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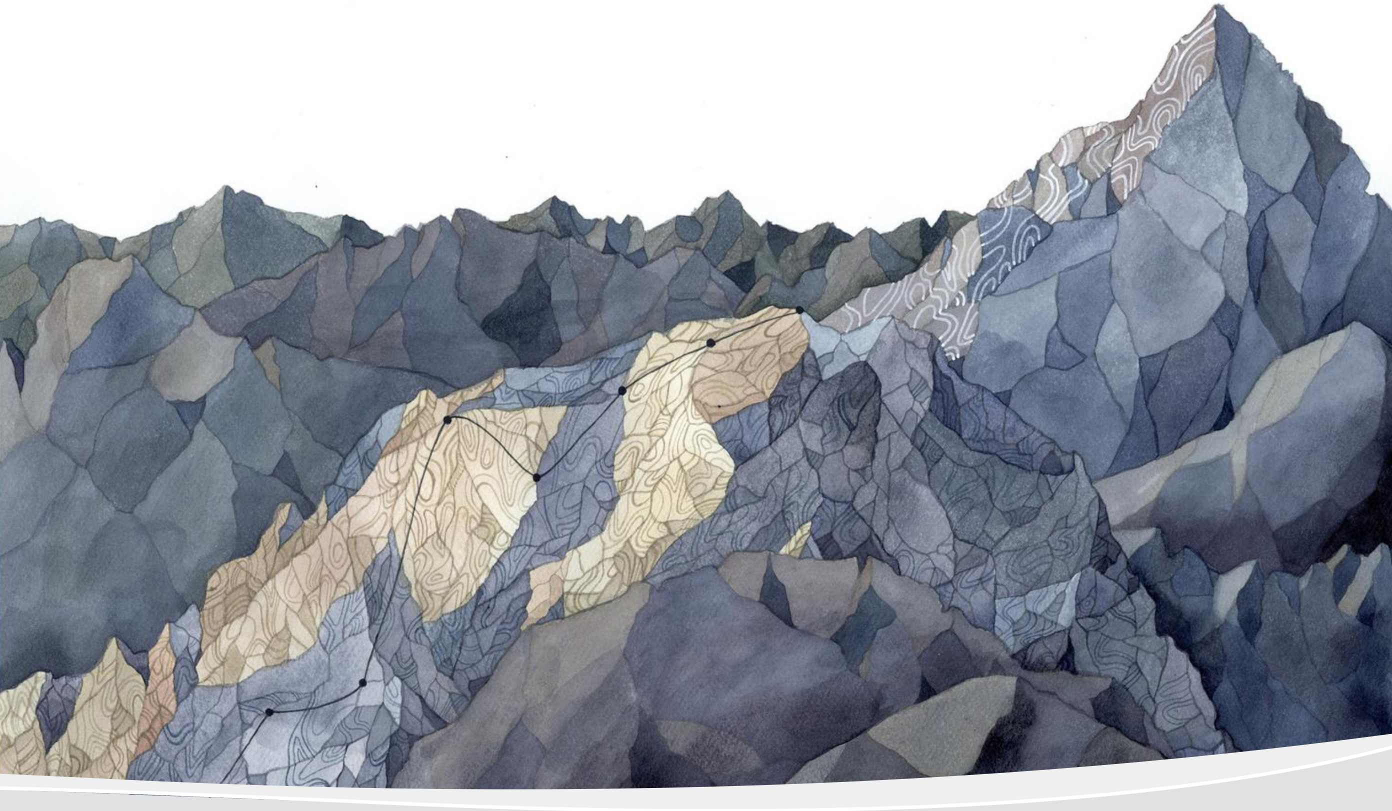
Old and New Patterns of the Anthropocene

Jan Zalasiewicz



Progression, © Jill Pelto

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—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, cities, and then empires, and all the marks of peace such as trade and farming, and of war, with its 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, 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 latest prodigious melt phase, by some seven thousand 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 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, recover, and endure to support the next human adventure. Only—as Paul Crutzen then felt so acutely—at some recent time in history, around about 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]

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[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*, no. 23 (2002): 415.

That word, as we now know, was to catalyze many things in a surprisingly short space of time (indeed, the catalysis 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 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 (GTS)—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 GTS; 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.

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 a supermajority vote. The GTS 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—dimensions that one may term respectively lithostratigraphical, chemostratigraphical, and biostratigraphical, in the jargon of the

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[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).

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 was calculated last year by Clément Poirier, one of the Anthropocene Working Group (AWG) members, and 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 in the atmosphere from the earth/ocean system over the past 15,000 years.

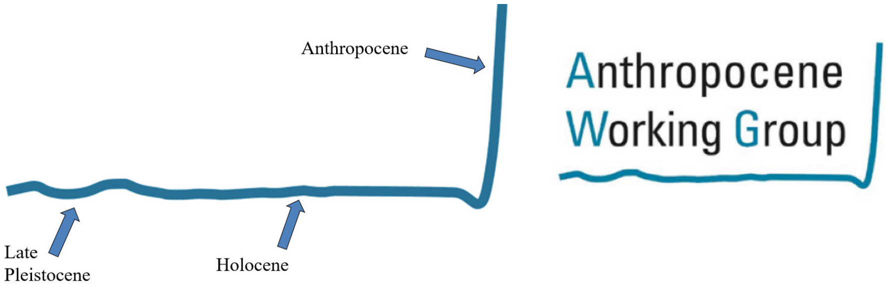

Figure 1. The AWG logo and its origin, based on the rate of change of atmospheric CO^2 over 20,000 years, as worked out by Clément Poirier.

For most of these fifteen millennia, this rate held almost steady. There are some slight wobbles in the first third of the line, representing the standard glacial-to-interglacial rise in atmospheric carbon dioxide from 180 to around 265 parts per million (ppm), largely due to 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

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[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.

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. The second, steeper part represents, from around 1950 CE, the time of the "Great Acceleration" of population, industrialization, and globalization, since which time more than 87 percent of the fossil fuels exploited have been consumed.[4] This is a large part of the reason why the human consumption of energy in the seven decades since 1950 CE is estimated to be greater than that in the previous 11.7 millennia of the Holocene combined.[5]

Carbon dioxide is just one parameter. A very similar pattern can be made from an analysis of human population growth, of atmospheric methane levels, and much else. The well-known "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, 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.

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[4] The diagrams that form the basis for the AWG logo are shown and described in Fig. 1 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): 319–33.

[5] This analysis, which ranges wider than energy consumption, is in J. Syvitski, C. N. Waters, J. Day, J. D. Millman, et al., "Extraordinary Human Energy Consumption and Resultant Geological Impacts Beginning around 1950 CE Initiated the Proposed Anthropocene Epoch," *Communications Earth & Environment* 1, no. 32 (2020): 1–13.

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

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 rise in carbon dioxide 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 in the form of fossilized air bubbles trapped in the annual ice-layers. Without this natural archive, we really would be groping in the dark to 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 carbon dioxide levels that took place during the Ice Age, and their exceedingly close correspondence with the temperature record deduced from other chemical properties of the ice archive: thus, we know that carbon dioxide levels regularly fluctuated between around 180 ppm in cold phases of the Ice Age to around 280 ppm in warm interglacial phases (of which the Holocene is the latest). On this scale, the modern outburst of carbon dioxide is clear as a near-vertical line, extending high above the upper limit 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 of the Ice Age—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—indeed, "as light as air"—they do possess mass. That "extra" human-produced carbon dioxide weighs about a trillion metric tons; that's 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

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[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 Zalasiewicz et al., "A formal Anthropocene," 323.

Figure 2.
The Exhaust © by Anne-Sophie Milon, 2020. The illustration portrays rising levels of atmospheric carbon dioxide that surround us all, invisibly, as we go about our daily lives.

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 fortnight, it will, at current rates, keep up with or outpace the growth of that child.[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 (and converted into carbon dioxide) in a matter of a few years or decades. However, carbon dioxide 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 glaciation of the Ice Age by some 50,000 years (with only modest further emissions being needed to prolong that to 100,000

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[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.

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.

This current increase in carbon dioxide is largely responsible for the rise in the Earth's temperature over the last century, which is now a little over 1 degree Celsius above pre-industrial levels. The rise has been irregular, with pauses, largely because of the irregular way that heat is exchanged between the oceans and the atmosphere during natural climatic fluctuations, such as that of the El Nino–Southern Oscillation (ENSO). Overall, the Earth is still, just, within the "normal" interglacial temperature limits of the Ice Age, although both the oceans and the atmosphere are on a clear heating trend. If continued, later this century the Earth will break through 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 but albeit still an "icehouse" world with a substantial Antarctic ice-sheet. But 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. This would be a fundamentally different kind of planet compared to the current one.[10]

As the Earth slowly warms in response to increased greenhouse gas levels, sea levels also respond, yet more slowly, to the increasing warmth,[11] partly by thermal expansion of seawater and partly through the melting of ice masses on land. So far, total sea level rise above the remarkably stable level of the last few millennia has been in the order of 20 centimeters, which is trivial (almost invisible) on the scale of deep geological time, but is nevertheless enough to result in perceptible changes to contemporary coastlines. The rate of sea level rise has accelerated from some 1 millimeter per year in the mid-twentieth century to around 3 millimeters per year early in this millennium, and up to approximately 4 millimeters per year in the last decade. This recent acceleration is largely due to the onset of major melting of Antarctica's and Greenland's ice-caps since

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[9] This forward projection—or at least a succession of alternative projections, depending on 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. Zannaa, S. Khatiwalab, J. M. Gregory, et al., "Global Reconstruction of Historical Ocean Heat Storage and Transport" *PNAS* 116, no. 4 (2019): 1126.

about 2000 CE—each has lost about 5 trillion tons of ice in that time, while some 10 trillion tons have been lost from mountain glaciers over a somewhat longer time period, 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 carbon dioxide 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 ice melt on Antarctica as the waters around it warmed (sea levels during the third-from-last interglacial period, about 400,000 years ago, may have reached yet higher levels[13]). When considering overall oscillations in sea level over million-year time scales, 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 times. Yet, as already noted, the human impact on this system has now moved, via the emission of greenhouse gases, well beyond the "subtle."

Today, trends in sea level are clearly pointing upwards. Projections suggest anything from a rise of some 65 centimeters to a couple of meters by the end of this century. Beyond this, the amount of further sea level rise will reflect whether carbon dioxide emissions are held back tightly (to allow preservation of most of the Greenland and Antarctica icesheets) or whether they continue to increase based on business-as-usual trends, triggering the ultimate loss of much or most of this ice and leading to a sea level rise of several tens of meters.[14] Given that many settlements on coastlines and deltas have been built to extend to the relatively stable sea level of the mid to late Holocene, even a 1–2 meter rise in sea level (still geologically very small) 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

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[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.

[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.

communities have often made their livelihoods more precarious, too, by settling in low-lying areas that are subject to local subsidence from land drainage and the pumping of groundwater, oil, and gas.[15] So, while sea level rise remains relatively small in relative geological terms, human populations have made themselves exceptionally vulnerable to even the slightest increases. 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 the 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 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 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 expanded further to give about 1,500 minerals, the natural complement of a dead rocky planet. When life appeared more than 3.5 billion years ago it initially made little difference to the Earth's mineralogy. But, when photosynthesis evolved to oxygenate the Earth's oceans and

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[15] J. P. M. Syvitski, A. J. Kettner, I. Overeem, et al., "Sinking Deltas Due to Human Activities," *Nature Geoscience* 2 (2009): 681–89.

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

atmosphere by 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 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 contrived, but there is a practical kind of logic to it. Without it, 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. Native copper is occasionally found, and iron yet more rarely as meteorites (such iron was prized in ancient times, for instance meteoritic iron implements were even found in Tutankhamen's tomb). Most metals in nature, though, are bound within chemical compounds—and humans have become adept at separating them. Firstly copper, tin, and iron in ancient times, and much more recently others such as aluminum and titanium, which 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 entire land surface of the United States 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.

This phenomenon goes well beyond metals; it includes many inorganic crystalline compounds synthesized in laboratories worldwide for a wide variety of purposes, such as novel synthetic garnets for lasers, tungsten carbide for ballpoint pens, semiconductor materials, the abrasive boron carbide ("borazon") that is harder than diamond, and many others. An early 2014 study hazarded that the number of minerals *sensu lato* may

Figure 3. Total world aluminum as kitchen foil covering the United States, © Yesenia Thibault-Picazo.

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 the 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 has, therefore, multiplied the number of "minerals" on Earth more than 40-fold, mostly over the last hundred years or so. In a commentary on this paper, the mineralogist Peter Heaney 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]

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[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.

[19] P. J. Heaney, "Defining Minerals in The Age of Humans," *American Mineralogist* 102 (2017): 925–26.

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 comparisons may be made, such as amber). But this family of modern "mineraloids" is rapidly growing to form a part of—or even overwhelm, some might say—the Anthropocene, with a capacity to become 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 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 ocean currents to distant shores 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 oceans—even sea-floor sediments in the very deep ocean, thousands of miles from land.

It is such a new 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 AWG 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 an important 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 more 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 them into the oceans for centuries, and likely millennia, to come. Those plastics are clearly becoming a damaging (and an indigestible and often lethal) part of the biological food chain, too, hence the rising public concern about them.

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[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.

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 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 ripe for study.

Bulk Materials

Plastics are one kind of newly created material that has 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 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 plastics are a one-thousandth part. Something more than a hundredth 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]

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[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 Waters et al., "The Anthropocene," 2262–62.

[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.

A large part of this crescendo of earth and rock movement is in the digging for such things as coal, where one needs 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 concrete) 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 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 transported annually 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, we are almost literally trudging ankle-deep though the debris of the Anthropocene, with progress becoming almost perceptibly harder each year.

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[24] Zalasiewicz et al., "Scale and Diversity," 12.

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 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 this. Even weighing a forest, which can be imaged precisely with a satellite and walked through in "ground-truthing," is not a trivial task. Nevertheless, a figure was arrived at for the mass of all life on Earth, totaling 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 billion 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 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: 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.

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

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 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 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, so that they could be fed to us. By this means, the total bulk of large vertebrates globally has increased perhaps ten-fold 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) 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 1950s, with the Chicken-of-Tomorrow program spurring American-based competitions that led to intense breeding together with industrial-scale “vertical integration systems,” putting breeding units, farms, slaughterhouses, and

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[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.

marketing into gargantuan combines that now dominate production in the United States and in many other parts of the world. As a result, the chicken 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*, by a considerable margin.

Figure 4.
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 for 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 London and the University of Leicester. Image reproduced here with permission.

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 worldwide appearance 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.

[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.

As one food chain grows, another one diminishes. This is not a pre-ordained rule; but at least for some parts of Earth's biology, it is now empirical observation. The steep decline in large wild animals 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 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 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 no 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, 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 highly urbanized central European

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[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.

country with modern agriculture? No—similar patterns and similar levels of insect decline have been reported elsewhere,[29] in the tropical forests of Puerto Rico as well as in Denmark and the United Kingdom. The precise reasons remain unclear. In Europe, factors such as pesticide use, habitat loss, and light and noise pollution are cited; in Puerto Rico, it's suggested that a warming climate is largely to blame.

Something big is clearly going on—indeed, on 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 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 a 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 marvelous 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, say, mollusks (or even dinosaurs) and paleontology; the insect exoskeleton is marvelously 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

[29] For example: P. Cardoso, P. S. Barton, K. Birkhofer, et al., "Scientists' Warning to Humanity on Insect Extinctions," *Biological Conservation* 242 (2020): 108426.

[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.

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 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 progressive developments in 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.

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,

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[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.

roads, dams, reservoirs, and farms (part of the farm machinery is now that 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.

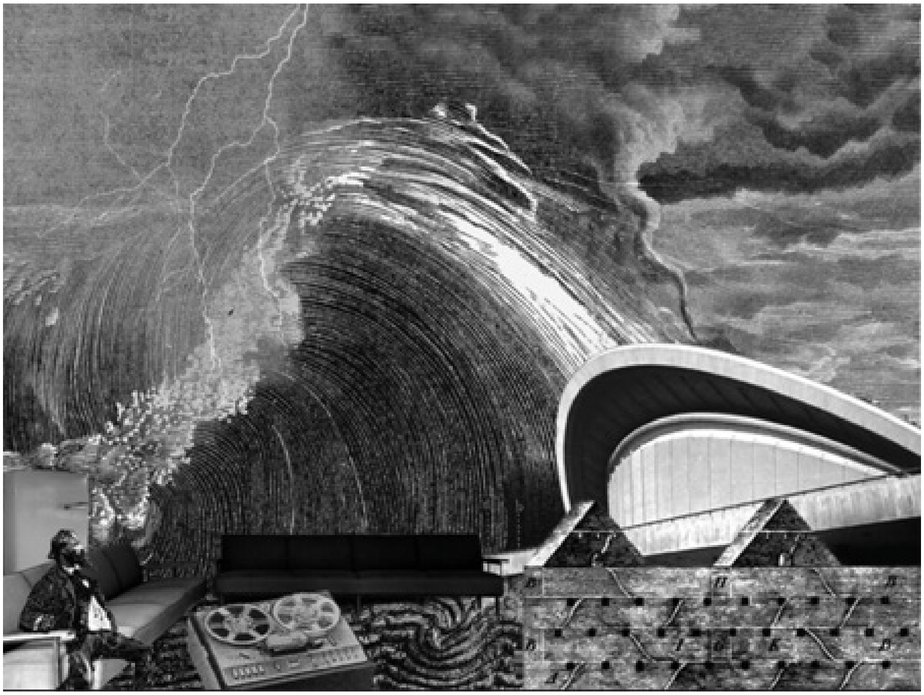

Figure 5.
Image is from the Technosphere Interview Collages created by Nina Jäger for the magazine *continent.*, Issue 5.2 (2016). CC BY 2.0, available from *continent.* via flickr.

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 thirty 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 it to 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 extraordinary 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.

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, formed 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 the 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 their biology, and the complex behaviors that allow such constructions are as much under direct genetic control as are the biochemical processes that make up their tissues and skeletons—and have also been integrated over geological timescales into the ecological webs of the Earth’s biosphere.

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[32] J. Zalasiewicz, M. Williams, C. N. Waters, et al.,“The Technofossil Record of Humans,” *The Anthropocene Review* 1 (2014): 34–43.

[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.

Figure 6. A random selection of discarded technofossils left between the cobbles of a street in Padua. In a form of technological selection, their presence has been determined by their size, shape, and density to escape the street cleaning process, while myriad of their local kin have been carried to a landfill site or incinerator. The cobbles, though more ancient, are now artisanally cemented into place to become technofossils in their own right. Photograph by the author.

Human technology 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; 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 then the last. Technological evolution is now completely divorced from the biological evolution of the 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.

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[34] See discussion in Zalasiewicz et al., "Scale and Diversity," 19–20.

This far exceeds the standing stock of biological species; of the order of ten million biological species exist today, many if not most being soft-bodied and therefore not easily fossilizeable. And, the 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 is, indeed, 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 a far future paleo-archaeologist might see in the strata that will represent our immediate future and 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 modelled and projected, based in part on solid physico-chemical principles and in part on the many examples we can read from ancient strata, reflecting the times when the Earth has gone through comparable crises. But when 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.

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[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.

What will determine which, if any, of these planetary options, which seem more like lurid sci-fi than respectable Earth System science, will emerge? How different will the emerging Anthropocene be from the Holocene—and from all the preceding geological epochs? The pathways, at least for now, still largely seem to depend on the interplay of human forces (that in turn determine the 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 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 and a sharp jump in atmospheric carbon dioxide 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 another matter entirely. 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.