CHAPTER 1

Science: Old and New Patterns of the Anthropocene

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In 2000, on that fateful day in Mexico, when Paul Crutzen gave in to a moment of irritation among a crowd of fellow scientists assembled to discuss the growing symptoms of a troubled Earth, he surely could not have foreseen the repercussions of his brusque intervention. What had got on his nerves was the constant reference to the Holocene Epoch, the interval of post-glacial geological time (in which we still, formally, live) and the new trends developing within it. These trends – of deforestation, of fundamental change to the chemistry of the atmosphere and the oceans, of accelerating biodiversity loss, of the onset of climate change – to him did not chime at all with the general concept of the Holocene. The Holocene, after all, is an epoch of relative stability, the latest of 50-odd interglacial phases of the 2.6 million years of the Quaternary Period (the Ice Age of common parlance); its conditions enabled humanity to burgeon. Here, one can see the growth of communities, towns and cities, and then empires, and all the marks of peace such as trade and farming, and of war, with destruction and despoliation, alternating in seemingly endless cycles. All this is preserved in a rich archaeological record, extending through – and indeed before – the 11.7-thousand-year span of the epoch.

Underlying all this feverish human activity, though, the signals of the Earth as a planet were ones of dependability: of climate, of sea level – once the mighty polar ice-sheets had finished their prodigious melt phase after the last Ice Age, some 7000 years ago – of geography, and of animals (bar mostly the large land animals beginning to suffer the effects of hunting) and plants. This was a planet as bedrock, a backcloth so reassuringly stable and supportive for human activities, of such

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seeming permanence, that it could be assumed to be always there. And, whatever the destruction wrought by the latest war, or by the spread of patches of nature tamed as farms and towns, this stable Earth would heal, would recover, and would endure to support the next human adventure. Only – as Paul Crutzen then felt so acutely – at some recent time in history, around the time when large-scale industrialization started, the human-wrought changes began to take on a quite different scale and order: of such a scale, indeed, as to threaten the planetary stability that supported both human civilization and the complex web of nonhuman life. Hence that outburst, that moment of inspiration and that on-the-spot improvised new word: the Anthropocene.[1]

That word, as we now know, was to catalyze many things in a surprisingly short space of time (the catalysis, indeed, continues, and at breakneck speed). One was simply the wider use of the term among the scientific community that Paul was part of, the Earth System science (ESS) community associated with the International Geosphere-Biosphere Programme. They simply voted with their feet, using the term matter-of-factly, as a vivid and useful conceptual addition to their discourse and their wider communication.[2] These were for the most part chemists, physicists, ecologists, oceanographers, and so on, dealing with the present world. Aware of the Geological Time Scale – of which the Holocene is the latest (and remains the latest) rung – they had, however, few dealings with the particular geological community that oversees the Geological Time Scale; no more so than most scientists have day-to-day dealings with the kinds of committees that decide, ponderously and with infinite meticulousness, the precise length of the meter or exact weight of the kilogram.

[1] Paul J. Crutzen and Eugene F. Stoermer, "The 'Anthropocene'," *Global Change IGBP Newsletter*, no. 41 (2000): 17. This journal issue includes several intimations, direct and indirect, of this new concept, which was later more widely broadcast in a vivid, one-page article: Paul J. Crutzen, "Geology of mankind," *Nature* 415 (2002): 23.

[2] This early adoption may be seen in, for instance: Michel Meybeck, "Global analysis of river systems: from Earth System controls to Anthropocene syndromes," *Philosophical Transactions of the Royal Society. Series B, Biological Sciences* 358, no. 1440 (2003): 1935–55; and W. Steffen, A. Sanderson, P.D. Tyson, et al., *Global Change and the Earth System: A Planet Under Pressure* (Berlin: Springer, 2004).

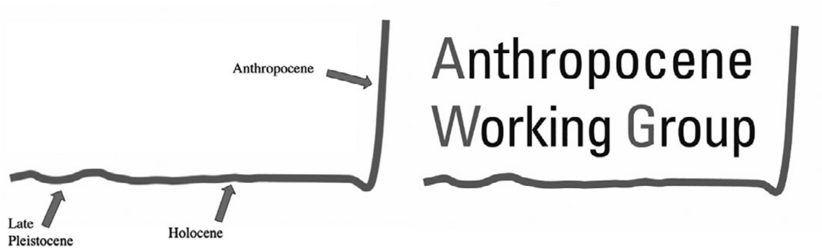
Nevertheless, a few years after the Anthropocene began its spread through the scientific literature, this particular community of geologists became aware of this new word, which was being used just as if it was a standard geological time term. But, of course, it was not: it had not gone through the exhaustive, lengthy, detailed analyses and scrutiny – one would say ordeal, if we were dealing with a human – that a term must go through before it is finally, after passage through several increasingly powerful committees, agreed upon (at all stages) by supermajority vote. The Geological Time Scale is meant to be stable, to provide a common grammar for the discipline across both national boundaries and generations. It is only modified rarely and grudgingly, for real purpose; and quite a few proposed terms have never made it into formal use, having fallen at one or other of these hurdles. The Anthropocene is now being prepared for just such a trial, in the next few years. There is no guarantee it will survive, formally.

While the formal lens provides only one perspective on the Anthropocene, there is also the question of the *reality* – the physical, chemical, and biological rationale that lay behind Paul Crutzen's intuition. These are all of course geological too, in that the Earth comprises all of these dimensions – that one may term respectively lithostratigraphical, chemostratigraphical, and biostratigraphical, in the jargon of the trade. Through these prisms, one may process an almost infinite amount of data – the Earth is a large and complex phenomenon, after all.[3] But many of the various patterns of the Anthropocene betray a striking simplicity. This new concept is not subtle, and does not need sophisticated statistical analysis to reveal some vague hidden trend in a sea of variability. It is terribly straightforward.

FUNDAMENTAL PATTERN OF THE ANTHROPOCENE

Take, for instance, the pattern that last year was calculated by Clément Poirier, one of the Anthropocene Working Group (AWG) members, and

[3] A good deal of the evidence is very tightly summarized in C. N. Waters, J. Zalasiewicz, C. P. Summerhayes, et al., "The Anthropocene is functionally and stratigraphically distinct from the Holocene," *Science* 351, no. 6269 (2016): 137.



1.1. The Anthropocene Working Group logo (right), based on the rate of change of atmospheric CO_2, over 20,000 years, as worked out by Clément Poirier, and (left) its relation to geological time units. The AWG logo image was devised by the Max Planck Institute for Chemistry, Mainz, and is reproduced with permission.

then worked into the new logo of the AWG, courtesy of Astrid Kaltenbach and the Max Planck Institute for Chemistry in Mainz. It is an almost-horizontal line that, at its right-hand end, turns into an almost vertical line. It represents the rate of rise of carbon dioxide into the atmosphere from the earth/ocean system over the past 15,000 years (Figure 1.1).

For most of these 15 millennia, this rate held almost steady: there are some slight wobbles in the first third of the line at its left-hand end, representing the standard glacial-to-interglacial rise in atmospheric carbon dioxide levels from 180 to around 265 parts per million (ppm), largely by outgassing from the ocean. This is quite a large rise, but it did take several millennia from start to finish, so the line does not depart much from the horizontal trend, which then persists *almost* until the present. The sharp inflection towards the vertical is humanity's contribution, mostly from the burning of gargantuan amounts of fossil fuels. The near-vertical line is not quite straight: the first part is a little less steep, and represents the time from about 1850 CE, the beginning of what is sometimes called the "thermo-industrial" revolution, and the second, steeper part represents the time from around 1950 CE, the time of the "Great Acceleration" of population, industrialization, and globalization, since which point more than 87 percent of the fossil fuels exploited have been consumed.[4] This is a large part of the

[4] The diagrams that form the basis for the AWG logo are shown and described in Fig. 1 in the 2019 response piece by J. Zalasiewicz, C. N. Waters, M. J. Head, C. Poirier, et al., "A formal Anthropocene is compatible with but distinct from its diachronous anthropogenic counterparts: a response to W.F. Ruddiman's 'Three Flaws in Defining a Formal Anthropocene'," *Progress in Physical Geography* 43, no. 3 (2019): 319–33.

reason why the human consumption of energy in the seven decades since 1950 CE is estimated to be greater than that in all of the previous 11.7 millennia of the Holocene.[5]

Carbon dioxide is just one parameter. A very similar pattern, though, can be made from an analysis of human population growth, of atmospheric methane levels, and much else. The notorious "hockey stick" of Earth's temperature proposed by Michael Mann[6] and his colleagues is part of this suite, albeit a (so far) blurred and relatively poorly developed one, as Earth's surface temperature has yet to catch up with the effects of climate drivers such as increased atmospheric carbon dioxide (the Earth is a big object, and so it will take some centuries for the increased heat to work its way back through to the atmosphere; at the moment, for instance, most of the extra heat is being absorbed by the oceans). This fundamental pattern, therefore, divides the old epoch and the (proposed) new one. As a first approximation, the Holocene is horizontal, and the Anthropocene is vertical.

CLIMATE CONTEXT OF THE ICE AGE

Is this striking pattern *geology*, though, or just a few millennia of environmental history? In other words, is the Anthropocene a blip, a minor fluctuation destined to be lost within the noise of Earth time, or is it something larger and more serious? Here, context is everything. The current CO_2 rise can be grafted onto the record of carbon dioxide fluctuations over the last 800,000 years – an astonishing archive that is perhaps the most valuable treasure yielded to us by the great Antarctic ice-sheet, as fossilized air bubbles trapped in the annual ice-layers. Without this natural archive, we really would be groping in the dark to

[5] This analysis, which ranges wider than energy consumption, is in J. Syvitski, C. N. Waters, J. Day, et al., "Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch", *Communications Earth & Environment* 1 (2020):32.

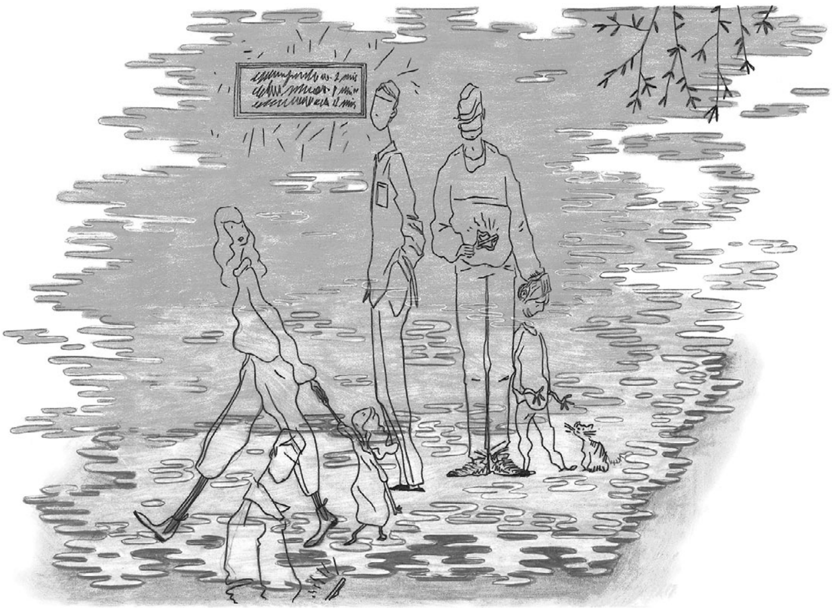
[6] Michael Mann is a climatologist at Penn State University, who has pioneered techniques of reconstructing the climate history of the past 1000 years. The pattern he obtained, of a sharp twentieth-century rise, is also shown by many other parameters of the Anthropocene.

understand the significance of the modern rise, given how difficult it is to divine ancient atmospheric carbon dioxide levels from "normal" strata made of sand, mud, and lime.

The ice-layers clearly show the extraordinarily metronomic oscillations of CO_2 levels that took place during the Ice Ages, and their exceedingly close correspondence with the temperature record deduced from other chemical properties of the ice archive: thus, CO_2 levels regularly fluctuated between around 180 ppm in cold phases of the Ice Ages, to around 280 ppm in warm interglacial phases (of which the Holocene is the latest). On this scale, the modern CO_2 outburst is clear as a near-vertical line, extending high above the upper limit boundary of these oscillations. Hence, since 1850 CE, more carbon dioxide (approximately 130 ppm) has been added to the atmosphere than is exchanged in normal glacial-to-interglacial transitions in the Ice Ages – and this has taken place more than a hundred times more quickly. It is, of course, still rising near-vertically. It may be the most rapid major change in atmospheric carbon dioxide levels in the Earth's history.[7]

The amount of "our" carbon dioxide is enormous, when we try to think of it in real terms. Although we intuitively think of gases as weightless – of being, indeed, "as light as air" – they do possess mass. That "extra" human-produced carbon dioxide weighs about a trillion metric tons, or about the same as 150,000 Great Pyramids of Khufu, hanging in the air above us. Considered as a layer of pure gas around the Earth, it is about a meter thick, and so waist-high to an adult, but already over the head of a small child. As it is now thickening at about a millimeter a

[7] The grafting of the Anthropocene carbon dioxide (and methane) trend onto the almost million-year Quaternary pattern preserved in Antarctic ice-layers is nicely shown in Fig. 2. in E. W. Wolff, "Ice sheets and the Anthropocene," in *A Stratigraphical Basis for the Anthropocene*, ed. C. N. Waters, J. A. Zalasiewicz, M. Williams, et al. (London: Geological Society London Special Publication 395, 2014), 255–63 (except that the diagram now needs to be perceptibly amended after another half-decade's worth of growth in atmospheric carbon dioxide and methane). In more detail, the shockingly abrupt rise that (in effect) terminates Holocene air, can be seen in Fig. 2 in J. Zalasiewicz, C. N. Waters, M. J. Head, C. Poirier, et al., "A formal Anthropocene is compatible with but distinct from its diachronous anthropogenic counterparts: a response to W.F. Ruddiman's 'Three Flaws in Defining a Formal Anthropocene'," *Progress in Physical Geography* 43, no. 3 (2019): 323.



1.2. *The Exhaust* by Anne-Sophie Milon. The illustration portrays rising levels of carbon dioxide that surround us all, invisibly, as we go about our daily lives. Image reproduced here with permission.

fortnight, it will, at current rates, keep up with – or outpace – the growth of that child (Figure 1.2).[8]

Some gases have only brief life-spans in the atmosphere. Methane, for instance, although a much stronger greenhouse gas than carbon dioxide, is oxidized in the atmosphere (to be converted into carbon dioxide) in a matter of a few years to decades. Carbon dioxide, though, has a relatively long residence time. It stays in the atmosphere for many millennia, until it is finally removed by the growth (and burial) of extra plant life, and by slowly reacting with rocks in what is termed "silicate weathering" – the latter probably being the most important (if slow-acting) thermostat-type control of Earth's temperature over geological timescales. The extra carbon dioxide added by humans so far has been estimated to be enough, already, to postpone the next Ice Age by some

[8] These calculations, and other equally extraordinary ones relating to the Anthropocene, may be found in J. Zalasiewicz, M. Williams, C. N. Waters, et al., "Scale and diversity of the physical technosphere: a geological perspective," *The Anthropocene Review* 4, no. 1 (2017): 9–22.

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50,000 years (with only modest further emissions being needed to prolong that to 100,000 years). This kind of timescale is already taking the Anthropocene beyond the scale of a "blip," even a geological one.[9] As we shall see, some aspects of the Anthropocene will have a longevity far in excess even of this.

That current carbon dioxide rise is largely responsible for the temperature rise the Earth has experienced over the last century, now a little over 1 °C above pre-Industrial levels. The rise has been irregular, with pauses, largely because of the irregular way that heat is exchanged between oceans and atmosphere during natural climatic fluctuations such as that of the El Niño-Southern Oscillation (ENSO). Overall, the Earth is still – just – within the "normal" interglacial temperature limits of the Ice Age, though overall both oceans and atmosphere are on a clear heating trend. If continued, this will see the Earth break through, later this century, into the kind of temperature regime last seen in the Pliocene Epoch some three million years ago, when the Earth was a couple of degrees warmer, yet was, albeit, still an "icehouse" world with a substantial Antarctic ice-sheet. If business-as-usual carbon dioxide emissions are continued for somewhat longer, then the world will be taken into the kind of world the dinosaurs enjoyed: a hothouse Earth *without* major polar ice-caps. That would be a fundamentally different kind of planet from today's.[10]

As the Earth slowly warms in response to increased greenhouse gas levels, sea level responds yet more slowly to increasing warmth,[11] partly by thermal expansion of seawater, and partly through the melting of ice masses on land. So far, the total sea level rise above the remarkably stable

[9] This forward projection – or at least a succession of alternative projections, depending how much carbon dioxide we ultimately emit – is clearly illustrated in P. U. Clark, J. D. Shakun, S. A. Marcott, et al., "Consequences of twenty-first-century policy for multi-millennial climate and sea-level change," *Nature Climate Change* 6, no. 4 (2016) 360–69.

[10] This perspective, in the sixty-plus million-year record of the Cenozoic, is shown in Fig. 1 of K. D. Burke, J. W. Williams, M. A. Chandler, et al., "Pliocene and Eocene provide best analogs for near-future climates," *PNAS* 115, no. 52 (2018): 13288–293.

[11] The amount of extra heat entering the oceans from the greenhouse effect of carbon dioxide far exceeds the direct energy we gain from burning fossils fuels; estimates include those by L. Zanna, S. Khatiwala, J. M. Gregory, et al., "Global reconstruction of historical ocean heat storage and transport" *PNAS* 116, no. 4 (2019): 1126.

level of the last few millennia has been of the order of 20 centimeters, which is trivial (almost invisible) on the scale of deep geological time, but nevertheless enough to give some perceptible change on contemporary coastlines. The rate of sea level rise, though, has accelerated from some 1 millimeter per year in the mid-twentieth century to around 3 millimeters per year early in this millennium to approximately 4 millimeters per year in the last decade. The recent acceleration is due largely to the onset of major melting of Antarctica's and Greenland's ice-caps since about 2000 CE (each has lost about 5 trillion tons of ice in that time) while some 10 trillion tons of ice have been lost from mountain glaciers over a somewhat longer time interval, stretching back to the last century.[12]

There is a telling geological context here, too. In the last warm interglacial phase, about 125,000 years ago, when CO_2 levels were about 270 ppm and global temperatures were only slightly higher than today, sea level rose to somewhere between 6 and 9 meters above today's level, probably because of substantial melting of ice on Antarctica as waters warmed around it (sea levels during the third-from-last interglacial, about 400,000 years ago, may have reached yet higher levels[13]). When considering overall interglacial oscillations in sea level over a period of approximately 130 million years, 5–10 meters clearly represents a small fluctuation – one that might take place (or not) depending on relatively subtle differences in the configuration of Earth's "climate machine" at different peak interglacial times. As already noted, human impact on this system has now moved, via emission of greenhouse gases, well beyond the "subtle."

[12] There have been a number of recent assessments of the accelerating ice melt, including J. Mouginot, E. Rignot, A. A. Bjørk, et al., "Forty-six years of Greenland ice sheet mass balance from 1972 to 2018," *PNAS* 116, no. 19 (2019): 9239; E. Rignot, J. Mouginot, B. Scheuchl, et al., "Four decades of Antarctic ice sheet mass balance from 1979–2017," *PNAS* 116, no. 4 (2019): 1095; and M. Zemp, M. Huss, E. Thibert, et al., "Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016," *Nature* 568, no. 3 (2019): 382–86.

[13] It seems that even parts of the "stable" East Antarctica ice-sheet may be lost at such times when, as was pointedly noted, carbon dioxide levels were not anywhere near as high as today's: T. Blackburn, G.H. Edwards, S. Tulaczyk, et al., "Ice retreat in Wilkes Basin of East Antarctica during a warm interglacial," *Nature* 583, no. 7817 (2020): 554–59.

Today, trends in sea level are clearly pointing upwards, and projections suggest anything from a rise of some 65 centimeters to a couple of meters by the end of this century, while beyond this, the amount of further sea level rise will reflect whether CO_2 emissions are held back tightly (to allow preservation of most of the Greenland and Antarctica ice-sheets) or whether they let rip in continued business-as-usual trends (to bringing about loss over centuries/millennia of much or most of this ice, triggering sea level rise of several tens of meters[14]). Given that many coastlines and deltas have been built out to extend to the approximately stable sea level of the mid to late Holocene, even a 1–2 meter scale (still geologically very small) sea level rise will inundate much densely populated land. The difficulties encountered in such a case will therefore not represent extreme Earth System change (in this respect at least), but will reflect how eagerly human populations have congregated around – and hardwired their enormous urban constructions into – the world's coastlines. These human communities have often made their positions more precarious, too, by causing meter-scale local subsidence of the ground by land drainage and the pumping of groundwater, oil, and gas.[15] So, while the provocation (thus far) remains small in relative geological terms, the human vulnerability is large. This is a manufactured vulnerability, and a natural part of an Anthropocene process.

A MINERAL EPOCH

While the processes behind Anthropocene climate change and sea level rise are pretty much as old as the Earth itself, other aspects are quite novel. The minerals that form our planet are its fundamental building blocks. Although intuitively one might think that Earth's mineral assemblage has been more or less constant through its history, our planet has in fact undergone a profound and distinctive form of mineral evolution, the course of which has been elegantly described by the mineralogist

[14] These scenarios and the feedbacks involved are discussed in J. Garbe, T. Albrecht, A. Levermann et al., "The hysteresis of the Antarctic ice sheet," *Nature* 585 (2020): 538–44.

[15] J. P. M. Syvitski, A. J. Kettner, I. Overeem, et al., "Sinking deltas due to human activities," *Nature Geoscience* 2 (2009): 681–89.

Robert Hazen and his colleagues.[16] They demonstrated a succession of mineral eras and epochs that have essentially showed increased mineral diversity through time.

The process begins in interstellar space, where primordial minerals condense as dust grains following supernova explosions; about a dozen of these have been identified, including diamond and a few carbides and nitrides. As dust clouds gathered to build our solar system, these dust grains were heated and aggregated into the building blocks of planets: asteroids and planetesimals, where new minerals formed, including various silicates and oxides. About 250 minerals were present in this phase, and these can be identified in meteorites that land on Earth, which represent the debris from this planet-building phase. As the Earth grew, and processes such as plate tectonics with volcanism and metamorphism began, planetary chemistry was further stretched out to give about 1,500 minerals, the natural complement of a dead rocky planet. As life appeared, more than 3.5 billion years ago, it initially made little major difference to the Earth's mineralogy. But, when photosynthesis evolved to oxygenate the Earth's oceans and atmosphere about 2.5 billion years ago, a large suite of oxide and hydroxide minerals formed, taking the total towards approximately 5,000 minerals. Since that time, this composition has stayed more or less stable – until now.

When humans entered the picture and began to manipulate the Earth's surface environment, they made new minerals, too, or at least new inorganic crystalline compounds, which are minerals in everything but formal classification. The International Mineralogical Association, which sets the standards for such things, recently *excluded* synthetic, human-made minerals from their classification. This exclusion is in itself wholly artificial, but there is a practical kind of logic to it, for otherwise mineralogists might have been overwhelmed by the flood of new materials for them to study.

What kind of "minerals" do humans make? Metals are one of the first examples. Pure "native" metals are rare in nature, with gold as the best-known exception, while native copper is occasionally found, and iron yet

[16] R. M. Hazen, D. Papineau, W. Bleeker, et al., "Mineral evolution," *American Mineralogist* 93 (2008): 1639–720.

more rarely as meteorites (such iron was prized in ancient times, meteoritic iron implements being found within Tutankhamen's tomb, for instance). Most metals in nature, though, are bound within chemical compounds – and it is humans that have become adept at separating them, firstly with copper, tin, and then iron in ancient times, and much more recently with others such as aluminium and titanium, that only exceedingly rarely occur as metal in nature, and molybdenum, vanadium, magnesium, and so on, which do not. Some metals are now separated in gargantuan amounts; the total amount of aluminum produced globally, which now exceeds 500 million tons (almost all since 1950 CE), is enough to cover the USA land surface and part of Canada in standard, kitchen aluminum foil. The amount of iron produced is well over an order of magnitude greater still. These novelties are therefore present in *geological* amounts – sufficient to help characterize Anthropocene strata, particularly in urban settings.

The phenomenon goes well beyond metals, to include many inorganic crystalline compounds synthesized in materials science laboratories worldwide for a wide diversity of purposes: novel synthetic garnets for lasers, tungsten carbide for ballpoint pens, semiconductor materials, the abrasive boron carbide ("borazon"), harder than diamond, and many others. How many? An early 2014 study hazarded that the number of minerals *sensu lato* may perhaps have been doubled by the synthesizing activities of humans.[17] That was way off the mark. In a thorough 2016 assessment of "Anthropocene mineralogy," Hazen and colleagues[18] noted the existence of a Karlsruhe-based Inorganic Crystal Structure Database, which then had records of more than 180,000 such inorganic compounds! (As of November 2019, there were more than 216,000 listed). Human ingenuity, therefore, has multiplied the number of "minerals" on Earth more than 40-fold, mostly over the last 100 years or so. In a commentary on this paper, the mineralogist Peter Heaney

[17] J. Zalasiewicz, R. Kryza, and M. Williams, "The mineral signature of the Anthropocene," in *A Stratigraphical Basis for the Anthropocene*, ed. C. N. Waters, J. A. Zalasiewicz, M. Williams, et al. (London: Geological Society of London Special Publication 395, 2014), 109–17.

[18] R. M. Hazen, E. S. Grew, M. J. Origlieri, and R. T. Downs, "On the mineralogy of the 'Anthropocene Epoch'," *American Mineralogist* 102 (2017): 595–611.

noted that while in most aspects, the story of the Anthropocene was one of destruction and reduction in diversity, in this respect the Anthropocene represented a huge, extraordinary *increase* in diversity, one with no parallels on any other planet in the Solar System – and perhaps with any planet in the cosmos.[19]

Among the materials that we synthesize are the plastics. These are not quite minerals as such, because they are organic compounds, with chemical compositions that can vary within fixed limits (nevertheless, there are organic "minerals" recognized in geology with which comparison may be made, such as amber). But this family of modern "mineraloids" is rapidly growing to become a part of – or even overwhelm, some might say – the Anthropocene, with a capacity to become a part of global geology that is in some ways greater than that of minerals *sensu stricto*. Plastics have a growth curve that closely resembles that of aluminum, with negligible pre–World War II production, growing to roughly 1 million tons per year by 1950, and then rapidly to more than 300 million tons per year today.

Plastics are so useful to us for a variety of reasons: they are light, strong, and resistant to abrasion, breakage, and decay, which is what makes them so geologically important. Once discarded (and much plastic is designed to be discarded immediately after a single use) plastic debris is easily transported by wind and water across landscapes and, with rivers as major conduits, to coastlines. From there it is carried by currents onto distant coastlines and into the deep ocean. A major component recognized only relatively recently is microplastics, especially textile-derived fibers, which have been shown to contaminate sediment almost universally in the ocean – even sea-floor sediments in the very deep ocean, thousands of miles from land.

It is such a recent, and recently recognized, global phenomenon that scientists are scrambling to get to grips with it. As a topic, it was barely on the radar when the Anthropocene Working Group began its analysis in 2009; by 2015, it had become a major issue in environmental studies generally, and as one spin-off, plastics were emerging as a major

19 P. J. Heaney, "Defining minerals in the age of humans," *American Mineralogist* 102 (2017): 925–26.

characterizing element of Anthropocene strata.[20] There are still many unknowns – for instance, paradoxically, the distribution of plastics on land is far more complex, and therefore difficult to assess, than it is in the oceans. The land is still by far the greatest store of plastics, and so will continue to leak plastics into the oceans for centuries, and likely millennia, to come. Those plastics are clearly becoming a (indigestible, damaging, and often lethal) part of the biological food chain, too, and hence the enormous public concern about them.

The incorporation of plastics into the sedimentary record – that is, into far-future rock strata – is significant in demonstrating the geological character of this modern material. Contemplating the plethora of distinctive far-future fossils that will be produced – something that may intrigue some far-future paleontologist – may seem abstract. But there is a more immediate and practical significance here too, working in the short term. When plastics are at the surface, it is clear that they can interact with the local ecosystem, almost always to its detriment. Once they are buried deeply enough to become part of some future stratum, they are removed from biological interactions, and may be thought to be safely and permanently sequestered. But it is the intervening stage – when plastics are buried out of sight for easy study but interacting with soil ecosystems on land and benthic ecosystems on the sea floor, and yet are still capable of being reworked back to the surface – that is critical, biologically significant, and currently largely mysterious. This transitional phase, when plastics are *becoming* geology – but have not yet become so – is now ripe for study.

BULK MATERIALS

Plastics are one kind of newly created material that have been produced on a geological scale; the approximately 9 billion tons produced so far since the mid-twentieth century would allow the whole globe to be wrapped in somewhere between one and two layers of standard kitchen food wrap. But other materials have been extracted and dispersed by

[20] J. Zalasiewicz, C. N. Waters, J. Ivar do Sul, et al., "The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene," *Anthropocene* 13 (2016): 4–17.

humans in far greater bulk – if perhaps not yet dispersed quite as widely as plastics.

Currently something like 316 *billion* tons of material are moved and reworked annually by humans[21] – of which, therefore, plastics are a one-thousandth part. Something approaching a tenth part is made up by concrete: a material that, although made (after a fashion) by the Romans, has become the signature synthetic rock of the Anthropocene, the graph of its seemingly inexorable rise in production[22] being remarkably similar to that of plastics, carbon dioxide emissions, "mineral" species, and many other of the aspects that Will Steffen, John McNeill, and their colleagues have demonstrated as showing the "Great Acceleration" of population growth, industrialization, and globalization in the mid-twentieth century.[23]

A large part of this crescendo of earth and rock movement is in the digging for such things as coal, where one needs to consider not only the mass of the material itself (with coal currently nearing 8 billion tons, or roughly double the mass of the annual production of cement) but also the mass of the earth and rock "overburden" that needs to be shifted in order to get to the hydrocarbon mineral itself. For coal, this can currently be up to 20 times the amount of the mineral itself; for a high-value mineral like diamond, up to ten tons of rock might be processed to obtain a single gram of diamond. And then, more prosaically, there is the scale of landscape movement, as towns and cities are built and rebuilt – which is much harder to assess globally (and even locally). In the study that produced the 316-billion-ton estimate, the arbitrary figure factored in for such landscape reshaping was twice that of the concrete involved, likely a large underestimate, while such forms of earth movement as

[21] A. H. Cooper, T. J. Brown, S. J. Price, et al., "Humans are the most significant global geological driving force of the 21st century," *The Anthropocene Review* 5 (2018): 222–29.

[22] See Fig. 1 in C. N. Waters, J. Zalasiewicz, C. P. Summerhayes, et al., "The Anthropocene is functionally and stratigraphically distinct from the Holocene," *Science* 351, no. 6269 (2016): 137.

[23] The original classic paper is: W. Steffen, P. J. Crutzen, and J. R. McNeill "The Anthropocene: are humans now overwhelming the great forces of nature?," *Ambio* 36 (2007): 614–21. It was later updated: W. Steffen, W. Broadgate, L. Deutsch, et al., "The trajectory of the Anthropocene: the Great Acceleration," *Anthropocene Review* 2, no. 1 (2015): 81–98.

ploughing, deep sea trawling, and mountain road construction were omitted altogether, to prevent the study, already gigantic in scope, from becoming endless and unfinishable. Hence the annual 316 billion tons calculated (the figure for 2015 CE, and now probably larger by a few billion tons) is likely to be a significant underestimate.

Nevertheless, the 316 billion tons comfortably exceeds – by some 24 times – the amount of sediment annually transported by rivers into the sea. Even this comparison has been skewed by the forces of the Anthropocene, for humans have interfered mightily with the world's fluvial plumbing in the construction of dams across most of the world's major rivers and a good proportion of the minor ones, with much sediment now being held back behind these dams, rather than reaching the sea.

Add all of this up, as another research group did – and this time to include the ploughlands, the trawled sea floor, and so on, all as part of what one might call the "physical technosphere" (more on the technosphere anon) – and a back-of-an-envelope calculation indicated that humans use, have used, and have discarded, some 30 trillion tons of Earth material, most of it since the mid-twentieth century.[24] This is equivalent to a layer of rubble and soil averaging 50 kilograms on each square meter of the Earth's surface – land and sea. As a species, therefore we are almost literally trudging ankle-deep though the debris of the Anthropocene, with progress becoming almost perceptibly harder each year.

THE SCALE OF ABSENT LIFE

While dealing with these multiples of billions of tons of mainly inorganic matter, we can note the comparison with the mass of life on Earth. This has recently been calculated – an extraordinary task! – with the error bars for some categories being very great. We know, for instance, that there is a "deep buried biosphere" of microbes with extremely slow metabolic rates living within fractures and pore spaces in rocks a

[24] J. Zalasiewicz, M. Williams, C. N. Waters, et al., "Scale and diversity of the physical technosphere: a geological perspective," *The Anthropocene Review* 4, no. 1 (2017): 9–22.

kilometer and more below the Earth's surface – but how much of such cryptic, subterranean life is there? Estimates have ranged from amounts comparable with visible surface life to only a small fraction of it. Even weighing a forest that can be imaged precisely with a satellite and also walked through in "ground-truthing," is not a trivial task. Nevertheless, a figure was arrived at for the mass of all life on Earth, totalling 550 billion tons of carbon-equivalent.[25] Add in the other elements of which life is composed, and the water content too, and life on Earth weighs in at some 2.5 trillion tons (or, about a trillion tons on a dry-mass basis, leaving out the water); a large figure, but dwarfed by the combination of our constructions and abundant cast-offs.

Much of this mass of Earthly life is made up of those forests – and here there is a clear human impact too. The authors of the study suggest, in a throwaway remark, that humans have roughly halved this living mass, largely by replacing forests with biotas that, while more immediately useful to us – such as pastures and cornfields – possess much less living *avoirdupois*. This trend, of course, has been in progress throughout much of the Holocene, if intensifying in the Anthropocene.

Within this overall decline, there have been some substantial winners and a rather larger number of losers. The major winners show up clearly on mass estimates of medium- to large-sized terrestrial vertebrates. These are humans, who collectively now make up about a third of the entire total of this category of body mass – a remarkable ascendency for one species. Most of the remaining two-thirds is made of the animals we keep to eat: the cows, pigs, goats, chickens, and others, though here the numerical abundance can only be regarded, for the animals concerned, as the most heavily qualified of victories.

The geological baseline clearly shows just how large this skewing of the terrestrial fauna has been. The paleontologist Anthony Barnosky in 2008 reviewed the number of species of terrestrial megafauna (those weighing more than 44 kilograms) in the Pleistocene, before humans

[25] Y. M. Bar-On, R. Phillips, and R. Milo, "The biomass distribution on Earth," *PNAS* 115, no. 25(2018): 6506–511.

began to make an impact on their numbers.[26] Then, this terrestrial biomass was divided among some 350 species, including such iconic forms as the mastodon, mammoth, and woolly rhinoceros. Hunting by humans (largely) then roughly halved this number between about 50,000 and 7,000 years ago in what has come to be called the Quaternary Megafaunal Extinction, with the peak losses being clustered about 10,000 years ago.

This reduction in wild terrestrial vertebrates, though, was later balanced and then outweighed by the growing stocks of domestic animals, a trend that was also caught up in the steep upswing of the Great Acceleration, notably when the synthesis of nitrogen-based fertilizers allowed the supercharged production of grain and increased pasture growth that allowed animals to be fed efficiently, before they were fed to us. By this means, the total bulk of large vertebrates globally has increased perhaps tenfold over long-term baseline values, and continues to increase, while populations of wild mammals continue to fall.

One animal that symbolizes this ecological metamorphosis is the chicken, and specifically the broiler chicken. Grown for meat, it is now a staple of supermarkets and ready-made sandwiches globally. The chicken has a long history of domestication, reaching back perhaps 8,000 years in tropical south and south-east Asia, where its free-running, long-lived ancestor, the red jungle fowl *Gallus gallus*, still lives. The domesticated version, bred for fighting as well as meat, was taken to the Mediterranean region and Europe (its bones being common at Roman archeological sites, for instance) and to the New World in the sixteenth century. Through all of this time, the bird did not differ greatly from its wild ancestor, at least as far as its basic skeletal infrastructure was concerned.

This changed in the early post-WWII years. A series of Chicken-of-Tomorrow contests among chicken breeders in the USA morphed into a program that led to genetic modification through intense breeding and industrial-scale "vertical integration systems". These new systems put

[26] A. D. Barnosky, "Megafauna biomass tradeoff as a driver of Quaternary and future extinctions," *Proceedings of the National Academy of Sciences (USA)* 105, no. 1 (2008): 11543–48.

breeding units, farms, slaughterhouses and marketing together into gargantuan combines that now dominate production in the United States and in many other parts of the world. As a result, the chicken is now bigger-boned, much heavier, with hypertrophied breast meat, and far shorter-lived (<2 months). It has become by far the most numerous bird globally, with a standing stock of some 23 billion (by contrast, the population of sparrows is about half a billion, and of pigeons about 400 million), and indeed it outweighs all the other birds in the world *combined*, more than twofold.

Since the mid-twentieth century, it has also become a different bird, some three to four times larger in bulk than its wild ancestor: its bones are super-sized to match, and are now clearly distinct from those of both the wild ancestor and of the chicken remains recovered from pre-1950 archaeological sites. Paleontologists would call it a new morphospecies – and one of extraordinary abundance, for its hyperabundance at any one time is combined with a life-cycle, from egg to abattoir, of little more than six weeks. There is a correspondingly huge flux of these hypertrophied bones, therefore, going from dinner plates to rubbish tips and landfill sites, where, buried, they are protected from immediate scavenging and decay, enhancing the prospects for long-term fossilization. Amid all of the complexity of biological change across the Holocene–Anthropocene interval, the sudden appearance worldwide of this monstrously overgrown chicken skeleton is one clear paleontological marker of the Anthropocene. To add to its distinctiveness, the bones are chemically recognizable too – the carbon and nitrogen isotope ratios are clearly distinct, reflecting the change from scratching around in farmyards and back gardens to a factory-controlled diet via multinational animal-feed suppliers.[27] It is yet one more consequence (a planned and earnestly desired one, this time) of the steep rise in fertilizer use, which fuels the new food chain designed for humans (Figure 1.3).

As one food chain grows, another one diminishes. This is not a preordained rule, but at least for some parts of Earth's biology it is now empirical observation. The steep decline in large wild animals

[27] C. E. Bennett, R. Thomas, M. Williams, et al., "The broiler chicken as a signal of a human reconfigured biosphere," *Royal Society Open Science* 5 (2018): 180325.

1.3. Comparison of the limb bones of a modern broiler chicken (left) and its ancestor, the red jungle fowl of Asia (right) at the same age of ~6 weeks. The jungle fowl can go on to live a decade or more, while the broiler chicken has reached slaughter age (and would not live much longer in any case). Image copyright of the Trustees of the Natural History Museum, London. The two specimens are held by the Natural History Museum and the University of London. Image reproduced here with permission.

worldwide, the contemporary continuation of the megafaunal extinctions, is at least obvious; these are large targets. But the extraordinary decline in flying insects is less obviously intuitive, as one thinks of flies, wasps, mosquitoes, and midges as the ultimate survivors, organisms that can survive and flourish in any circumstances. Hence, the palpable sense of shock that followed the beautifully conducted if deeply sobering study of the Krefeld Entomological Society, that showed these age-old pests of humans to be sensitive and indeed acutely vulnerable to changes in the world around them.[28] The study is a classic example of painstaking, systematic, methodical – and, to be sure, highly tedious – data collection, with no guarantee that any striking scientific result will

[28] A. Hallmann, A. Sorg, E. Jongejans, et al., "More than 75% decline over 27 years in total flying insect biomass in protected areas," *PLOS One* 12, no. 10 (2017): e0 185809.

emerge. Indeed, it would have been much better in hindsight if the results had been as tedious and mundane as the research behind it.

The study was carried out annually from 1986, trapping flying insects in nature reserves in Germany, collecting them, and weighing them. Obtaining meaningful results in such a study is a decidedly non-trivial exercise. The insects were logged on average every 11 days at 63 different locations, giving a haul of 53.54 kilograms of insects (equivalent to, say, the body mass of a small adult human) from a "total trap exposure period" of 16,908 days (or just over 46 years). Cleaning out the Augean Stables, that legendary task of Hercules, seems to represent a light spring-clean by comparison. The weighing alone was a fraught exercise, as the insects were stored in alcohol: a full half-page of text is taken up outlining the careful protocol needed to weigh alcohol-sodden dead insects and extract a representative mass value from the results. And as for looking in more detail – trying to identify the insects taxonomically instead of treating them all together in their *en masse* laboratory grave – the researchers merely said that that was another task for another (yet longer) day.

As it happens, there was probably not quite the need for such hair-splitting exactitude: the results are not in the least bit subtle. Over that 27-year period, the mass of flying insects in *nature protected* areas (not farms, not towns or cities) declined by three-quarters – and in summer by over 80 percent. It is a striking reduction in organisms near the base of the food chain. Was it just a regional phenomenon, in a central European country that is highly urbanized, and with modern agriculture? No – similar patterns and similar levels of insect decline were reported elsewhere,[29] in the tropical forests of Puerto Rico, as well as in Denmark and the UK. The precise reasons remain unclear. In Europe, factors such as pesticides, habitat loss, and light and noise pollution are quoted; in Puerto Rico, it's suggested that a warming climate is mainly to blame.

Something big is clearly going on – indeed, of a geological scale, with reverberations beyond the insect world, as concomitant declines in insectivorous birds are being reported too. *But*, most of these extraordinary studies, like those of the Krefeld community, began towards the end

[29] For example: P. Cardoso, P. S. Barton, K. Birkhofer, et al., "Scientists' warning to humanity on insect extinctions," *Biological Conservation* 242 (2020): 108426.

of the twentieth century, well after the phenomena of the "Great Acceleration" were underway, and so insects were likely already in considerable decline even at the start of these studies. Indeed, as landscape changes from agriculture and urbanization date back well into the Holocene, it is likely that insect communities were beginning to change thousands of years ago.

The trouble comes when trying to get any sensible idea of the scale of these changes. For this, one would need to have a *long-term* baseline measure of flying insect abundance, in the way that ice cores provide a marvellous record of atmospheric carbon dioxide measurements, and the way that cores of lake sediment can show when long-lived pesticides such as DDT, dieldrin, and aldrin began to become widely dispersed, even in remote environments, in the mid-twentieth century.[30] Insects and paleontology, though, do not go together as easily as do, say, molluscs (or even dinosaurs) and paleontology; the insect exoskeleton is marvellously adapted to serve these organisms in life, but many are too small and frail to help transfer into the fossil record after death. And so this particular kind of biological change is not easily inscribed into the usual geological archives.

That is not to say that insects do not fossilize at all. There is that almost fabled record of fossilized dragonflies with half-meter wingspans from the coal forest swamp strata of Carboniferous times, for instance (the fable turns out to be true in this case – albeit very rarely encountered). And there are some well-established paleontological cottage industries among the many forms of science done on the deposits of the Ice Age: the fossilized wing-cases of beetles and head-capsules of midges are among the kinds of biological proxy used to help reconstruct the scale and speed of climate change in the past. But it is one thing to do this kind of science where the discovery of just one fossil specimen can provide a clue to past climate, and quite another to use these patchy finds to work out the total biomass of all flying insects in the region at

[30] Scotland's Lochnagar is a nicely studied example: D. C. G. Muir, and N. L. Rose, "Persistent organic pollutants in the sediments of Lochnagar," in *Lochnagar: The Natural History of a Mountain Lake, Developments in Paleoenvironmental Research*, ed. N. L. Rose (Dordrecht: Springer, 2007), 375–402.

some prehistoric time. The power of the Anthropocene concept in providing deep-time baselines can therefore vary markedly, depending on the "fossilization" potential of each component phenomenon within the Earth System. Will some ingenious paleo-entomologist ever manage to work out a technique to provide a plausible baseline against which the modern insect decline can be placed? That would be a fascinating, and indeed important, development in paleontology.

THE RISE OF TECHNOLOGY

The driver of all of these changes is of course in one sense the ingenuity, social nature, and manipulativeness of the growing number of humans on this planet, as the term "Anthropocene" implies. But, for all of the extraordinary powers of the human brain, individually and collectively, and of the opposable thumb, there is much more to it than that. To take over a planet, one needs the proper tools. Given the potential of those two human organs, these tools came to be.

Technology is clearly a means to ratchet up human ability to win and use resources for our species' benefit. This has been the case from the Stone Age times of the late Pleistocene onwards, with the ubiquity of flint arrowheads and axe heads and the progressive developments through the use of metals, textiles, and other materials through the Holocene. But as technology has vastly diversified and become more powerful, sophisticated, and pervasive since the Industrial Revolution, one might say that it is now arguably the key driver of Anthropocene change.

The geologist Peter Haff speaks of it in terms of the *technosphere*,[31] and makes several points about this new "sphere" on Earth. One is that it is not just the sum total of all our technological objects, interpreted widely to be not just machines but also buildings, roads, dams, reservoirs, and

[31] P. K. Haff, "Technology as a geological phenomenon: implications for human well-being," in *A Stratigraphical Basis for the Anthropocene*, ed. C. N. Waters, J. Zalasiewicz, and M. Williams (London: Geological Society of London, Special Publication 395, 2014), 301–9. See also: P. Haff, "The technosphere and its physical stratigraphic record," in *The Anthropocene as a Geological Time Unit: A Guide to the Scientific Evidence and Current Debate*, ed. J. Zalasiewicz, C. N. Waters, M. Williams, and C. P. Summerhayes (Cambridge, UK: Cambridge University Press, 2019), 137–55.

farms (part of the farm machinery is now the supermarket chicken, a technological construct, quite unable to survive in the wild and fated to endure its short existence within a still-biological and sentient frame). Humans, in this view, individually and collectively, are also components of the technosphere: utterly dependent upon it – for without our various technological aids the Earth could not support more than a few tens of millions of people, living as in the Pleistocene as hunter-gatherers. Much human effort is now directed to maintain and ever further develop the already gigantic, and growing, technological construct on this planet. And the technosphere is taking on – perhaps not quite a life (yet) – but at least a momentum and dynamic of its own.

The technosphere is greater than the sum of its parts. In the same way that the biosphere is not just the total tally of all the animals, plants, and microbes on Earth, but includes all of the fluxes and interactions of matter and energy between them – and also between it and the rocks of the lithosphere, and the water and air of the hydrosphere and the atmosphere. The technosphere includes all of these interactions and is now large and powerful enough to change the nature of these other spheres. It unfolded from the biosphere, and is now growing rapidly at the expense of it.

The rate of growth and evolution of this planetary novelty is extraordinary. The biosphere can change and show major innovations too, of course, and the nature and rate of this change can be tracked in the geological record. Of famously rapid transitions, the most iconic is the development of a complex ecosystem of multicellular animals, following the billions of years of microbial domination of Earth. This half-billion-year-old transition, the "Cambrian explosion," that so puzzled Charles Darwin, is indeed a step change in the Earth System. And yet, anatomized in real time as generations of geologists have pored over the critical intervals of strata, this "explosion" turns out to have taken some 30 million years, encompassing, as stages within it, the emergence of burrowing animals, the development of hard skeletons, and the appearance of those poster-child fossils, the trilobites, that went on to dominate the sea floors of the Paleozoic Era. As Preston Cloud, that noted savant of Precambrian times, observed, it was more like a "Cambrian eruption."

The development of a technosphere, now becoming comparable in mass and energy consumption to the whole of the biosphere, took, by contrast, a matter of a few millennia (if one wants to include its early, locally dispersed stages) or a few centuries if one considers it as an interconnected planetary system. Most of its growth and diversification has happened since the mid-twentieth century Great Acceleration. How can one appreciate its scale and scope? Considering it in terms of human technological history puts it in a category that is *sui generis* – phenomenal, but isolated, with nothing to compare with in the natural world. But considering it as something that lies within the reach of paleontology does provide a certain kind of context.

The manufactured objects of the technosphere are artifacts to an archaeologist or historian, putting them firmly within the human realm. But thinking of them as biologically constructed, potentially fossilizeable objects – technofossils[32] – brings them into the realm of ichnofossils, also known as trace fossils, where they share conceptual space with fossilized burrows and footprints. Perhaps more particularly, technofossils may be compared to some of the more elaborate constructs of the animal world. Among the million-year-old volcanic strata of Tenerife, for instance, there are fossil soils among which can be found hundreds of acorn-sized and -shaped nests made by burrowing wasps, constructed of carefully selected pumice fragments as precisely and neatly assembled as any of the stone huts made by our ancestors. And on a larger, more collective scale, there are the mega-skyscrapers of the insect world: the termite nests that entomologists marvel at, with their myriad internal passages and heat regulation and air conditioning systems, which can be up to 10 meters high and a thousand cubic meters in volume. These intricate structures can be fossilized too – fine examples have been found in Africa and South America, ranging back to Jurassic antiquity. Such structures yield little to the Empire State Building in sophistication – and suggest that thinking of the technological constructions of humanity through a paleontological lens may not be completely outlandish as an exercise.

[32] J. Zalasiewicz, M. Williams, C. N. Waters, et al., "The technofossil record of humans," *The Anthropocene Review* 1 (2014): 34–43.

The petrified early Jurassic termite nests of South Africa show "advanced" construction, according to their discoverers.[33] Hence this iconic kind of animal architecture has existed on Earth for some 150 million years – having evolved from simpler constructions that have been found amongst the strata of the Triassic Period, some 50 million years previously. The hardware manufactured by these organisms is therefore evolving at rates comparable to biological evolution, where individual species spans are typically a few million years, and more fundamental changes in biological ground plan – the appearance of plankton communities with calcium carbonate skeletons, for instance (also an invention of Jurassic times) – take place every few tens or hundreds of millions of years. The "technology" of nonhuman animals is thoroughly a part of the biology of those organisms, and the complex behaviors that allow such constructions are as much under direct genetic control as are the biochemical processes that make their tissues and skeletons – and have also been integrated over geological timescales into the ecological webs of the Earth's biosphere.

Human technology, though, has departed from this long-established pattern. The earliest human technologies – indeed, pre-dating our own species – remained much the same over many millennia. Technology and the nature of artifacts evolved, in fits and starts, more quickly over the Holocene. But, an eighteenth-century human, even one living, say, in the heart of Paris, Berlin, or London, could not have foreseen the speeding – the *zoom,* as the science journalist Andrew Revkin has put it – of the rate of this kind of evolution, nor the rate of increase in the diversity and sophistication of the technological objects that were to come. Now, one human lifetime can encompass the change from typewriters and fountain pens to computers and the internet; little more than one human decade can see the introduction of a novelty like the mobile phone, and see it spread across the entire world and undergo several generations, each more sophisticated than the last. Technological evolution is now completely decoupled from the biological evolution of the

[33] E. M. Bordy, A. J. Bumby, O. Catuneanu, et al., "Advanced early Jurassic termite (Insecta: Isoptera) nests: evidence from the Clarens Formation in the Tuli Basin, Southern Africa," *Palaios* 19 (2004): 68–78.

humans that make the technology. It might even be argued that it is at least partly detached from the cultural evolution of humans (while technological evolution may be, rather, to a greater extent, driving cultural evolution).

Whatever the social and technological processes at the heart of this, the *paleontological* record will be one of the sudden appearance of an almost surreal hyper-diversity of fossilizeable objects. There are now likely hundreds of millions of distinct "technospecies," many of which are built for robustness and durability[34] – and hence, fossilizeability. This far exceeds a standing stock of biological species; of the order of ten million biological species exist today, many, if not most, soft-bodied and therefore not easily fossilizeable. And, these novel technospecies are now evolving several orders of magnitude more quickly than organisms have evolved at any time in Earth's previous history. The rate of evolution, indeed, is so great that few strata, natural or human-made, will be capable of preserving its precise pattern into the far future. Even a single landfill site may span all of humanity's electronic revolution. Any paleo-archaeologist of the far future[35] will see a transition as abrupt as the Cretaceous–Tertiary boundary, but expressed as an evolutionary radiation – at least of technofossils (and minerals too) – rather than as a mass extinction.

POSSIBILITIES

The possibilities here – of what our far-future paleo-archaeologist might see in the strata that will come to overlie the ones we know – seem too various now to project, perhaps even to enumerate. The trajectory of global warming, of sea-level rise, of ocean acidification, even of mass biological extinction, can be modeled and projected, based in part on solid physico-chemical principles and in part on the many examples we

[34] See discussion in J. Zalasiewicz, M. Williams, C. N. Waters, et al., "Scale and diversity of the physical technosphere: a geological perspective," *The Anthropocene Review* 4, no. 1 (2017): 9–22.

[35] The perplexities of a far-future paleontologist are explored in J. Zalasiewicz, *The Earth After Us: The Legacy That Humans Will Leave in The Rocks* (Oxford: Oxford University Press, 2008), 272.

can read from ancient strata, reflecting the times when the Earth has gone through comparable crises. But, dealing with one of the true novelties of the Anthropocene, the global spread and intensification of the technosphere, we have nothing to go on.

Will the technosphere's evolution be brought to a rapid halt, overwhelmed as its waste products destabilize Earth's heat balance and stifle the capabilities of its human intermediaries to maintain it? Will it undergo a succession of boom–bust cycles before attaining some kind of stable relationship with the biosphere, instead of (as at present) parasitizing and weakening it? Can it become independent of humans – and indeed come to behave as if the biosphere was expendable? Silicon intelligence (that does not necessarily have to be sentient) coupled with technological agency is a wild card in Earth history that makes narrative options alarmingly open.

What will determine which, if any, of these planetary options, which seem more like more lurid sci-fi brought alive than respectable Earth System science, will emerge? And so how different will the emerging Anthropocene be from the Holocene – and from all the preceding geological epochs too? The pathways, at least for now, still largely seem to depend on the interplay of human forces (that in turn determine these physical *forcings* affecting the planet), within familiar political, economic, and social arenas. These are the forces that will be discussed next, as Julia Adeney Thomas takes this narrative further and deeper. *Much* further and deeper, indeed, into realms that are far more complex and mysterious than anything that this simple narrative has produced.

Part of this leap in what one might call the scale of perplexity is the difference between tackling problems of cause and effect. It is a difference that is seen in geology, too. For instance, the end-Cretaceous mass extinction is now pretty well tied down to a giant asteroid impact on Mexico, 66 million years ago. The effects are uncomplicated enough: a whole lot of fossil species disappear at that stratal level, and new ones slowly begin to appear in the younger levels above; a thin layer at the disappearance level appears with more iridium than is seemly, with tiny particles of physically shocked mineral, and so on. It took a lot of steady work to pin down this physical succession (impatient scientists need not

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apply for this kind of task), but the techniques are generally straightforward, and the resulting patterns are as simple as you please – just as sharp and simple as are the Anthropocene patterns of a sudden flood of plastic particles, of a sharp jump in atmospheric levels, and so on. The resulting picture is clearly defined, and about as subtle as a brick.

Ah, but, working out quite *why* the Mexico impact was so lethal is quite another matter. There were other large impacts in the geological record that did not generate anything like so much mayhem within the biosphere – so what particular combination of blast forces, chemical fallout, climate feedbacks, ecosystem responses, and so on (one can carry on adding potentially significant factors for quite some time) were responsible for the scale of the mass kill, and how did they work? This conundrum is still a work in progress.

There are many such riddles in geology, where one has to try to puzzle through the workings of physical, chemical, and biological processes. But none so far, where one has to also factor in investment decisions by brokers, political ambitions, military strategy, religious ideals, community traditions, football team allegiances, tax policy, advertising revenues, agricultural subsidies, women's rights, levels of economic inequality (and here one can go on for *much* longer than in considering the workings of Cretaceous times). All these socio-economic and political factors are in the process of producing geology, some on a huge scale. This is something quite new and quite bewildering for geologists, who are not so much fish out of water here, as fish tipped into outer space on the far side of some distant asteroid.

This is where the kind of narratives developed by Julia Adeney Thomas in the following pages are so important, in beginning the task of making sensible and useful patterns out of this ever-changing and growing maelstrom of human activity. It really is key to understanding, and seeking to come to terms with, the Anthropocene. Such stories, as she says, matter.

And if, all in all, among these stories, amid this interlacing of age-old and terribly new power struggles, the Earth is seen as a player and not simply a stage, then perhaps the Anthropocene can still remain Holocene-like enough to remain a mere epoch, rather than growing monstrously into a period, era, or eon. If it remains modest, it might perhaps remain, also, a friend to us.

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