although ideas of human domination of our planet's geology have surfaced at intervals since, they were generally dismissed. For humans, in their minuscule time-span on Earth, could not — surely — rival the great forces of nature.

Little more than a decade ago, though, the atmospheric chemist and Nobel-Prize-winner Paul Crutzen suggested that humanity was indeed a force of nature. We no longer live in the Holocene, he said, but in the Anthropocene. The chemical, physical and biological changes are dramatic and sometimes frankly alarming: atmospheric carbon dioxide concentrations are now at levels last seen more than two million years ago and rising fast; invasive species have been introduced to every continent and a sixth great mass extinction event may be with us in mere centuries; landscapes are transformed. Imagining a look back from some far future, it is hard to see how the twenty-first century could not be seen as a turning point in Earth history.

The idea of the Anthropocene has spread widely in the past five years or so. The term is used in both scientific papers and popular articles. No less than three journals devoted to Anthropocene science will shortly appear. The concept provides both a summation of the diverse human impacts on Earth and a vivid reminder that we live in a deeply changed world — and that humanity must learn to ride this new planetary tiger as it leaps into the unknown.

Interest in the Anthropocene stems partly from its potential formalization

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— the idea that it may be so real that it will one day feature on the geological timescale. To be useful to geologists, the Anthropocene must be thought of not just as history, but as rock — strata deposited during the Anthropocene that geologists can see and map. But what strata could physically have formed within a few centuries, a geological blink of an eye?

We might consider the changing landscape. Burgeoning cities comprise 'urban strata' — a geologically durable mass of brick, concrete, glass and metal. In another sense, they are an entirely novel and quite gargantuan trace fossil system, one that extends kilometres deep into older rock in the form of millions of boreholes and mineshafts. Out to sea, most of the continental shelves have now been scraped and smoothed by trawler-nets, altering both sediments and biota: these churned deposits might also form part of Anthropocene strata. There will be chemical signals in modern strata, too. These will come from carbon that is isotopically lightened by the influx from fossil fuels, and from nitrogen that is altered by the Haber-Bosch process that creates the fertilizer required to sustain the Earth's growing population.

Mapping the Anthropocene's complex products — within the deep-time context of the rock record — will help us understand our place in Earth history. But does it matter whether the Anthropocene is formalized? The term is currently informal, without even an agreed beginning. Yet, it looks set to stay, formal or not, and to spread to a much wider community than just geologists. The concept has already entered discussions of international law, where formalization may carry weight in the demarcation of human rights and responsibilities in a changing world. As the geological past is summoned as context for our tumultuous present, perhaps formalization of the Anthropocene should not only depend on scientific justification (as that is a given), but also on its use to the world beyond geology. ❐

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The mystery of atmospheric oxygen

Readily available O_2 is vital to life as we know it. **James Kasting** looks at how and when the first whiffs of oxygen began to reach the Earth's atmosphere.

The early history of the Earth's atmosphere has long fascinated both geologists and biologists. Geologists were intrigued because the atmosphere influences the types of mineral deposits that formed back then — some of which, such as banded iron-formations, still have economic importance today. Biologists were interested, because atmospheric composition most certainly influenced the early evolution of life and, in some theories, life's origin as well. In the past years, atmospheric scientists (like me) and astronomers have also taken an interest in this subject. We atmospheric types want to understand the basic processes that control atmospheric composition and climate over long timescales. Astronomers, who are now on the verge of being able to search for Earth-like planets around other stars, want to know what such planets might look like from afar and whether they might be able to use our knowledge of the early Earth to determine whether these planets harbour life.

Two main questions have guided investigations of oxygen in the early Earth's atmosphere: how much O_2 existed before the advent of life, and what exactly caused the rise of atmospheric O_2. The issue of prebiotic O_2 levels is not new. In the late 1960s, it was suggested that O_2 could have built up to an appreciable fraction of its present level, simply by photodissociation of water vapour followed by escape of hydrogen to space. But advances in our understanding of hydrogen escape to space showed that the amount of O_2 that could accumulate from this process is extremely small, about 10^{-13} times the present atmospheric level. More detailed calculations showed, however, that an O_2 layer, analogous to today's ozone

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layer, could form in the stratosphere as a consequence of photolysis of CO_2. Through this mechanism, the stratospheric O_2 abundance could reach around 10^{-3} times present-day levels.

But it is the question of the timing of the rise of atmospheric oxidation levels that has seen the greatest advance in the past few years. It was the recent application of multiple sulphur isotopes to Archaean-aged rocks that allowed us to constrain the irrevocable rise of atmospheric oxygen levels. Termed the Great Oxidation Event by Heinrich Holland, who sadly passed away in the first half of 2012 and will be sorely missed, the rise in oxygen is generally thought to have occurred rather precisely 2.45 billion years ago, although a few workers are still calling for a much earlier origin of oxygenation. And in one sense, everyone agrees on its broad cause: cyanobacteria. Cyanobacteria are single-celled organisms — true Bacteria to a biologist — that are capable of performing both oxygenic and anoxygenic photosynthesis. But a new debate has sprung up: namely, exactly when cyanobacteria started producing O_2. And, if this date was earlier than the Great Oxidation Event, what kept atmospheric O_2 from increasing right away?

These questions are currently driving considerable research. Organic biomarkers that are characteristic of cyanobacteria or O_2-dependent organisms have been reported in sediments as much as 2.7 billion years old. But it is unclear whether these compounds are indigenous to these old rocks or whether they were carried there at some later time, for example by oil migration. More subtle oxygen indicators such as enhancements in molybdenum and rhenium have been identified in shales dated at 2.5 billion years. These elements bind tightly to sulphur, and so their high concentration in Late Archaean shales suggests that weathering of sulphide minerals on land under oxygenated conditions was occurring — at least regionally — some 50 million years before the Great Oxidation Event. Other evidence for the weathering of sulphides tentatively pushes oxidative weathering back to 2.7–2.8 billion years ago.

Evidence for early oxidative weathering might well reconcile putative early oxygen production and the timing of the Great Oxidation Event. If oxygenic photosynthesis did indeed originate well before the main oxidation, O_2 could have been produced by cyanobacteria living in localized oxygen oases in the near-shore surface ocean. Plumes of O_2 emanating from these oases could have drifted inland and oxidized sulphides in the areas they passed over. Although this hypothesis has not been studied quantitatively, it seems rather unlikely. More plausibly, the entire atmosphere might have become oxidizing for brief periods before switching back to the dominantly reducing conditions of the Late Archaean eon.

A switch between reducing and oxidizing atmospheric conditions is easily triggered, similar to an acid–base titration: O_2 (or pH) stays low until just the critical amount of oxygen (or base) is added. Equivalently, O_2 could have stayed low until the input of reductants such as reduced volcanic gases fell below some critical level. Because the rate of reductant input is unlikely to have been steady, atmospheric O_2 could have risen and fallen multiple times. And certain signals of brief whiffs of oxygen, the sulphur isotope signal in particular, could conceivably be invisible within the broader geologic record.

Answers to questions about the nature of the Earth's early atmospheric evolution may, however, not lie in the sulphur isotope record, or even on the Earth itself. Instead, future insights may be found outside our Solar System, on Earth-like planets circling other stars. If we build proposed missions such as NASA's Terrestrial Planet Finder and the European Space Agency's Darwin we can begin to observe such Earth-like planets, but neither mission is actively being pursued at this time. Some exoplanets found by these missions may be similar to the present-day Earth, and some may be analogues to the Earth during its ancient geological history. Ultimately, by studying them, we can hope to understand how both the Earth and life itself evolved. ❐

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The great sea-ice dwindle

Record minima in Arctic summer sea ice have been trumping each other. **Marika Holland** reflects on the likely fate of the northern sea ice cap.

This past summer, the Arctic experienced the most rapid rate of sea-ice retreat ever recorded. On 16 September 2012, sea ice extent bottomed out at a new record minimum. The ice remaining in the Arctic at that date, about 3.4 million square kilometres, was roughly half of the ice cover during the 1990s when I was a graduate student starting research on Arctic climate. Rapid and alarming Arctic change is now a reality — and it came with a warning from climate modelling.

Before 2007, the Arctic had experienced considerable ice retreat with record summer minima in 2002 and again in 2005. But in 2006, climate models indicated that significantly more rapid ice loss was likely in the near future[1]. In the simulations, long-term retreat was punctuated by instances of abrupt loss, over four times faster than anything that had yet occurred. The most dramatic of these simulated events showed a loss of 4 million square kilometres — about 60% of the September sea ice — within only 10 years, and resulted in near ice-free Septembers by 2040. At the

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