



Inaugural lecture

How to read a rock:
*The Science (and art)
of Petrology*

Paul Mason



Utrecht University

How to read a rock: The Science (and art) of Petrology

Inaugural lecture, delivered upon acceptance of the Chair in Petrology,

at Faculty of Geosciences of Utrecht University, on Wednesday, 28 March 2018

by Paul Mason

COLOPHON

ISBN

978 90 6266 502 0

Published by

Utrecht University, 2018

Graphic design

C&M (9408) – Faculty of Geosciences – Utrecht University

Cover

Banded Iron Formation in the Barberton Greenstone Belt, South Africa – Paul Mason

Mijnheer de Rector, lieve vrienden en familieleden, geachte collega's en belangstellenden,

Imagine walking into a library in China. All around you, you see books containing a wealth of information, a whole world of fact and fiction. For most of us, who don't have the gift of knowledge of the Chinese language, it is meaningless. All you can see are the coloured spines of the books. The intricate design of the bookcases and the architecture of the building. The experience is serene. You enjoy the silence of the library and feel the weight of the knowledge that surrounds you. The content of the books is accessible only to those who are trained in the language that you do not know.

If you haven't (yet) been trained in geology, you will most likely have a similar experience when you stand on an outcrop of rock. If you look closely, you might see some dull and some bright colours. There are lines in the rock and you can see it has some sort of structure. In many ways it is a beautiful object to observe, and looking at it might give you the chance to congratulate yourself on your sharp observational skills. But beyond that, the context of the rock outcrop is likely to be way more important to you than the object itself. It might be a beautiful hillside, a view or a beach that engages your attention. And rightly so, since the Earth is a beautiful and intriguing place. But the rock itself has a story to tell, about timescales that are difficult for many of us to comprehend.

Geology takes us from the present day, back in time towards when the Earth formed approximately 4.5 billion years ago (Figure 1). The Netherlands is very young, geologically speaking, and we must go further afield towards the centre of old continents such as Africa, Australia and North America to find the oldest remnants. Many of the rocks we can find there were not only formed a long time ago, but have survived over long periods of time, recording changes in the Earth's crust and surface environment along the way. Let's consider a rock that spends most of its time sitting on the windowsill of my office at Utrecht University (Figure 2). Almost as old as the planet itself, it was made when the diversity of life as we know it was absent, when the atmosphere was impossible for you to breathe, the Moon was much bigger in the sky and meteorite impacts scarred the surface of the small landmasses that poked out from the apparently lifeless oceans. The rock was then buried deep in the Earth, preserved in a fluid a bit like silica gel and then cooked tens of kilometers beneath our feet. It sat there for millions of years before emerging in high mountains that then crumbled in rainwater and washed away in rivers to leave us with this strange looking rock found on the desert floor. It looks now much like a roof tile (*dakpan*) from a Dutch house, but it is actually a small piece of one of the oldest suggested 'fossils' on Earth. This is all that remains of a colony of bacteria that would have been the most

advanced life form on our planet, and possibly in the universe, at that time! How can we deduce such extravagant claims? And why does it matter?

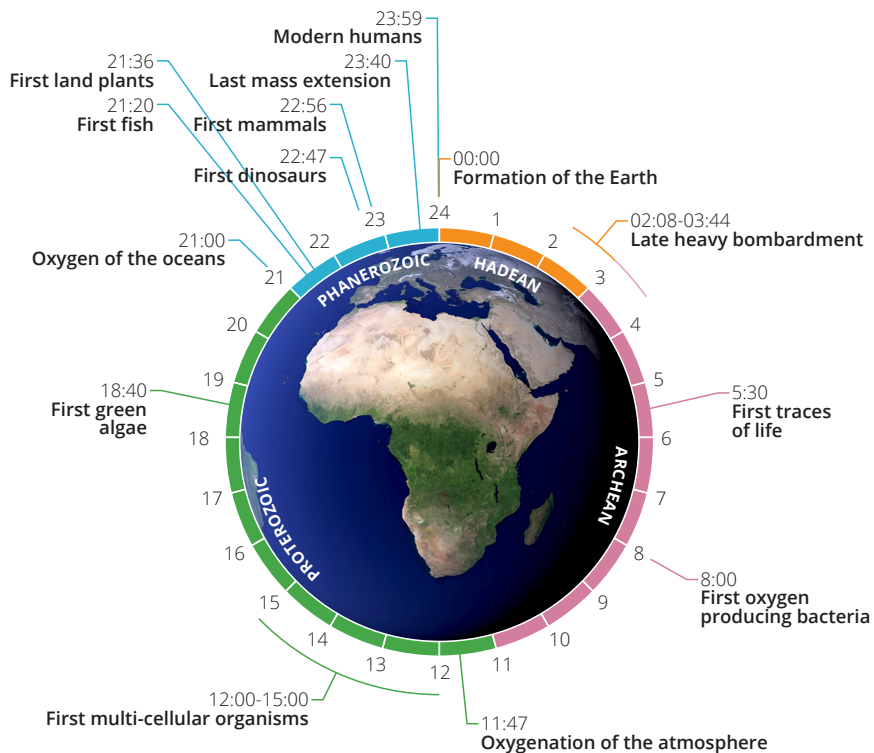


Figure 1. The geological timescale represented as a 24-hour clock face. The four major Eons that make up the geological timescale, Hadean (orange), Archean (red), Proterozoic (green) and Phanerozoic (blue) are shown around the outside. Major geological and biological events are indicated with dates converted into approximate times on the clock. Human beings have been on Earth for only the last second in this analogy. Life could technically have existed from as soon as the Earth cooled in the Hadean, but the first convincing traces have only been found so far in the early Archean at around 05.30 am. The timescales for biological evolution on Earth remain uncertain but were clearly vast. Photo: ©NASA.

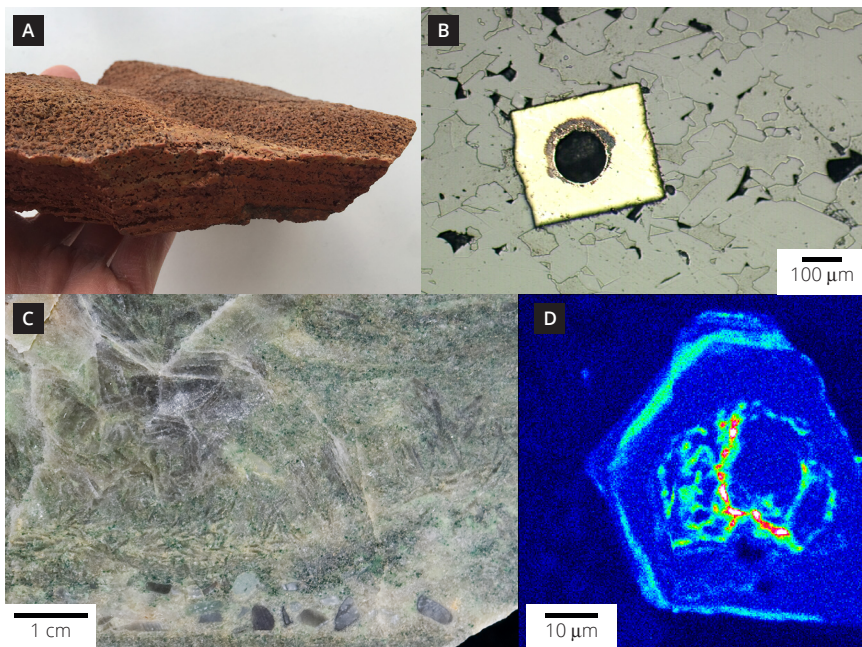


Figure 2. Examples of rocks and minerals, on a variety of scales, which are critical for the study of the Earth's earliest biosphere. (A) A piece of an early Archean Stromatolite rock from the Pilbara region of northwestern Australia. This rock, that might be mistaken for a roof tile is thought to be part of one of the Earth's oldest fossil bacterial colonies from almost 3.5 billion years ago. (B) A crystal of pyrite in an ancient Archean sedimentary rock that has been sampled for stable isotope analysis with a laser in our lab to produce a circular crater. (C) A cross-section through a piece of barite rock from the 3.2 billion year old Barberton Greenstone Belt in South Africa. The needles of barite capture sulfate from the Earth's early oceans. This sulfate has isotope ratios that suggest it was processed by early microorganisms that lived in seawater. (D) A chemical map for the element nickel in a pyrite crystal. The concentric lines show different growth stages, analogous to tree rings. Advanced laboratory measurement techniques can be used to determine tiny variations in each 'ring' showing how the environment changed as the crystal grew.

I have invited you today to this lecture, many of you who don't work in geology, the Earth Sciences or science at all, to share with you the way in which we can read rocks.

As you can already appreciate, rocks provide information about *deep* time. They are our window into the past, right back to the Hadean Eon (named after the Greek god of the underworld, *Hades*, Figure 1). The science of geology provides a framework of knowledge about how planets can evolve and yield complex life over timescales of billions of years. The essence of geology is its chronological perspective, information that is not provided by the companion sciences of physics, chemistry and biology that many of you are more familiar with.

I want to share with you how we can solve big and exciting problems using what we call the *rock record*. I will explain what it is we do as geologists, how it works and why it is important. We will look at some important scientific questions that are perplexing us at the current time and I will make predictions about where the field of research will go in the next ten to twenty years. I have given examples of work done by some of the recent PhD students and postdocs that have completed their work in our research group. Our current group of PhDs is busy taking this further right now as I speak. Much of the work we do is called ‘fundamental’ or ‘basic’ science, in that we pursue the gain of knowledge through pure curiosity, in order to further knowledge itself. I want to give you my own personal perspective on why it is important to do this and how it is useful for society. I will also share with you my thoughts about being a scientist in 2018 at a leading international, publicly funded university.

What is Petrology?

Petrology is defined in the Oxford English Dictionary as ‘*The branch of geology concerned with the origin, structure, and composition of rocks*’. It is not, as the name suggests, related to petroleum, both words having similar derivations from ancient Greek. Many students who have studied earth science degrees associate the term with high temperature igneous or metamorphic processes such as melting and crystallization. Although strictly correct, petrology is much broader than this. The reopening of the chair in petrology at Utrecht University represents a modern interpretation of the subject that encompasses the study of rocks of all flavors from igneous to metamorphic and sedimentary in nature. Petrology is at the core of the discipline of geology, providing information not only about the rock itself, but also about the environment where it formed. The environment in question could be the ocean floor, a soil crust in contact with the atmosphere or a magma chamber beneath an erupting volcano.

In my position I will be the sixth regular professor to have been appointed in petrology by Utrecht University, since the end of the nineteenth century. Geology, as an academic study, started in the Netherlands in Delft. It soon spread to other universities and in 1879 the first professor who took petrology (amongst other things) under his wing was Arthur Wichmann. Petrology has remained as a key subject area for earth science students until the present day. Clearly a geologist needs to be able to identify and interpret the components that make up a rock. Analysis is done on a variety of scales, from what you see in front of you, through the microscopic scale and down to the level of the individual atom. Rocks, and the minerals they are made of, can be seen as ‘time capsules’ that preserve information from the past, which we now interrogate today. This provides us with a framework within which the Earth’s evolving tectonic plates, biosphere and climate can be interpreted. It also provides a baseline of information from which we can study other planetary bodies within our solar system and beyond. While petrology is often seen as an empirical and observational science, it is also directly linked to the principles of thermodynamics and quantum mechanics. We thus can use our knowledge from physics and chemistry to design experiments, run numerical simulations and interpret the information stored in rocks.

What information is stored in a rock?

In the first year of the earth science degree at Utrecht University, students learn how to identify minerals and rocks. We explain to them that this is not only essential if you want to call yourself an earth scientist, but is also a useful life skill. In the future, when they become an *Oma* or an *Opa*, they will be able to impress their grandchildren by explaining to them what the pebbles are that they found on the beach. This is great fun to do, but the study of earth materials goes much further than simply identifying what they are. The exciting part is to know about their origin and history.

The first thing to look for in a solid material is its physical and morphological form (Figure 2). Rocks are made up from minerals that crystallize under specific conditions such as temperature, pressure and bulk chemical composition. Their textures, grain size and crystal shapes reflect the forces that acted on their environment both during and after formation. Many of the components in a rock exist in *disequilibrium*. This is important because it means that they didn’t fully react with one another in chemical reactions over geological timescales. This would have obliterated a lot of the information that was captured into the rock and it is this complexity that we want to study as earth scientists. Let’s use some analogies from everyday life to explore this further. When you bake a cake

you add lots of different ingredients and many of these are impossible to identify once the cake comes out of the oven. The best cakes often have secret recipes that are handed down in families from generation to generation. The reactions that happen as the cake cooks, bring the ingredients to a new equilibrium that hides the secret recipe, keeping it safe from those who want to copy it. We don't want this to happen in a rock. Different parts of the rock might record different processes that it experienced at different times. For example, think about an organism that lives in the ocean. When it dies it sinks to the ocean floor and it will start to rot. If it reaches equilibrium with the oxygen-rich bottom water it will completely react away to make carbon dioxide and will be lost. If it remains in disequilibrium with its surroundings, the material it is made of might be later preserved in a rock. The carbon and the other molecules or atoms it contains could be used to tell us something about the chemistry of the original ocean.

Rocks thus contain different types of chemical information, recorded in the components that don't reach full equilibrium. The first of these is what we call 'major elements' that are the main constituents at a percentage level concentrations. Major elements are the building blocks that give the material its characteristic properties and might be written in a chemical formula to represent the bulk system. For example kitchen salt is NaCl, whilst dunite rock made of olivine in the deep mantle is $(\text{Mg,Fe})_2\text{SiO}_4$. Trace elements on the other hand are present at very low levels and are often incorporated by chance into a material. They are most easily thought of as small amounts of contaminants that (usually) don't have much of an effect on how the solid behaves. Their presence or absence can be used as a type of 'fingerprint' for the material. Each crystal will have a distinctive trace element pattern and this will tell us something about its origin, the pressure and temperature under which it formed, and even what happened after the rock formed while it was sitting at depth in the Earth's crust.

Many major and trace elements have different isotopes, which have the same chemistry, but different mass. Some of these isotopes are radioactive and may decay in abundance over geological timescales, whilst others are radiogenic and form within the rock or mineral. These changes form the fundamental basis of the science of geochronology for dating rocks. Most isotopes are stable however and are only affected to minuscule amounts by chemical and/or biological reactions. It is this last category of information in rocks that has revolutionized the field of geochemistry over the last 50 years.

When we study a rock, we can look at the whole rock in one go, a so-called 'bulk rock' analysis. Or we can look at chemical variability within individual components such as minerals, reworked fragments of other rocks or even organic matter. At Utrecht University

several of our research groups have been pioneers in microanalysis in recent decades. I was initially hired to come to Utrecht in 1997 to set up the laser ablation inductively coupled plasma mass spectrometry laboratory (LA-ICP-MS). Although this is a bit of a mouthful to say, it is a rather simple and elegant technique. We use a laser to vaporize small portions of minerals on a microscopic scale in order to measure their trace element composition, a field where science and *Star Wars* meet.

Scientific problem solving

Scientific research is a problem-driven endeavour. In everything we do at the university we take carefully chosen problems, and then carry out actions to get to a result (the so-called PAR method). When I was first hired onto the permanent staff in Utrecht in 2002, my boss at the time, and the previous professor of petrology, Bernard de Jong, brought my attention to a quote that has resonated ever since:

The secret of science is to ask the right question, and it is the choice of problem more than anything else that marks the man of genius in the scientific world

Henry Tizard, 1885–1959

There are many problems remaining to be solved in our society that require urgent attention. Many of these have direct benefit to you and I, such as curing disease, finding better and more sustainable sources of energy, water, raw materials and food. Other critical problem areas such as climate change or biological evolution are equally (or depending on your point of view, more or less) important. Arguably without exception these are complex and seemingly intractable issues. Many of the key problems in these areas cannot be solved by an individual alone. Science is a team effort, transcending disciplines as well as national boundaries. At the same time we are encouraged as individual academics to find our own niche, and one that hopefully has the potential for big impact. So with Henry Tizard in mind, I started to look in the mid-2000s for a new scientific problem to work on. This needed to be sufficiently exciting, but also solvable by the PAR method, and preferably within the timescale of an individual research project.

Tackling most of the big problems in science is like trying to make a jigsaw puzzle where each research team only gets to work on one or two pieces. Only when we put these together can we begin to address the overall issue on a level understandable to wider society. Imagine that the jigsaw in question is one of a small lighthouse on a rock in the middle of the ocean. Most of the jigsaw is made of frustrating featureless pieces of blue

sky or blue sea whilst the easily identified lighthouse is a tiny proportion of the whole. However, only with the sea and sky in place does the true significance and context of the lighthouse become clear. You don't stop making the puzzle with only the lighthouse complete! Science works in a similar way. The lighthouse will be the highlight of solving the problem. This represents the publications in *Nature* or *Science*, or if you are lucky enough a Nobel prize (only ever once awarded to anyone close to being an earth scientist, William Bragg in 1915). Most scientists get to work on the more mundane, but essential parts of the story, the sea and the sky in our analogy. These are equally important, but less well-recognized to the outside world. Without the larger number of context studies, repeat experiments and testing of assumptions, methods and reasoning, science would lose its strength and validity and may even lead to potentially damaging false leads.

Back in the world of petrology, what are the big problems remaining to be tackled that I was puzzling with back in 2005? For most of the late twentieth century, petrologists were busy contributing to the development of the concept of plate tectonics. This is the central paradigm around which the earth sciences have developed since the 1960s. I was one of the many people who did their PhD research attached to this particular 'jigsaw puzzle' problem, my own work concerning the subduction of one plate beneath another, between 1 and 15 million years ago, in the area that is now present-day Transylvania in Eastern Europe. This involved figuring out how much melting occurred deep in the mantle, how melts migrated through the crust, and how rapidly they could build chains of volcanoes at the surface. This work continues today and remains important in continuing discussions about how plate tectonics has configured our continents through time. It also provides useful information for other scientists who try to predict future volcanic activity and how it might impact society.

Around the turn of the millennium I was involved in the development of the ICP-MS technique together with a team of colleagues in analytical chemistry departments from around the world (e.g. Mason et al., 1999; 2006). With these developments we helped to open a new research field, and measure for the first time stable isotopes of elements from the periodic table that previous generations of scientists could only dream about. This was a useful starting point for me when thinking about Henry Tizard. The elements I chose to focus on have been sulfur (spelt with US English, to keep my American colleagues happy!), selenium and iron. Each of these elements has a critical role in metabolism, the chemistry of life. Over the last ten years or so, and thanks to the encouragement of Bernard, I changed research directions to study when life began in deep time and how it has been influencing the planet, as well as being influenced itself by how the planet has developed. This is where geology meets microbiology and involves novel ways to read rocks.

Petrologists in the search for the earliest life on Earth

The Earth is currently the only place in the universe where we know that life exists. Both Mars and the Earth lie in the habitable zone of our solar system, Venus just beyond the inner edge of an optimistic interpretation of this zone. After broadly pondering why this might be, several scientific questions immediately jump to mind. What is the extent of life in the solar system, either today or in the past? How long have we had life on Earth? How quickly after the formation of our planet did life first appear? How long has it taken to evolve? And why has it taken such a long time to evolve self-conscious human beings that can ponder these questions for the first time? These are all questions where we could use some petrology, as part of a multidisciplinary attack.

When looking for the oldest life forms on Earth, we should use the extensive work of our colleagues in biology as a guide for what to look for. If we follow this reasoning we can use the ribosomal RNA phylogenetic tree of life to reach two important conclusions: (1) all life is linked back to the same initial starting point, called the last universal common ancestor; and (2) the earliest organisms were most likely to have been single-celled prokaryotes, similar to modern bacteria. The most obvious feature to look for when looking for life in a rock would be a fossil. If you show a fossil to someone else they are most easily convinced that it was made by an organism that lived at some point before the rock was deposited. Unfortunately, bacteria are microscopic organisms that do not easily leave behind solid traces in their environment after they have died. Sometimes spherical and rod-like structures are preserved in rocks and could be microfossil bacteria. Bacteria can also make biofilms across the surface of sediments that might be recorded as laminations in rocks. These have been proposed by geobiologists and are called 'stromatolites'. Stromatolite-like structures are found all the way back through the geological record, and have been used, somewhat controversially, to argue for life as long as 3.8 billion years ago. Before we get too excited about this it's worth pointing out that abiological processes, such as the escape of water from sediments or accumulation of mineral grains in layers in rivers, can also lead to features that look like microfossils or stromatolites. Thus this evidence doesn't stand alone, and represents only one piece in our finding life jigsaw puzzle. Each of these pieces can be called a *biosignature*, a physical or chemical feature that was produced by life.

Another approach is to look at the organic matter that is preserved in rocks. Many ancient sedimentary rocks are black in colour due to a relatively high content of reduced organic carbon. These are thought to represent the remains of dead organisms that were preserved in the rock. There are many distinctive molecules in organic chemistry that, as far as we

know, can only be produced by biological processes. Teams of scientists have looked for these in ancient rocks. Present-day contamination must be avoided when you collect your samples to avoid false positive results. International research teams have taken much care and effort to avoid this problem. Unfortunately there are further complications due to the metamorphism of organic matter in many of the places where we want to look for early life. A good way to think about the metamorphism problem is to consider what happens to organic matter when you bury it into a rock. All of the rocks older than about 2.7 billion years old that we know of today have been metamorphosed to some degree. This is logical since they were buried in the crust for extended periods of time where they experience elevated temperature and pressure. This typically results what we call 'greenschist facies' metamorphism (identified from the petrology of the rock by the minerals that grow in during temperature and pressure increases), that indicates temperatures in excess of 300°C. Imagine putting a chicken in the oven and leaving it there at 300°C for tens of thousands of years (typical metamorphic timescales). What would be left over at the end? This would look something like the black gunk that I find on the inside of my oven at home, a material called kerogen, that is difficult to study and does not directly indicate that life was the source of the carbon (I have to thank my colleague Roger Buick at the University of Washington for this analogy!).

We thus need another approach to tell us that life was present in the environment when a rock was formed. A method that has received a lot of attention in recent years is to look at stable isotope ratios that are influenced by biological processes (Figure 3). These are often preserved into minerals that crystallize at the time that the rock forms, and then can remain unchanged for up to billions of years, even during metamorphism. The sulfur isotope system is a good example of a stable isotope system that can be used as a biosignature. Sulfur has four stable isotopes: ^{32}S , ^{33}S , ^{34}S and ^{36}S . Many bacteria living in the modern seafloor use the compound sulfate (SO_4^{2-}) to respire. Just as we breathe with oxygen, and use that to burn organic matter (CH_2O) to make water vapor and CO_2 , bacteria can react sulfate with organics to make hydrogen sulfide (HS^-) and bicarbonate (HCO_3^-). They gain energy from this respiration process that they then use to grow. During respiration the sulfate reacts in a redox reaction and gains electrons from the organic matter, which you can think of as the 'food' consumed by the bacteria. The sulfur atoms in the reactants and products of this reaction will end up with different amounts of the lighter ^{32}S and heavier ^{34}S (and ^{33}S and ^{36}S) isotopes (Figure 3). The changing distribution of the isotopes is called 'fractionation'. One way to think about it is that (just like you and I) bacteria are 'lazy' and will use the least amount of energy possible to break down the sulfate molecules that they are breathing. It is faster to break the $^{32}\text{S}^{16}\text{O}$ bond than it is for $^{34}\text{S}^{16}\text{O}$, so the isotopes become fractionated from one another. Hydrogen

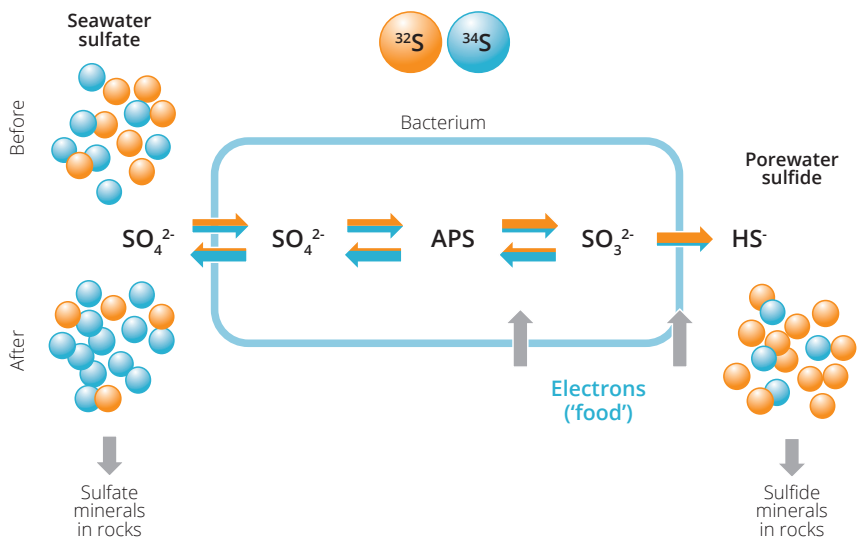


Figure 3. A diagram to show how bacteria can respire with sulfate (SO_4^{2-}) and exhale sulfide (HS^-). This process happens in a number of steps going through the molecules Adenosene 5'-phosphosulfate (APS) and sulfite (SO_3^{2-}). As this happens the ratio of the two main sulfur stable isotopes, ^{32}S and ^{34}S changes, called 'isotope fractionation'. This is represented by the orange and blue balls on the figure, and the amount of flow at each step is represented by the thickness of the coloured arrows. The sulfate and sulfide that are produced by this process can be captured into minerals that crystallize into rocks, enabling us to trace this process in deep time.

sulfide produced by this process contains more of the ^{32}S compared to ^{34}S and can be rapidly scavenged by soluble iron (Fe^{2+}) in seafloor sediments to make the mineral pyrite (FeS_2). This can then be buried into rocks along with some of the sulfate into the minerals gypsum (CaSO_4) and barite (BaSO_4). With PhD student Marjolijn Stam we crawled in the mud in the Western Scheldt estuary here in the Netherlands to sample modern sulfate reducing bacteria for our lab experiments (Stam et al., 2011). Marjolijn investigated how the amount of isotope fractionation ($^{32}\text{S}/^{34}\text{S}$) could be linked to parameters in the environment such as temperature and organic matter availability. After cutting our teeth in the freezing February rain in Zeeland, we also went to sample sediments in the saline lakes of California and volcanic vents of Vulcano island in Italy (Stam et al., 2010). These are

what we call analogue environments for where the Earth's first colonies of microorganisms might have been found. Marjolijn found that isotope fractionation could be a very useful and distinctive biosignature in all of the environments that she studied.

The next step of our work was to look at stable isotope ratios in barite and pyrite minerals that have survived unchanged in ancient rocks. If what we found was similar to the lab observations with sulfate reducing bacteria, then we could argue that these organisms were present in the ancient oceans. We focused on sulfur-rich sedimentary rocks from the 3.5 to 3.2 billion year old Barberton Greenstone Belt in South Africa after being introduced to the area under the expert guidance of Wout Nijman from Utrecht and Thomas Reimer from Wiesbaden. Desiree Roerdink started her PhD with us in Utrecht and one of her most exciting results was to show that microorganisms left a signature behind in the stable isotope ratio of seawater that was then captured in rocks that formed across the globe. We see this in rocks from Australia, India and South Africa (Roerdink et al., 2012; 2013; Montinaro et al., 2015). This work was followed up very nicely by Aleksandra Galić in her PhD which revealed that in the deep ocean floor these organisms were of a completely different type, processing elemental sulfur in the place of sulfate (Galić et al., 2017). We showed that the early microbial biosphere was not only present but rather diverse, very early on in geological history. Life evolved remarkably fast after the Earth had become habitable from its initially inhospitable and meteorite bombarded state!

The sulfur isotope method is unfortunately not infallible as isotope fractionation can also happen when we heat geological fluids to high temperature ($>200^{\circ}\text{C}$), forming apparently identical minerals to those made with the help of bacteria (e.g. Roerdink et al., 2016). The chemistry to consume sulfate that microorganisms perform at low temperature ($<120^{\circ}\text{C}$) can also happen in different ways and with similar or different reactants and products in a hydrothermal (means literally *heat and water* are present) or metamorphic environment. Thus using isotopes is another example of a potentially inconclusive story as we need independent evidence from our rock that the minerals that we use for the biosignature work were formed at and remained at low temperature throughout the history of the rock. In my opinion, and that of many of my colleagues, there is currently no such thing as a *smoking gun* biomarker that gives stand-alone convincing evidence for the appearance of life in the rock record. This is an area where future research needs to be concentrated. One of the key environments where early life may have begun were seafloor hydrothermal vents, similar to those we find today at the Mid-Atlantic Ridge or the East Pacific Rise. These are places where we will need to develop robust biosignatures, which work when the environment approaches the boiling point of water where many bacteria are able to thrive!

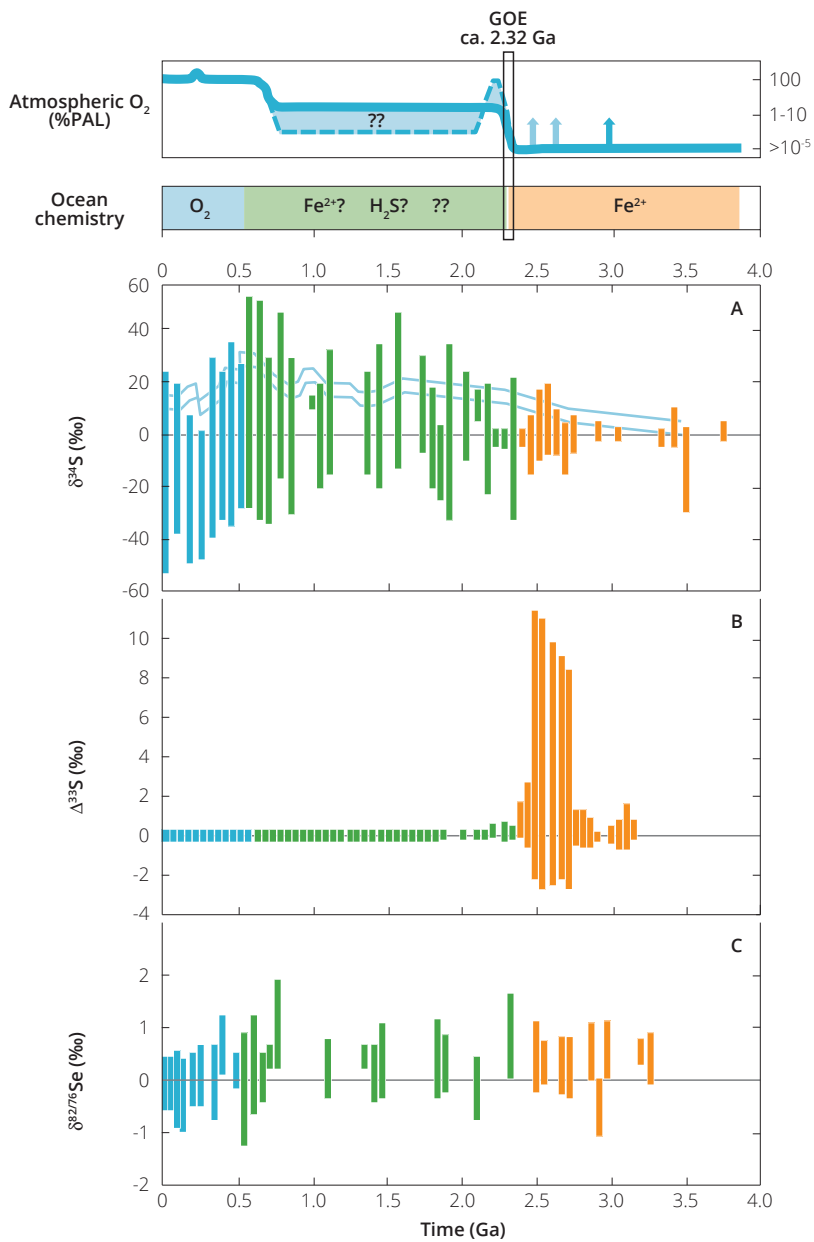
It is important to say a quick word here about how we obtain our samples. If you go to any of the places on earth today where we have old rocks, such as the Australian outback, Southern Africa, Greenland and northern Canada, you will find that you encounter a largely flat, or heavily-weathered topography. Many of the rocks here have been degraded by interaction with oxygen-rich surface waters and the atmosphere. These are typically not suitable for the type of geochemical and isotopic analysis that gives us reliable biosignatures. To get around this problem we can drill, down to hundreds of meters or kilometers beneath our feet. Large multi-partner international projects have resulted where teams of scientists have come together to pool resources, ideas and methodologies. From Utrecht, we have been involved in, and helped to lead, scientific drilling projects in the Barberton Greenstone Belt and in the Asbestos Hills in South Africa. This has brought its own technological and organizational challenges but also very rewarding spin-offs. The work of our international team in Barberton, has, for example helped to put the town on the map as a UNESCO world heritage site and a tourist destination.

The search for more reliable biosignatures to date the appearance of life on Earth has brought us to look at other elements from the periodic table. We have targeted those that have multiple stable isotopes, a metabolic function and are preserved in different oxidation states into different minerals. One of these elements that we started working on in Utrecht with great enthusiasm around ten years ago is selenium. Selenium sits below sulfur in the same column of the periodic table and they thus share some chemical similarities. Selenium is a micronutrient, meaning that it typically occurs as a trace element (it is rare at the Earth's surface) and it is required for the biochemistry of your cells to function correctly. Many people take Se as a supplement to prevent deficiency as it is scarce in many continental areas across the world. However in some areas, such as the Punjab in India where it is was studied by postdoc Kathrin Schilling in our group, it can also cause serious health problems due to its toxicity (Schilling et al., 2015; 2016). Selenium has the narrowest range of any element in the periodic table between being essential and toxic for human beings.

Just like S, Se has multiple isotopes that are fractionated when selenate is reduced to more reduced forms, in this case selenite and elemental selenium. In our research group we carried out a similar approach to what we had done with S isotopes, with lab experiments compared against measurements made on rocks and soils that we collected in the field. Our work was amongst the first produced anywhere in the world on this isotope system. It was not easy to do and we would not have been successful had it not been for Tom Johnson and his team from the University of Illinois at Urbana Champaign coming to the rescue.

We made a very useful and novel discovery with our work on Se. Unlike S isotopes, which predominantly record the respiration and hence presence of bacteria, Se isotopes more strongly record the uptake of the element as a nutrient into organic matter. Microorganisms need Se just like we do and they suck it up in the oceans and store it in their cell membranes where it is processed into more useful molecules. When organisms die, the Se gets recycled through the food chain and remains associated with organic matter. Our PhD student Kristen Mitchell looked at rocks from across the geological record from the 3.5 billion year old oceans to the present day (Mitchell et al., 2012; 2016). One area of focus was to look at ocean anoxic events (OAEs). These are periods of time when large parts of the ocean became oxygen-free leading to death of many species and the mass deposition of organic-rich mud (what often goes to make oil source rocks). What we found in Kristen's project is that the isotopes of Se appear to have been processed into organic matter in a similar way all the way through the geological record. It is another piece of evidence that helps us to argue that life is ancient. There are small changes in the way this happened close to two key dates: 2.4 billion years ago and 600 million years ago. This brings us to the next big problem that we have been able to attack as a scientific community by reading the rock record, the change in the composition of the atmosphere and oceans through time.

Figure 4. (see right page) A diagram to show how the concentration of oxygen has changed in the atmosphere, along with the chemistry of the oceans throughout geological time from the Phanerozoic (Blue box and bars), through the Proterozoic (Green box and bars), back to the Archean (Red box and bars) (after Lyons et al., 2014). We do not have any data for the Hadean, since rocks from that time are not well-enough preserved today. Panel (a) shows the stable sulfur isotope record (after Canfield, 2005). The bars represent the range in $^{34}\text{S}/^{32}\text{S}$ measured in sulfide minerals in sedimentary rocks. The two blue parallel lines on this figure show how the same isotope ratio varies in sulfate minerals. The difference between the two shows how bacteria have controlled the variability we see in the rocks through all of the Phanerozoic and Proterozoic and in some places in the Archean. Panel (b) shows the mass independent sulfur isotope record measured in both sulfide and sulfate minerals through time (represented as $\Delta^{33}\text{S}$, data compilation from James Farquhar). The big change at 2.32 Ga shows how this ratio recorded the oxygenation of the atmosphere at that time. Panel (c) shows how selenium isotopes ($\delta^{82}/^{76}\text{Se}$) in samples of bulk sedimentary rocks remained relatively constant throughout the Archean and Proterozoic with a slightly reduced range in the younger Phanerozoic samples. This records the oxygenation of the oceans for the first time around 600 million years ago. Data are from Mitchell et al. (2016).



Oxygenation of the Earth: how do biology and geology interact?

All of us are sitting in this room breathing oxygen. We need to respire oxygen to support the large energy needs of our metabolisms and to help our brains ponder the nature of the world around us. It might surprise you to know that our atmosphere has not always been oxygen-rich. For most of the first half of the lifetime of our planet the atmosphere was oxygen-depleted (Figure 4, see previous page) and consisted of N_2 and CO_2 along with reducing gases such as H_2 and CH_4 . It is not an automatic consequence that when an earth-like planet forms it will have an O_2 rich atmosphere and detecting the presence of O_2 in the atmospheres of distant exoplanets will thus be a major target in the hunt for possible life elsewhere in the universe in the near future (more on that later). The availability of oxygen through geological time may have been a key issue in driving biological evolution, possibly leading to the first multi-cellular organisms that appeared in the Neoproterozoic eon as well as the Cambrian explosion of life (Figure 1).

So how can we reach such a major conclusion about the evolution of our atmosphere and oceans through time? Again, petrological and geochemical data from the rock record are critical pieces of evidence. Geologists have known for many decades that some of the oldest rocks on the planet (dated using the radioactive decay of U to form Pb in the mineral zircon) are unusual in their composition. Rocks rich in Fe called banded iron formations (BIF) are found in the Archean and Paleoproterozoic eons with a peak of abundance in the period 2.7 to 2.4 billion years ago. These were deposited simultaneously over vast distances of hundreds of kilometers on the ocean floor along with large amounts of silica (SiO_2). The most simple explanation for the large amounts of iron that we see here is that it was present as dissolved Fe^{2+} in the oceans which then reacted with oxygen to form ferrihydrite ($Fe^{3+}_2O_3 \cdot 0.5H_2O$) particles that sank to the ocean floor to make the BIF. This is a similar process to what happens when you leave your bike chained to a railing in the Dutch weather and you see it slowly rust away onto the cobbles beneath. The oceans absorbed oxygen as it was produced on the early Earth so that it didn't have the chance to accumulate in the atmosphere. The Earth rusted on a vast scale! The most likely source of the oxygen was from microorganisms that used sunlight to split water, a process called oxygenic photosynthesis that was also probably the cause of the stromatolite mats that we discussed above.

This is a great hypothesis, but what geologists have puzzled over is the fact that BIF occurs in rocks of many ages and perhaps appears episodically. Its abundance might not only have been related to oxygen production but also iron supply. As with tracing early life, multiple techniques are required to solve the problem and again stable isotopes come to

our rescue. Remember that S has four stable isotopes. We discussed the $^{32}\text{S}/^{34}\text{S}$ ratio above simply because these are the most abundant isotopes of S, ^{32}S being about 94.99% and ^{34}S close to 4.25% of the total S. Deviations around these numbers reflect the changing $^{32}\text{S}/^{34}\text{S}$ ratio. But S also has the rare ^{33}S and ^{36}S isotopes. These were ignored by most geochemists, largely because they were difficult to measure, until around 15 years ago. At that time a startling discovery was made by James Farquhar (now at the University of Maryland, who along with Harald Strauss in Münster and Martin Whitehouse in Stockholm have been key collaborators making this all possible). James discovered that the rare isotopes can be fractionated in a very distinctive way in sulfur-rich volcanic gases in a close to oxygen-free atmosphere (Farquhar et al., 2000). This type of effect is called mass independent fractionation (MIF) and its presence in ancient rocks allows us to date the exact time at which O_2 crossed the threshold of 10^{-5} of the present atmospheric level (i.e. there was less than 0.001% of what we have now!). We see the MIF process happening today during large volcanic eruptions that eject material into the stratosphere, and the MIF signal sometimes finds its way into Antarctic ice cores before it gets lost as it dilutes into the oceans. Back in the oxygen-free Archean world (Figure 1) this effect was much stronger and more persistent than today. The oxygenation of the atmosphere has been dated using the loss of MIF to have occurred 2.32 billion years ago (Figure 4). In our research group, and together with Hari Tsikos at Rhodes University, another good colleague and friend, we have looked in detail at the rocks that accumulated just before this point in time and what happened as the oxygen started to increase. The oceans went through a transition from being Fe to more Mn-rich (Tsikos et al., 2010). Massive deposition of Mn at this time produced the Kalahari manganese field in the Northern Cape province of South Africa, the most important and extensive deposit of this metal worldwide. In a recent partnership with Hari and his colleagues in South Africa, and funded by the mining industry, we have used not only S isotopes to study these rocks but also Fe isotopes that help us to identify how the Fe can be sequestered from seawater into different minerals present in the rock. This formed the backbone of a PhD recently completed in our group by Paul Oonk. A key goal of our work is to determine how oxygen reacted with other chemical components at the Earth's surface once the iron had been used up (once your bike has rusted away you will find evidence somewhere else that something else has reacted with the atmosphere) (Oonk et al., 2017; Lantink et al., 2018). This is of critical importance to determine why the atmosphere could change from its reducing to oxidizing state. Paul has shown in his work how oxygen first reacted with Fe and Mn before a global glaciation event and massive volcanic activity that might have been triggers for the start of the so-called great oxygenation event (GOE). One of the biggest remaining questions is to figure out what tipped the balance and enabled the Earth to make the switch from and oxygen-poor to

an oxygen-rich atmosphere. This cannot happen automatically and would have required a major climate, volcanic or biological event to cross over the threshold.

If we go back to our Se isotope record, and look at Kristen's data, we can see that there was no significant change 2.32 billion years ago at the GOE, but a reduction in isotopic variability in marine shales at around 600 million years ago (Figure 3, Mitchell et al., 2016). This was initially puzzling to us, but then we started to think that this might be better explained by what happens in the oceans rather than the atmosphere. The oceans have not always been in equilibrium with the atmosphere and they became oxygenated much later than the GOE at around the start of the Phanerozoic, 600 Million years ago (Figure 1, Figure 4). If we add more dissolved O₂ to seawater then organic matter will be more rapidly recycled back into biomass and less likely to be buried into sediments on the seafloor. The significance of the 600 million year date is that it occurred just before we start to see the appearance of the fossil record that reflects an explosion of marine life in the Cambrian. Adding dissolved oxygen to the oceans could have been a major driving force in biological evolution. The Se isotope record is a useful extra piece of our jigsaw in attempting to build a picture of changes in both the atmosphere and oceans over time.

We still have a lot to learn about whether global oxygenation has been a cause or a consequence of biological evolution (or whether there is no link at all?). This is a variation on the *nature* versus *nurture* discussion at the centre of human development. Did geology control biology or vice versa? Who was in the driving seat? One of the greatest remaining unknowns is when multi-cellular organisms first appeared in the geological record (Figure 1) and if there was a trigger for this process from the Earth itself. The timescales involved in all of these processes are vast, despite the fact that we know bacteria can evolve very rapidly (think about the recent development of antibiotic resistance).

It has taken close to 4 billion years for life to evolve on Earth, from its beginnings, to what we see around us today. This is approximately a quarter of the lifetime of the universe! There are an estimated 40 to 60 billion Earth-sized exoplanets orbiting in the habitable zone of Sun-like stars in our galaxy alone! If we were to find life elsewhere in our galaxy or the wider universe would it be like us? Would it have developed at the same rate? Or might it be very different because the planet in question evolved in a geologically-different way? Despite the fact that the laws of chemistry and physics are constant throughout the universe, those of geology and biology may have changed significantly. These questions are particularly pertinent at the current time as the scientific community is about to develop new high-power and high-resolution telescopes to investigate the composition of the atmospheres of distant exoplanets. Perhaps one of the greatest scientific discoveries of our

lifetimes will be to find convincing signs of life elsewhere in the universe, a development that could have profound implications for society at large. Validating the evidence for this will rely heavily on what we know about our own planet back through time, from *reading the rocks*.

A case for curiosity-driven research

One of the great privileges of being an academic is to be able to follow your own curiosity and design your own research programs. I have been lucky to be able to do this in the areas I outlined above with financial support from diverse sources. Finding research funding to do this work is challenging and highly competitive. Funding agencies and governments have directed a large proportion of public research money in recent years towards addressing specific problems. These research programs are less curiosity-driven and more powered by the need to address the challenges that currently face our civilization. This strategy is understandable given the enormity of the problems we face, for example in designing a low carbon economy, predicting future climate change, finding sources of clean energy and even expanding our footprint out into other parts of the solar system. However all of these problems are complex jigsaw puzzles (from our analogy above) that still require components from more curiosity-driven parts of the scientific endeavour. In designing techniques for carbon capture we need to have a mechanistic understanding of how materials react at depth in the ground. For predicting future climate change we need to know how the climate reacted in the past and what happened to our planet during extremes. In finding new sources of clean energy we need to assess the sensitivity of global biogeochemical cycles to our current carbon-based economy and how this compares with how these cycles operated back through the geological record. And if we want to put humans on Mars, we should be able to assess the current limits of life on Earth and know more about the extent of life in the solar system. All of these areas benefit directly from curiosity-driven science. In facing the (as yet unknown) challenges of the future we need a strong, healthy and diverse scientific community.

Beyond this there are many reasons for rigorously supporting basic science in our universities where research and teaching are closely interlinked. In terms of the research itself, supporting a curiosity-driven approach leads to breadth in many disciplines. Casting the net wide increases the chance to make novel and unexpected breakthroughs. Important discoveries are often made through unconventional approaches or at the interface between disciplines. Fundamental science is a fertile and rich ground where scientists can sharpen their teeth, develop and hone their skills and polish their techniques. What we might

call 'hardcore' physics and chemistry, biology and geology, with no apparent direct use to society, are essential basics that must be mastered before attempting to address more derivative and applied problems. The job of a scientist is to create knowledge as well as solving problems. The pursuit of knowledge for its own right should continue to be seen as a pillar of an advanced civilization, as it has been since ancient Persian, Greek and Roman times.

In 2016 the Dutch government undertook a unique consultation process with its citizens. This included politicians, policy makers, academics, industry leaders, funding agencies and non-governmental organizations, but perhaps most importantly non-specialists from diverse parts of the general public. The *nationale wetenschaps agenda* (NWA) resulted in a list of the 140 most pressing scientific problems thought to be important in our country at the present time. This list was collated into a more focused set of questions by combining and integrating similar ideas, resulting in a final list of 25 key topics. Of this a very small number were finally chosen to receive funding from the Dutch government. These thus represent some of the most important questions that society wants its academic community to answer.

One of the questions that was chosen to be funded in this process, asks 'how and when did life originate on Earth and what is the extent of life in the universe'? This has resulted in the creation of the *Origins Center*, which is a collaboration between astronomers, planetary scientists, chemists, physicists, mathematicians and earth scientists from across the Netherlands. Our university will play a key role in the new Origins Center and will help our small country to take a leading international role in this field. This exercise is direct evidence of the value that the general public at large can give to basic curiosity driven science. Earth science lies at the heart of many of these grand challenges and it is very encouraging to see that this is valued by the wider community.

Why does society need geologists?

The job of a modern university is to produce research and teach the next generation of students in equal measure. It is my opinion that these two core tasks should be closely integrated by the academic staff, each benefitting from investment of time and energy in the other. Earth sciences is best taught firmly rooted in solid scientific principles, whilst enabling links to cutting edge research areas and maximizing career and training opportunities for the students. Our product, the graduating students, should not only have the capability to be world-class researchers, but also highly qualified individuals who can

use the expertise and insight gained from an earth science education throughout wider society.

Before going further into the benefits of an earth science education, I would like to say something about my own route into this field. I first decided to be a geologist at around the age of 11. I went on a trip to the Peak District in northern England with friends and their parents and, not surprisingly for that part of the world, it poured with rain when we arrived. We went on a short hike through the limestone karst scenery, visited a cave and climbed over a large landslip area on the side of Mam Tor. On returning to the cars at the end of the day the adults went to the pub (this was the early 1980s) and left the children to fend for themselves in the car park. The rain stopped, the sun came out and we sat on a limestone wall looking at the fossils it contained. We then proceeded to smash parts of the wall to pieces to get to the best brachiopods and crinoids, competing with one another to find the best examples. I decided pretty much on that day that I wanted to become a geologist.

I was educated from 1984 to 1989 at Bingley Grammar School in a town in the north of England. The school is old, with roots dating back to 1529 and at the time that I studied there, gave a very traditional type of education (the most famous alumnus of my school was the physicist Fred Hoyle who was responsible with others for the inception of the big bang theory, although nobody every told us when I was a teenager). I'd like to give a short example from my school days of how science shouldn't be taught and how things can potentially go wrong with unintended consequences. In the first year of my O-level education, at the age of 13, we had to learn Newton's laws. We had to be able to recite, in an exam, the definitions word-for-word and any mistake would mean you got zero marks and had to go back and learn it again. I can remember, to this day, the definition for Newton's second law and we were taught it as follows: '*The rate of change of momentum of a body is proportional to the applied force and takes place in the direction in which the force acts*'. This is a written way of stating that force is equal to mass times acceleration ($F = Ma$). I have to confess that I never understood at the time how you could relate the written definition with such a simple equation. It wasn't until I was much older that I worked it out for myself! The physics teacher at my school spent so much time drilling the definitions into us that he didn't bother to explain what it actually meant. We were taught at school that science is black and white, right and wrong. I'm sure many of my classmates were put off by this and struggled to find enjoyment in the subject. No wonder there is mass confusion today about complex issues such as climate change when we were all taught that scientists 'know it all' and we have to think about scientific ideas in binary terms. I hope teaching at British schools today has improved since 1984.

After leaving school I went to Durham University to study a degree in Geology. This was the time that I really came to love the subject and enjoy the pretty much unique experience that it offers students. One key aspect of being a geologist is that we spend a lot of time in the field. This involves standing on the top of rock outcrops discussing ideas. You know you are in a bus containing geologists when everyone looks out of the window at the same time as you pass through a road cutting! There are few sciences where the discussion leaves the classroom and takes place completely immersed within the subject of study. An earth science degree combines the rigor of quantitative science with a perhaps unique way of spatial thinking. This involves not only three dimensions but also the factor of time, the essence of geology.

I came to the Netherlands after finishing my PhD and a postdoc in London in 1997. A key motivation for me to come here was to search for my roots, my *Oma* having been originally born in Friesland. You may wonder why a country such as the Netherlands, which seems to have not much of a geology to speak of, needs to train earth scientists? Why should we couple this to spending valuable taxes on research that is done predominantly in other parts of the world? This was an easy question to answer not so long ago when the oil and gas industry, a big part of our economy, was in its ascendancy. Now that we are embarking on a journey into a low-carbon or even post-carbon world, the need for earth scientists is no less acute. Many of our resources are still obtained from mining or extraction of raw materials from the subsurface. The Netherlands is one of the top international consumer markets for rare earth elements and other so-called strategic metals, which are used in the electronics and high technology industries. A Dutch presence in the international mining community and commodities markets is clearly of strategic importance. We must also not forget a problem we have inherited from our fossil fuel heritage. Induced seismicity in Groningen is now regularly in the news and is likely to continue for decades to come. A future, more sustainable energy policy might involve geothermal energy. These are areas where we need trained earth scientists, those who are capable of dealing with complex, multi-dimensional problems.

A degree in earth sciences teaches students new ways of thinking about, collecting and interpreting data. Geology is a largely empirical science, but can also be model-driven. Students are trained in a unique way of problem solving that equips them with a skill-set highly valued in the labour market. Beyond the potential benefits of training scientists for careers in the applied earth sciences, our university has nurtured many of the top academics that now research and teach in the geosciences all over the world. Graduates of Utrecht University have an excellent name internationally and a high proportion of our students go on to obtain PhDs.

Education and outreach to wider society does not stop with young people. In recent years there have been multiple initiatives to engage with the general public through the media, through publications and events. One particular area where we have been involved in Utrecht is to lead geological excursions to some of the areas in the world where we have been active. Later this year I will lead a trip to South Africa with the organization *Georeizen*, to explore the rocks that hold traces of the earliest life on Earth.

Closing thoughts

Petrology remains in my opinion as relevant (or perhaps more so) to the earth sciences in 2018 as it was since it was first taught here in Utrecht close to 140 years ago. The ability to correctly read the information stored in a rock provides a central framework for interpreting how our planet has evolved through geological time. This can be combined with work from other disciplines to solve some exciting problems that wider society wants us to answer, such as how our planet and life have co-evolved. Beyond that we can contribute towards solving small but critical parts of big problems dealing with the development of the deep or shallow earth, energy, resources, climate and the environment.

The *science of petrology* involves tackling well-defined problems, being a skilled and patient field geologist, analyst or modeler, resulting in strong, well-argued evidence to advance our knowledge of the Earth.

The *art* is to do this within the limited resources that we have available to us, to share our ideas and results as much as we can with our fellow scientists and wider society, and to have fun along the way!

Acknowledgements

There are many people who I would like to thank for helping me in my career so far. I have been lucky to work with some excellent students, PhD students and colleagues. It's hard to remember everyone, so I apologize to those who are not on the list below, but who have been a great source of inspiration, motivation and ideas.

Firstly I would like to thank the funding agencies who have supported my work: the Netherlands Organization of Scientific Research (NWO), the European Science Foundation (ESF), the National Science Foundation in the United States (NSF),

the Natural Environment Research Council in the UK (NERC), stichting dr Schuurmanfonds, Rhodes University, Assmang, BHP Billiton, South 32, IAMGOLD and the international continental scientific drilling program (ICDP).

To the students here today: I am firmly of the opinion that you can reach the levels of the best graduates internationally in the Earth Sciences. Thank you for working hard and sharing your inspiring ideas. Thanks for keeping the more senior staff around you young and enthusiastic. I consider it a great privilege to work with you.

To the PhDs who have worked with me: you are the backbone of our scientific system. Doing a PhD is demanding and comes with high expectations from all sides. Your perseverance and determination has been and is commendable. I have had tremendous fun working with you and learning the highs and lows of being a 'science parent'. Thank you for being here to share this moment with me.

To my colleagues: Utrecht has a very vibrant and productive academic staff. It is hard to keep up with you, let alone try to stand out. Thank you for steering me in new and challenging directions. I have learnt more than I can remember about science, how to be a scientist, how to survive in academia and how to do it with a smile on my face. I am very proud to be a part of your community.

To my international colleagues: You have shown me that being a scientist is much more than the science alone. Our network spans huge national, ethnic and personal diversity. You have shown me how to help build a scientific community that strives to encompass the ideals of a meritocracy. This gives me great optimism about the future. I am very honored that you have travelled to be here today.

To my friends: Thank you for keeping my feet firmly on the ground and making me question what I am doing in my life and in science. Thanks for your encouragement but also for your questions about why we need science in our lives. You keep me sane with your jokes and escapades. Thanks also for encouraging me to stay fit and healthy and not to forget that there is a life outside the university.

Finally to my family: You have always been wonderfully warm and supportive. I love you in ways that are hard to put into words. Just like any family we have not always had it easy. We have survived our mishaps and tragedies and you have shown me how to become a strong person because of it. You have taught me that every second of life is worth living

well. I hope I can pass on to others the attitudes of curiosity, determination, openness and tolerance towards other people that you have taught me.

Ik heb gezegd!

References

The text above is by no means exhaustively referenced, but by means of illustration I have included some key publications, and relevant ones from our group, below:

- Canfield, D.E. 2005. The early history of atmospheric oxygen: Homage to Robert M. Garrels. *Annual Review of Earth and Planetary Sciences*, 33, 1–36.
- Farquhar, J., Bao, H., Thiemens, M. 2000. Atmospheric influence of Earth's earliest sulfur cycle. *Science*, 289, 756–758.
- Galić, A., Mason, P.R.D., Mogollón, J.M., Wolthers, M., Vroon, P.Z., Whitehouse, M.J. 2017. Pyrite in a sulfate-poor Paleoproterozoic basin was derived predominantly from elemental sulfur: Evidence from 3.2 Ga sediments in the Barberton Greenstone Belt, Kaapvaal Craton. *Chemical Geology*, 449, 135–146.
- Lantink, M.L., Onk, P.B.H., Floor, G.H., Tsikos, H., Mason, P.R.D. 2018. Fe isotopes of a 2.4 Ga hematite-rich IF constrain marine redox conditions around the GOE. *Precambrian Research*, 305, 218–235.
- Lyons, T.W., Reinhard, C.T., Planavsky, N.J. 2014. The rise of oxygen in Earth's early ocean and atmosphere. *Nature*, 506, 307–315.
- Mason, P.R.D., Kaspers, K., Van Bergen, M.J. 1999. Determination of sulfur isotope ratios and concentrations in water samples using ICP-MS incorporating hexapole ion optics. *Journal of analytical atomic spectrometry*, 14, 1067–1074.
- Mason, P.R.D., Kosler, J., de Hoog, C.J., Sylvester, P. and Meffan-Main, S. 2006. In-situ determination of sulfur isotopes in sulfur rich materials by laser-ablation multiple-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS). *Journal of Analytical Atomic Spectrometry*, 21, 177–186.
- Mitchell, K., Mason, P.R.D., Van Cappellen, P., Johnson, T.M., Gill, B.C., Owens, J.D., Diaz, J., Ingall, E.D., Reichart, G.-J., Lyons, T.W. 2012. Selenium as paleo-oceanographic proxy: A first assessment. *Geochimica et Cosmochimica Acta*, 89, 302–317.
- Mitchell, K., Mansoor S.Z., Mason, P.R.D., Johnson, T.M., Van Cappellen, P. 2016. Geological evolution of the marine selenium cycle: Insights from the bulk shale $\delta^{82}/^{76}\text{Se}$ record and isotope mass balance modelling. *Earth and Planetary Science Letters*, 441, 178–187.
- Montinaro, A., Strauss, H., Mason, P.R.D., Roerdink, D., Münker, C., Schwarz-Schampera, U., Arndt, N.T., Farquhar, J., Beukes, N.J., Gutzmer, J., Peters, M. 2015. Paleoproterozoic sulfur cycling: Multiple sulfur isotope constraints from the Barberton Greenstone Belt, South Africa. *Precambrian Research*, 267, 311–322.
- Onk, P.B.H., Tsikos, H., Mason, P.R.D., Henkel, S., Staubwasser, M., Fryer, L., Poulton, S.W., Williams, H.M. 2017. Fraction-specific controls on the trace element distribution

- in iron formations: Implications for trace metal stable isotope proxies. *Chemical Geology*, 474, 17–32.
- Roerdink, D.L., Mason, P.R.D., Farquhar, J., Reimer, T. 2012. Multiple sulfur isotopes in Paleoproterozoic barites identify an important role for microbial sulfate reduction in the early marine environment. *Earth and Planetary Science Letters*, 331, 177–186.
- Roerdink, D.L., Mason, P.R.D., Whitehouse, M.J., Reimer, T. 2013. High-resolution quadruple sulfur isotope analyses of 3.2Ga pyrite from the Barberton Greenstone Belt in South Africa reveal distinct environmental controls on sulfide isotopic arrays. *Geochimica et Cosmochimica Acta*, 117, 203–215.
- Roerdink, D.L., Mason, P.R.D., Whitehouse, M.J., Brouwer, F.M. 2016. Reworking of atmospheric sulfur in a Paleoproterozoic hydrothermal system at Londozi, Barberton Greenstone Belt, Swaziland. *Precambrian Research*, 280, 195–204.
- Schilling, K., Johnson, T.M., Mason, P.R.D. 2014. A sequential extraction technique for mass-balanced stable selenium isotope analysis of soil samples. *Chemical Geology*, 381, 125–130.
- Schilling, K., Johnson, T.M., Dhillon, K.S., Mason, P.R.D. 2015. Fate of Selenium in Soils at a Seleniferous Site Recorded by High Precision Se Isotope Measurements. *Environmental Science and Technology*, 49, 9690–9698.
- Stam, M.C., Mason, P.R.D., Pallud, C., Van Cappellen, P. 2010. Sulfate reducing activity and sulfur isotope fractionation by natural microbial communities in sediments of a hypersaline soda lake (Mono Lake, California). *Chemical Geology*, 278, 23–30.
- Stam, M.C., Mason, P.R.D., Laverman, A.M., Pallud, C., Van Cappellen, P. 2011. $^{34}\text{S}/^{32}\text{S}$ fractionation by sulfate-reducing microbial communities in estuarine sediments. *Geochimica et Cosmochimica Acta*, 75, 3903–3914.
- Tsikos, H., Matthews, A., Erel, Y., Moore, J.M. 2010. Iron isotopes constrain biogeochemical redox cycling of iron and manganese in a Palaeoproterozoic stratified basin. *Earth and Planetary Science Letters*, 298, 125–134.



Paul Mason was born in Hull, northern England in 1971. He grew up in the town of Bingley, West Yorkshire before going to Durham University to read Geology. He obtained a PhD in geochemistry from Birkbeck College, University of London in 1995 with a thesis entitled 'Petrogenesis of subduction related magmatic rocks from the East Carpathians, Romania'. He was employed as a postdoc at Imperial College London at the Center for Analytical Research in the Environment, before moving to the Faculty of Earth Sciences at Utrecht University in 1997. He joined the permanent staff as Assistant Professor in 2002. Highlights of his career include the award of a prestigious NWO Vidi grant, the Hugh Kelly fellowship at Rhodes University in South Africa, a sabbatical at the University of Maryland partly funded by the NSF and the Utrecht University young lecturer of the year award. He has helped to lead an international consortium of researchers to drill some of the Earth's oldest rocks in South Africa. He was named as the most recent in a long line of professors in petrology at Utrecht University on 01 March 2017.

