microbiologists and geochemists. From this cross-disciplinary environment, the relatively new field of geobiology has emerged with the aim of understanding how life and the Earth's surface conditions have evolved and influenced one another over the more than 4 billion years of Earth's history. Perhaps the key element of this question is reconstructing the geological history of atmospheric oxygen. Today, most life on Earth depends on molecular oxygen, yet for most of Earth's history, the atmospheric concentration of oxygen has been only a fraction of the 21% it is today<sup>6</sup>. How the evolutionary history of life was shaped by low and variable atmospheric oxygenation remains an active topic of research.

Throughout the second half of the 20th century, it was widely agreed that the first major rise in the atmospheric oxygen level—a time referred to as the Great Oxidation Event—directly paved the road for the evolution of eukaryotic cells. Then, further oxygen increase at the end of the Proterozoic Eon created favourable environmental conditions for the origin and earliest diversification of animals<sup>7</sup>. This idea, however, has been extensively challenged and updated, owing to new findings and advances in techniques used to analyze geological records.

As a notable example, numerous lines of evidence in the last decade suggest that the rise of oxygen-producing cyanobacteria in the ocean—a key biological innovation—likely occurred several hundred million years before the Great Oxidation Event. This casts doubt on the traditional view that invoked a causal link between ocean oxygenation and the evolution of aerobic life in the ocean, and the rise of atmospheric oxygenation and aerobic life on land<sup>8</sup>.

Our ability to understand the relationship between oxygenation of the surface environment and the evolution of life now rests on the development of more mechanistic Earth System models that not only explain and capture modern processes but

can also confidently generate and test hypotheses on the link between the evolution of life and Earth's redox state. This new generation of models must not only rely on the advances made in our understanding of physical processes but, by employing powerful statistical techniques such as machine learning, take full advantage of the rather large dataset built from geological records<sup>9</sup>.

Existing Earth System models are used to study the co-evolution of life and Earth, mainly based on and calibrated to the observations in the well-oxygenated modern oceans. We will need to build models that focus on and capture processes in anoxic environments, more representative of the early Earth. This approach can further help us in understanding and predicting the impact that climate-

change-driven ocean deoxygenation can have on the habitability of our planet.



Credit: Bernd Hildebrandt/Pixabay

#### Ola Kwiecien: Past continental temperatures, quantified

Think about this summer. Does it feel warm or hot? Hotter than the last year? Or than the summers of your childhood? When we look back at the last 170 years we can compare modern temperatures with instrumental records, but this is not possible for the geological past. At a global scale and at low resolution, we can estimate temperatures quantitatively, in physical units of °C, since the start of the Phanerozoic. However, the reliability of future climate projections strongly depends on the availability of regional and local input data. At the regional scale, we have ways to estimate whether it was relatively colder or warmer, but an accurate reconstruction of absolute continental temperatures is still elusive. The stable oxygen isotope composition ( $\delta^{18}\text{O}$ ) of carbonates has the potential to record absolute temperature yet there is a snag: it is a function of not only temperature but also the  $\delta^{18}\text{O}$  of the formation water. The requirement to assume an isotopic value of formation water compromises the accuracy of the method, and renders reconstructions of temperature ambiguous.

Carbonate-clumped isotope ( $\Delta_{47}$ ) thermometry now appears to be turning the tables on continental carbonates as palaeothermometers. This powerful geochemical tool considers not only the isotopic ratio of a single element but the bonding (or clumping) between particular carbon and oxygen isotopes in a ( $\text{CO}_2$ ) molecule. The clumping is dependent on temperature, but not on the  $\delta^{18}\text{O}$  of formation water. The clumped isotope system is sensitive to kinetic fractionation, for example by evaporation or  $\text{CO}_2$  degassing, hence this method has most successfully been applied to subaqueous carbonates. However, analyses of pedogenic carbonates, tufas, and terrestrial gastropod shells have

provided promising and reliable absolute estimates of continental temperatures. At the same time, the international clumped isotope community presented a holistic framework to address discrepancies between laboratories, in an enormous effort towards robust standardization of clumped isotope measurements. We can now move on to extend the scope of carbonate archives and reduce the sample size while maintaining the precision of measurements.

The prospect of mapping past regional temperature variations in time and space across the continents is an exciting one, as is the possibility, pending the choice of adequate material, that we might be able to estimate absolute seasonal temperature variations. Knowing the absolute temperature has another added value; researchers have spent frustrating years trying and often failing to disentangle the combined effects of temperature, precipitation and evaporation rates, and isotopic composition of lake water on the  $\delta^{18}\text{O}$  value of lacustrine carbonates. By substituting for one unknown in the equation, and through combination with traditional proxies, carbonate clumped isotope thermometry offers help in understanding continental hydroclimate changes.

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