The Anthropocene

Jan Zalasiewicz and Colin Waters

Summary

The Anthropocene hypothesis—that humans have impacted “the environment” but also changed the Earth’s geology—has spread widely through the sciences and humanities. This hypothesis is being currently tested to see whether the Anthropocene may become part of the Geological Time Scale. An Anthropocene Working Group has been established to assemble the evidence. The decision regarding formalization is likely to be taken in the next few years, by the International Commission on Stratigraphy, the body that oversees the Geological Time Scale. Whichever way the decision goes, there will remain the reality of the phenomenon and the utility of the concept.

The evidence, as outlined here, rests upon a broad range of signatures reflecting humanity’s significant and increasing modification of Earth systems. These may be visible as markers in physical deposits in the form of the greatest expansion of novel minerals in the last 2.4 billion years of Earth history and development of ubiquitous materials, such as plastics, unique to the Anthropocene. The artefacts we produce to live as modern humans will form the technofossils of the future. Human-generated deposits now extend from our natural habitat on land into our oceans, transported at rates exceeding the sediment carried by rivers by an order of magnitude. That influence now extends increasingly underground in our quest for minerals, fuel, living space, and to develop transport and communication networks. These human trace fossils may be preserved over geological durations and the evolution of technology has created a new technosphere, yet to evolve into balance with other Earth systems.

The expression of the Anthropocene can be seen in sediments and glaciers in chemical markers. Carbon dioxide in the atmosphere has risen by ~45 percent above pre–Industrial Revolution levels, mainly through combustion, over a few decades, of a geological carbon-store that took many millions of years to accumulate. Although this may ultimately drive climate change, average global temperature increases and resultant sea-level rises remain comparatively small, as yet. But the shift to isotopically lighter carbon locked into limestones and calcareous fossils will form a permanent record. Nitrogen and phosphorus contents in surface soils have approximately doubled through increased use of fertilizers to increase agricultural yields as the human population has also doubled in the last 50 years. Industrial metals, radioactive fallout from atomic weapons testing, and complex organic compounds have been widely dispersed through the environment and become preserved in sediment and ice layers.

Despite radical changes to flora and fauna across the planet, the Earth still has most of its complement of biological species. However, current trends of habitat loss and predation may push the Earth into the sixth mass extinction event in the next few centuries. At present the dramatic changes relate to trans-global species invasions and population modification through agricultural development on land and contamination of coastal zones.

Considering the entire range of environmental signatures, it is clear that the global, large and rapid scale of change related to the mid-20th century is the most obvious level to consider as the start of the Anthropocene Epoch.

Keywords

Anthropocene, stratigraphy, technofossils, chemostratigraphy, extinctions, climate change

The Nature of Geological History

Given that the Anthropocene is typically considered as an interval of Earth history, or stratigraphy, rather than of human history, we need first provide some explanation of the ground rules of stratigraphy.

The enormous duration of Earth history—in excess of four and a half thousand million years—is made tractable by means of the construction of the Geological Time Scale and of its units. This involves separating out intervals of Earth history that are distinctive because they share recognizable combinations of the Earth's preserved biological, chemical, or physical characters.

Within stratigraphy there are two parallel means of classifying Earth history. There is a classification simply as time intervals within which certain events and processes took place (for example, the Jurassic Period). Then, there is also a parallel time-based classification of the material (stratal) record that preserves the evidence of that history (thus, the Jurassic System, comprising all the strata laid down during the Jurassic Period).

Both sets of time units are defined using a prominent and widespread environmental change. Typically for the last half billion years of geological time, this is through recognition of the appearance of a common and representative fossil species, which broadly coincides with that environmental change. However, such a species would not have appeared (or disappeared) everywhere simultaneously around the world and hence, cannot define a single time plane but it is a *guide to* the time boundary. Geologists circumvent the problem by selecting, at one place in the world, a single level at which this fossil first appears, and then define this as the instant when the time interval begins. Then, geologists try to trace this level within strata all around the world, by any means possible. This single level is the well-known "golden spike," more technically, a Global Boundary Stratigraphic Section and Point (GSSP). Importantly, the exact level chosen remains the reference point, even if the key fossil is later found to have appeared lower down in strata (i.e., earlier) at the same location (which has indeed sometimes happened).

The Geological Time Scale is also hierarchical, with smaller units of shorter duration and less markedly distinctive character, nested within larger ones. We currently live within the Phanerozoic Eon, the fourth eon of Earth time, which started some 542 million years ago, with the defining event being the evolution of multicellular animals from the single-celled organisms that had comprised life on Earth beforehand.

Within the Phanerozoic, we live within the last of its three subdivisions, the Cenozoic Era, which began 65 million years ago, at the mass extinction event that saw the disappearance of the dinosaurs (and of many other lifeforms across the planet). This dynastic change to the Earth system was abrupt and caused, or largely caused, by a large meteorite strike, which over large parts of the world is recorded as a thin layer with high concentrations of iridium, an element rare at the Earth's surface but common in meteorites.

Within the Cenozoic, we live in the last of its three subdivisions called the Quaternary Period (the strata of which comprise the Quaternary System). This commenced two and a half million years ago. In general, it is the time from when the world most recently entered a phase of overall bipolar glaciation. Within the Quaternary, we formally live within the Holocene Epoch. This is just the latest of some 50 marked oscillations of climate within the Quaternary Period, when the world emerged from a phase of glacial climate and high global ice volume (and therefore low sea level), into a warm (or interglacial) phase with higher sea level. Although it is just one of many interglacials, it is the one that has experienced a human population explosion, while its deposits (i.e., the Holocene Series) make up important parts of our landscapes—soils, river floodplains and coastal plains, deltas and so on.

The formal definition of the Holocene Epoch is also relevant to the consideration of the Anthropocene. The Holocene, until 2009, used to be defined numerically (as are, still, most of the geological time units prior to the Phanerozoic). Its beginning was placed at 10,000 radiocarbon years before the present (the present being defined as 1950 CE in this case). Studies of both Greenland ice cores and deep ocean sediments showed that the northern hemisphere last emerged from glacial cold into temperate warmth with extraordinary abruptness: a good deal of the change took place over a mere three years. This change can be identified in Greenland ice layers, which in this narrow time interval show chemical evidence of suddenly increased warmth and humidity (the ice layers become thicker and less dusty). Hence, the boundary level has been placed at the ice layer that shows the beginning of this change. As a historical event, it is thus located very precisely, with approximately annual resolution; however, because of the difficulty of working out precisely when this took place, there is a larger error bar (of a couple of centuries) of quite how long ago this happened. This uncertainty is expressed as the boundary in the "golden spike" ice core being dated to 11,700 years before present (the present now being taken to be 2000 CE) plus or minus 99 years. The resultant interplay between relative and "absolute" (numerical) dating is also of significance to defining the Anthropocene.

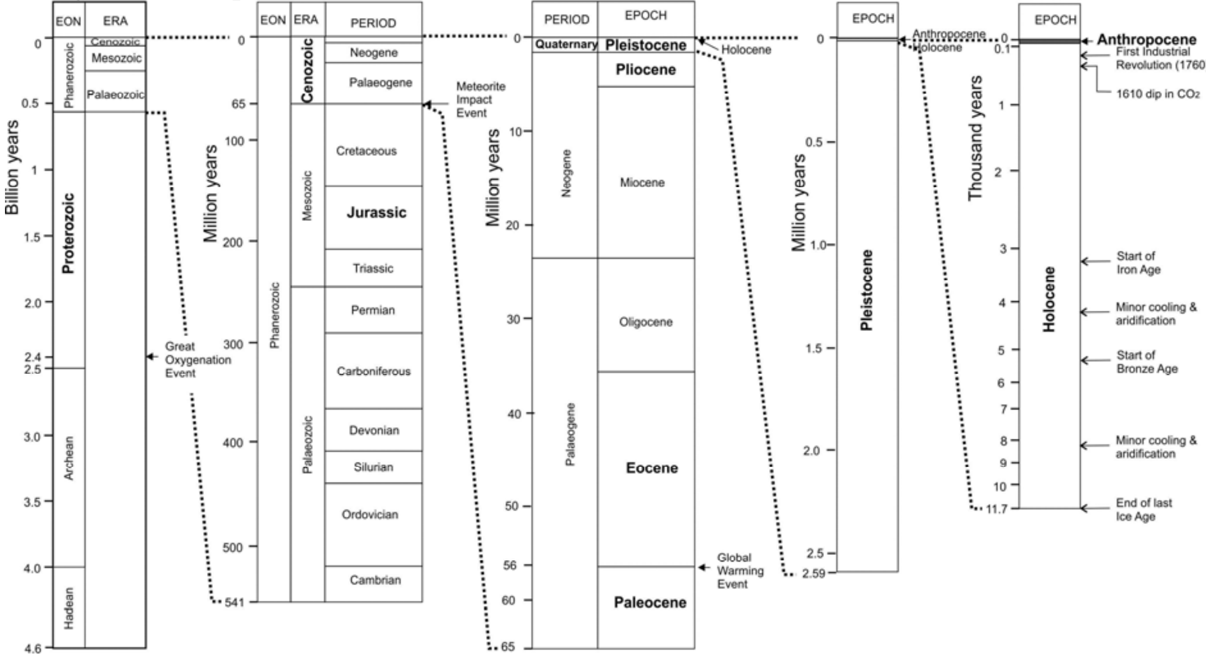

Figure 1: Geological Time Scale, with increasing resolution to the right, showing the extremely short duration of the Anthropocene in comparison with all geological time. Geological time units that are referred to in the text are shown in bold and selected events are indicated. Sourced from the ICS Geologic Time Scale.

The Anthropocene: Historical Beginnings

We still live, formally, within the Holocene Epoch. However, the general idea that humans can cause significant change to the Earth has been circulating for a long time—since, the Comte de Buffon's 1778 work *Les Époques de la Nature*. In this, Buffon divided our planet's history into seven epochs, the last and current one being "when the power of Man assisted that of Nature."

The idea resurfaced intermittently. George Perkins Marsh, the "first American conservationist" catalogued human-driven environmental change in his 1864 *Man and Nature*; Antonio Stoppani, in his 1871–1873 *Corsa di Geologia*, suggested an "Anthropozoic Era," emphasizing that the human activity was changing not just the Earth's present, but its future also. In the early 20th century, the Russian scientist Vladimir Vernadsky developed the concept of the Earth’s biosphere and, with Eduard Roy and Teilhard de Chardin, of the noosphere (a “sphere of human thought” now enveloping the Earth). At the same time, the geologist Robert Sherlock took a more material approach, counting up the impressive amounts (even then) of rock and soil moved and transformed into construction materials by humans.

These early ideas were, until recently, not taken seriously by geologists. Appreciation of the very great age of the Earth rendered the human timescale almost absurdly short by comparison. And, the very great geological transformations of the past, including the growth and erosion of mountain ranges, the creation and destruction of entire ocean basins, and extraordinary volcanic outbursts and meteorite strikes, seemed to make the transformations wrought by humans both superficial and fleeting.

A wider realization that human impact could be geologically significant came with the development of what has become known as Earth system science, in which it became clear that seemingly subtle changes (for example, in the levels of the trace gases, carbon dioxide and methane, in the atmosphere) could nevertheless have far-reaching changes to the Earth system, largely via changes in climate. The scale and long-term effects, too, of changes to the Earth’s biology was becoming more widely understood, too, as was the scale of physical change to the Earth’s surface.

Several “geological” time terms arose in the late 20th and early 21st century to express this appreciation. There was the Anthrocene of the environmental writer Andrew Revkin, the Homogenocene (to reflect the homogenization of the Earth’s biological communities via human-driven species invasions) of the zoologist John Curnutt, the Myxocene of the oceanographer Daniel Pauly (to denote the future ocean of “microbial slime and jellyfish”) and so on.

However, the term that caught on was independently created by two scientists, Eugene Stoermer and Paul Crutzen. At a meeting of the International Geosphere-Biosphere Program (IGBP) in Mexico in 2000, Crutzen had been listening to debate where the present state of the Earth was continually being referred to as the Holocene. At one point he lost patience, and interjected that we were not in the Holocene but in—a and here he improvised the word—the Anthropocene. Much of the subsequent discussion, he recalled, revolved around this new idea.

He later researched the term, found that Stoermer had independently coined it, and wrote to him, suggesting they published jointly on it, which they did in the *IGBP Newsletter* (Crutzen & Stoermer, 2000), where this idea was first disseminated within an Earth systems science community. Subsequently, Crutzen restated the concept in *Nature* (Crutzen, 2002), which was when the term obtained global exposure.

From then, the term began to be used increasingly frequently in the literature, both within the earth sciences and also more widely beyond it. Commonly, it was employed simply as if it was part of the Geological Time Scale. However, the Anthropocene was (and remains) informal and it was rather vaguely defined, with a range of ideas about its duration, definition and hierarchical level, often being referred to somewhat interchangeably as either an epoch or an era—two very different things in formal stratigraphy.

Hence, the Anthropocene was discussed by the Stratigraphy Commission of the Geological Society of London, to see whether there was sufficient evidence for it to be formally considered as a time unit (Zalasiewicz et al., 2008). The majority view was that, at least on preliminary inspection, there was merit in the term, and it might be considered further with a view to eventual possible formalization. However, this national commission does not have any power over the international Geological Time Scale, which is not easily or lightly amended. As its terms underlie basic communication in the Earth sciences, there is a need for stability of nomenclature, and hence the approach taken to its modification is deliberately conservative.

In 2009, an Anthropocene Working Group, part of the Subcomission on Quaternary Stratigraphy, a component part of the International Commission on Stratigraphy (itself under the aegis of the International Union of Geological Sciences) was established, to gather and consider evidence regarding the Anthropocene as a formal unit. So far, it has produced two thematic sets of papers, published by the Royal Society (Williams, Zalasiewicz, Haywood, & Ellis, 2011), and the Geological Society of London (Waters, Zalasiewicz, Williams, Ellis, & Snelling, 2014) and a number of other articles. It aims to produce a body of evidence, together with (at least interim) recommendations, by 2016.

Stratigraphic Analysis of the Anthropocene

Analysis of the Anthropocene may partly be carried out by “classical” analysis of information contained within strata, particularly where these form well-ordered successions (annual layers of snow on ice-caps, or sediment laminae in lake deposits). However, unlike exploration of older Earth histories, there is also an increasingly sophisticated and detailed observational record over the past centuries and (especially) decades. So, analysis may also involve taking “environmental” evidence and translating this into geological, and more precisely stratigraphic, terms. The analysis is rendered yet more complex both by the very short timescales involved, and also by several novel aspects of human-driven geology, that have little or no precedent in Earth history.

In outline, the evidence may be ordered as in classical stratigraphic analysis, involving physical aspects of the deposits (within lithostratigraphy), chemical signatures (chemostratigraphy), and biological patterns (biostratigraphy). These together provide the basis upon which chronostratigraphic division might be attempted (to define a recognizable and correlatable Anthropocene Series), the material equivalent of a time unit of the geochronological time scale (a putative Anthropocene Epoch).

Lithostratigraphy

The mineral signature

The material record of the Anthropocene consists in essence of the rock succession that will result, albeit that much of that now consists of unconsolidated sediment. Rocks and sediments are made of component minerals, and hence the mineralogical signature of the Anthropocene is a fundamental part of its characterization.

Here a deep-time context may be provided by the review of Robert Hazen and his colleagues, who proposed a pattern of mineral evolution that showed an increase in mineral diversity from about a dozen or so minerals recognized in cosmic dust, to an increase through reactions that take place in the spinning debris disk around a young star (about 250 minerals that have been recognized in meteorites). Once a planet forms, the melting and crystallization taking place at different depths further increase the number of minerals, while on Earth the processes and diversity of mineral-forming environments associated with plate tectonics increased the number still further, to around 2,000 minerals. The origin of life, in particular the beginning of photosynthesis and resultant oxygenation of the atmosphere, known as the “Great Oxygenation Event” of the early Proterozoic, about 2.4 billion years ago, roughly doubled the number of minerals, to a little in excess of 4,000 by creating a wide range of new oxides and hydroxides. Most of these minerals are extremely rare. Subsequent changes, including the origin of multicellular animals, considerably increased the diversity of mineral shape (in complex shell-related forms, for instance) but added little to the total inventory of mineral species.

Humans have added a considerable, if poorly constrained, number of minerals to the Earth's inventory as detailed by Zalasiewicz, Kryza, and Williams (2014). Prominent among these are uncombined metals (which are rare in natural settings), including iron and steel, aluminium, titanium, copper, vanadium and others. These have been made in very considerable amounts. For instance, some 500 million tons of aluminum have been produced globally to date, almost all since the mid-20th century—enough to completely coat the United States (and part of Canada) in standard aluminum kitchen foil. The amount of iron and steel produced has been roughly an order of magnitude greater. Other novel minerals include boron nitride, an abrasive that is harder than diamond, tungsten carbide (that makes the ball in many ballpoint pens), novel garnets (for lasers), graphene, and so on. There are also common "mineraloids," notably glasses and plastics made in very large amounts (some 6 billion tons of plastics have been produced to date, for instance, again almost all since the mid-20th century) and widely distributed over the Earth's surface. There are also minerals that, relatively rare in nature, have now become much more widespread, such as ettringite, hillebrandite, and portlandite in cement and concrete. There are novel and widespread mineral forms too, such as fly ash (both spherical carbonaceous particles and inorganic ash spheres) that have been dispersed since the mid-19th century from the early industrialized countries, and in greater amounts and globally since the mid-20th century.

The scale of mineralogical novelty, the product of many active materials sciences laboratories, is increasing, but quite unknown in detail. However, the scale of this new phase of mineral evolution is almost certainly the greatest since the "Great Oxygenation Event." The longevity of these minerals fossilized within strata is untested in detail (given that by definition they have no precise natural analogues), but it seems likely that many can survive in some form buried within strata.

The rock signature

Minerals make up rocks, and humans have made a significant addition to Earth's inventory of rock types. The most widespread and conspicuous are those associated with construction of different types: concrete, brick, cinder-block, asphalt, plaster. There are also heterogenous "rock types" associated with garbage-dump fills, and more specific lithologies such as ceramics of different types.

Concrete is a major and distinctive component. It is a combination of cement (itself largely a combination of limestone and clay, fired to produce a mineralogy that transforms and hardens with the addition of water) and aggregate (typically sand and gravel). It is a cheap, easily moulded, and robust building material that has been used since at least Roman times (much of the Colosseum is made of it, for instance), but which in recent decades has been used in extraordinary quantities. The total amount produced worldwide is of the order of 500 billion tons, which is equivalent to about a kilo for every square meter of Earth, land, and sea. Of that, well over 90% has been made since the mid-20th century, and over 50% in the last couple of decades—and its production is still accelerating. Concrete blocks, invented in the 1830s, have seen technological innovation with development in the 1930s of lightweight cinder/breeze blocks which incorporate fly-ash wastes and reinforced concrete, with internal iron bars providing the reinforcement that allowed development of tower-blocks, the urban innovation of the 20th century.

Bricks are essentially metamorphosed clays with various admixtures of sand, where the heating process in kilns is taken to the point of melting. This scale of rapid heating is unusual in nature at the Earth's surface, and so bricks have a distinctive texture and mineralogy. Bricks have been made for several millennia (the early ones typically sun-dried), and their production now exceeds a trillion a year. Similar techniques were employed to produce ceramics and pottery. Important for producing food storage vessels and for artistic figurines, these materials form a common component, and are used to date, the archaeosphere (Edgeworth et al., 2015).

The global road network is about 50 million kilometers, the distance from Earth to Mars. Much of this is graded soils, but in Europe and North America tarmacadam, an asphalt/aggregate admixture, with an aggregate sub-base forms the dominant road type with some 1600 million tonnes of asphalt produced in 2007.

A particular form of "rock" is that in garbage dumps. Typically a highly heterogenous and poorly sorted conglomerate or breccia, its individual components reflect the human activities of the times, including unused food material, packaging, disused furniture and building material, clothes, nappies, and toys. The middens of archaeological times are often dominated by shell and bone material, while today's rubbish dumps have metals, plastics, and paper as major components (Ford, Price, Cooper, & Waters, 2014). These rock types can make up substantial strata.

Anthropogenic strata

Minerals and rocks are arranged into strata of various types and geometrical shapes, and the classification of rock strata is the business of lithostratigraphy. The classification largely reflects their physical nature and mineral composition.

While this account focuses on human-influenced strata, it must be recognized that the Anthropocene (formal or informal) is simply a time unit, which will include anthropogenic strata, strata which appear "natural" but which have some anthropogenic characters on closer examination, and strata which will have little or no human influence even upon close examination. Similarly—and depending where the Anthropocene boundary is placed—strata that remain within the Holocene may include a notable anthropogenic component.

The terrestrial realm

Human influence is most visible and pronounced in the terrestrial realm and humans have modified the ground surface in various ways: to provide habitation, to enable transport, to grow crops, to extract resources, to create agreeable (to us) landscapes in peacetime and degraded ones in war. These surface alterations almost always include a third dimension, hence a subsurface component.

Therefore these anthropogenic surfaces may be underlain by what geologists term as artificial ground, and what has recently been termed the archaeosphere (human-disturbed ground, often including artefacts, that lies above the "natural") within the archaeological community (Edgeworth et al., 2015). There are also soils of various kinds, which are strongly modified by humans in agricultural and urban settings, and where (particularly for the latter) the term "anthrosols" has been proposed.

Artificial ground of various sorts is common to ubiquitous in urban areas, and increasingly figures on geological maps because of its importance to engineers and environmental planners. It may be meters to tens of meters thick, and in general it is voluminous. In the United Kingdom alone, almost a billion tons of rock and soil are moved annually by human activities and the scale of this activity worldwide is now greater than that of natural processes of erosion and sedimentation—perhaps by as much as an order of magnitude.

These heterogeneous strata can be classified in great detail but there are some main general categories, recognized by such organizations as the British Geological Survey (Ford et al., 2014): made ground is material dumped on the surface, as in raised embankments; worked ground is simply excavations in the ground, such as quarries and road cuttings; infilled ground represents holes in the ground, that have been wholly or partly infilled, such as quarries that have become landfill sites; disturbed ground is rock that has been involved, say, in a zone of collapse around an old underground mine working; and landscaped ground is a general term used where it is difficult to distinguish the various other individual categories, such as is the case beneath much urban housing.

As well as deliberately moved rock and soil, and the soil moved in agriculture, there is the human impact of increased sediment transport in rivers in response to deforestation and introduction of agriculture; this has been evident for thousands of years and has increased with time. However, the great number of dam schemes across major rivers, most constructed since the 1940s (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015) has caused large volumes of sediment to accumulate behind the dams (Syvitski & Kettner, 2011). There are more subtle effects associated with changes in land use. For instance, in the Fenlands of eastern England, there used to be a surface peat stratum up to at least four meters thick, extending over something like 2000 square kilometers. This has almost completely disappeared, mostly since the 19th century, by deflation (windblow) and oxidation following drainage of the ground.

Subterranean modifications

The human-modified areas have deep roots. Extending beneath urban, agricultural, and what may be otherwise considered "wild" landscapes are foundations and tunnels, underground wires and pipes, and mines and boreholes used for the extraction of resources including metals, coal, oil and gas, and water. These may be regarded as analogous to animal burrows, but whereas nonhuman animals typically burrow to a maximum of only a few meters depth, human burrowing—that has been termed anthroturbation—extends to several kilometers depth (Zalasiewicz, Waters, & Williams, 2014). It is extensive; oil boreholes alone in the United States have been calculated to total some 5 million kilometers in length, and a total for the world might reasonably be 50 million kilometers, roughly the same as the total length of the surface road network. There are substantial amounts of other boreholes, too—for water, mineral exploration, and for scientific purposes like those of the Ocean Drilling Project. In one particular borehole type, atomic bombs were lowered down along them, to be detonated as tests. Between 1951 and 1998, some 1500 underground nuclear explosions were detonated to produce large (up to hundreds of meters across) masses of radioactive breccia and melt rock up to two kilometers underground.

The scale and nature of this anthroturbation is geologically novel, and these traces, being well below surface erosion processes, will persist for many millions of years in the rock mass. Stratigraphically, however, it is not simple, as these structures always cross-cut older rocks, and hence behave geologically a little like the sheets of magma that inject along fractures (igneous dykes) underground.

Coastal lithostratigraphic signals

A range of specific human-driven lithostratigraphic signals are present around coastlines, partly because of the concentration of human habitation around the shore, where coastal plains and deltas have for centuries offered fertile ground with access to marine resources and communication. Phenomena here (often generated or accelerated in more contemporary times) include various harbor and breakwater structures and, more extensively, meters-scale subsidence caused by groundwater and hydrocarbon extraction, sediment loading by buildings and sediment starvation as a result of the building of dams upriver. Deltas worldwide, notably the Mississippi, Ganges, and Yangtze, have shown, as a consequence, a pattern of subsidence that broadly began in the 1930s and is at a rate that greatly outpaces current relative sea level rises associated with global warming (Syvitski & Kettner, 2011).

Other major changes resulting in large anthropogenic stratal bodies are the building up of shorelines in land reclamation including in a number of cases the use of garbage as fill material. Well-known examples include Palm Island and Hong Kong airport (Syvitski & Kettner, 2011), while a less well-known but even larger-scale example is the building of a sea wall along the Chinese coastline that will be ultimately 11,000 kilometers long, dwarfing the examples in, for instance, the Netherlands. These structures are not only very large rock bodies in themselves, but they also heavily modify the nature of sedimentation both in front and behind them.

The continental shelf and slope

The undersea realm has a far shorter history of direct human perturbation than the terrestrial realm. Physical anthropogenic change in this realm now includes such engineered structures as oil platforms and pipelines.

The most widespread impact is bottom trawling, the dragging of weighted nets along the sea floor to capture bottom-living fish, shrimp, and other edible marine creatures. This has been practiced in some shallow near-shore waters since at least the 14th century, but with the advent of powered fishing-boats has now impacted on most continental shelves, in recent decades extending into continental slopes down to depths of one kilometer. The effect is similar to that of plowing on land, and can be similarly destructive to native biota. The most obvious examples of major perturbation are the trawling of slow-growing deep-water coral stands, which are devastated by the practice. Elsewhere, the repeated scraping of the sea floor can smooth topography and redistribute sediment, typically releasing plumes of fine sediment that drift off into deeper water, leaving a reworked surface layer (often with a coarsening-upward pattern) in which the biological composition shifts toward those species that are tolerant of (or even favored by) repeated disruption.

Deep ocean anthropogenic signature

The deep ocean has so far been affected by little in the way of direct sediment redistribution or the siting of engineered structures. However, the deep-sea sediments, which range from relatively rapidly accumulated turbidite deposits to very slowly accumulating pelagic oozes, have been increasingly affected by the addition of anthropogenic debris of different types. Scattered shipwrecks have been landing on the sea floor since humans began seafaring, but their number has been increasing in tandem with the development of global trade in which now 90 percent by volume is transported by sea. There is material simply dropped overboard, and the garbage signature has changed as technology has changed. One characteristic element comprises the “trackways” of coal clinker along the routes of the old steamships. More modern elements, and more widely dispersed, are tins and glass bottles and (since the mid-20th century) plastic, ranging in size from microplastic particles (now recognized to be almost ubiquitous in modern marine sediments) to larger objects, not least discarded fishing nets. As exploitation of the marine realm continues, it seems likely that characteristic new strata will be formed in the near future, such as those resulting from the extraction of deep-sea manganese nodules across wide areas of the abyssal plains.

Chemostratigraphy

Chemostratigraphy in geology is a rapidly developing tool that can help correlate strata of all ages across wide areas by means of particular features of chemical composition. It may involve both organic and inorganic components, and a particularly widely used aspect is ratios of isotopes of various elements (such as carbon, oxygen, nitrogen, neodymium) because these can be expressed and maintain their pattern in rocks of widely different contents of the elements involved—and also because these isotopic ratios often reflect fundamental changes to the Earth system. A number of chemical changes and patterns are associated with the Anthropocene, because of the extent of human modification of surface processes, and some of these chemical signals may prove crucial in defining this time unit.

Carbon

There are a number of surface-related reservoirs of carbon including living organisms, soil, permafrost, atmosphere, ocean waters (a much bigger reservoir than the atmosphere) and sub-seafloor sediments. Carbon is cycled through surface and subsurface environments on various time scales. Short-term cycling is associated with photosynthesis and respiration, and long-term cycles with carbon burial in strata and exhumation, and yet longer ones with carbon being taken into the Earth's interior via subduction zones and released by volcanism. Levels of the greenhouse gas carbon dioxide in the atmosphere have been a primary determinant of climate over geological time, as exemplified by the variations in its levels between ~180 ppm in glacial phases of the Quaternary and ~260–280 ppm in interglacial phases. The bulk of this gas is taken into the deep ocean in glacial phases and released at the beginning of interglacial phases, with observed close correlation of global temperature and carbon dioxide levels seen in ice cores (Wolff, 2014).

Human perturbation of the carbon cycle, largely by the burning of fossil fuels, has seen atmospheric carbon dioxide levels rise from ~275 ppm at the start of the Industrial Revolution to ~400 ppm today, with the bulk of the rise since the mid-20th century (Steffen et al., 2015). Although this can be directly seen in ice cores, a much more widespread (and permanent) signal in rock and fossil material reflects the input into the atmosphere of isotopically light carbon (i.e., with a greater proportion of ^{12}C to ^{13}C) derived from hydrocarbons. This produces a large, rapid negative (i.e., light) carbon isotope shift in, for example, the shells of foraminifera (common marine protozoans that secrete a calcium carbonate shell and so provide a widely used palaeoenvironmental archive in Cenozoic deposits). This shift is already of some ~2 permil (parts per thousand) in size. Significant geologically, this isotope anomaly is similar to (if still smaller than) the negative carbon isotope anomaly that was produced in an ancient carbon release/global warming event at the end of the Paleocene and beginning of the Eocene epoch, 55 million years ago, and used to define the base of the latter. The developing carbon isotope anomaly for the Anthropocene can form an equally striking marker.

A 1610 dip in atmospheric CO_2 has been linked to depopulation of about 50 million people following colonization of the Americas and has been proposed as a potential signature for the start of the Anthropocene (Lewis & Maslin, 2015).

There are other effects of the carbon dioxide input, including acidification of the oceans (Tyrrell, 2011) that also shows a marked change since 1950 (Steffen et al., 2015). This can produce physical effects (the acidification event at the Paleocene-Eocene boundary literally dissolved large areas of the ocean floor to produce a carbonate gap), but is of more significance as regards biological effects to organisms, including reef corals, that secrete skeletons of calcium carbonate.

Nitrogen and phosphorus

The doubling of the surface reservoir of reactive nitrogen, largely caused by the production of nitrogenous fertilizers from atmospheric nitrogen via the Haber-Bosch process, is a significant event in geological history. The relative scale is difficult to quantify, but this perturbation has been regarded by some scientists as the greatest change to the nitrogen cycle since the Great Oxygenation Event of the early Proterozoic, 2.4 billion years ago. Its reflection in strata is not straightforward, but a generally consistent change in nitrogen isotope composition has been detected in lakes far from direct human activity (Wolfe et al., 2013), presumably via long-distance transport of nitrogen-containing aerosols (which also fertilized the lakes to produce a change in the assemblages of diatoms—microscopic single-celled plants that secrete a siliceous shell). These changes began to appear after 1850, but accelerated in the mid-20th century, concomitant with the great expansion of nitrogenous fertilizers (Steffen et al., 2015), and have been suggested as providing the basis for a “golden spike” for the Anthropocene (Wolfe et al., 2013). Elevated ammonium concentrations are also found in mid-latitude glaciers in response to agricultural emissions and in Greenland nitrate levels rose by a factor of two during the twentieth century, mainly between 1950 and 1980 to levels higher than over the previous 100,000 years ago (Wolff, 2014).

The content of phosphorus in surface soils has also roughly doubled, though in this case from the excavation of phosphorus from ground-based sources by mining. Although a consistently detectable stratal “phosphorus anomaly” has not been reported, one effect of the increases in both nitrogen and phosphorus has been the creation and growth of “dead zones” in the ocean (Tyrrell, 2011). These are the result of runoff of excess fertilizers via rivers into shallow, poorly circulating coastal waters. These stimulate plankton blooms which, upon dying, sink to the sea floor and decay, using up dissolved oxygen and suffocating bottom-living faunas; these are generally seasonal kills, as autumn and winter bring storms which stir oxygen back into the waters (hence the surviving biota is that best adapted to rapid recolonization). Currently there are about 400 dead zones in the world, covering in total an area of some 250,000 square kilometers, the best known being in the Baltic Sea, the Gulf of Mexico, and Chesapeake Bay of the eastern United States. Although these phenomena are not yet on the scale of anoxic events of the geological past, further atmosphere/ocean warming will cause the seas to become more strongly thermally stratified, and so more prone to oxygen deprivation.

Metals

The importance of metals to the technology of human civilization means that there has been considerable “selective erosion” of them by mining, to bring them from subsurface (often deep subsurface) levels to the surface. Although much of the metals have been processed into artifacts of different kinds, the overspill from the mining, smelting, and production processes have spread metal-rich plumes into waters, soils and near-shore marine sediments. Working out the precise scale of these local metal anomalies is not straightforward, as pre-disturbance background levels need first to be evaluated, but clear enrichments in the environmental levels of lead, cadmium, mercury, and other metals have been widely recognized in industrialized regions (Gałuszka, Migaszewski, & Zalasiewicz, 2014). More widely, aerosols (particularly of lead, from smelting and formerly from lead additives in fuel) have changed the composition of peat bogs, glaciers and icecaps, and these changes may readily be detected. Indeed, various sources of lead have been discriminated in these stratigraphic archives by means of lead isotope ratios, and these patterns are significant to defining and recognizing the Anthropocene.

Organic compounds

In addition to the many thousands of new solid mineral forms that human industry has created, there are many thousands of compounds, notably complex organic compounds, which have been created for various purposes and have subsequently been dispersed through the environment. Among these are what have been termed "persistent organic pollutants" (POPs), which are only degraded slowly in the natural environment, some with half-lives of at least decades, which are only weakly soluble in water and tend to bind to sediment, especially clay particles. Hence, rather than simply traveling with water through the surface and subsurface environment, they can be preserved within sediment layers as an archive of the history of the arrival of these POPs into the local environment. Lake sediments are among the best of these archives, though these compounds have also been detected in sediments within rivers, estuaries, and seas.

POPs include organochlorine pesticides such as aldrin, dieldrin, and DDT, and industrial chemicals such as the polychlorinated biphenyls (PCBs) and dibenzofurans. In parts of the world these chemicals were only used for a few decades, before adverse environmental effects caused them to be banned, while elsewhere their use persisted. Hence they can provide a complex stratigraphic pattern involving their invention, more or less widespread use, and termination of input through legal ban or obsolescence.

Stratigraphical analyses of POPs have come a distant second to environmental monitoring studies, but the research carried out to date have shown that, superimposed on geographical variability, many of the commoner and more distinctive POPs appear from the mid-20th century. How long will this signal last? This will clearly vary from compound to compound, and being novel compounds there are no direct analogues. Nevertheless some organic compounds can persist for millions of years in strata essentially unaltered, such as the "TEX" long-chain alkanes used for palaeotemperature analysis of Cenozoic ocean floor strata.

Artificial radionuclides

The explosion of the first nuclear ("Trinity") test bomb at Alamogordo, New Mexico, on July 16, 1945, began the dispersal of novel radionuclides into the surface environment (Zalasiewicz et al., 2015). This early test, and the only two (thus far) wartime uses, at Hiroshima and Nagasaki, Japan, only produced local effects (including the beginning of the formation of a fused radioactive sand rock type, trinitite, around the test site). However, many subsequent tests, from the early 1950s until the comprehensive test ban treaty in 1996 (albeit still not ratified), saw the global dispersal of these radionuclides worldwide, mainly in mid-latitudes, but with clearly detectable amounts in low-latitudes and both the Greenland and Antarctica icecaps (Waters et al., 2015). Other sources of widespread radioactive pollution include the nuclear accidents at Windscale (now Sellafield, Cumbria, U.K.) in 1957, Chernobyl, Ukraine, in 1986 and Fukushima, Japan, in 2011, and also events such as the fall of the SNAP 9 satellite off Mozambique in 1964 and the Soviet Kosmos 954 satellite over Canada in 1978, scattering radioactive debris.

The novel radionuclides involved—including caesium, americium, and plutonium—have different half-lives, the longest being that of plutonium 239, the signal of which can remain detectable for ~100,000 years (Waters et al., 2015). There was also significantly increased production of ^{14}C above its natural abundance, a signal that was absorbed within many carbon reservoirs including wood and shell and bone material, to form another clear nuclear "spike" that will endure roughly half as long as will the plutonium signal.

This artificial radionuclide signal is not problem-free. Radionuclides can migrate within some sediments, rather than staying absorbed to the sediment lamina they were deposited in. And, particularly in deep ocean settings, the radionuclides can make a long (decades) journey before eventually settling to the sea floor. In deep-sea settings, too, the burrowing activity of sea floor organisms can disrupt the primary order of these slowly deposited sedimentary layers. Nevertheless, this particular chemical signal has a strong claim to be regarded as a primary marker of the Anthropocene, and there have been suggestions that the boundary may be placed either at the moment of the Trinity test in 1945 (Zalasiewicz et al., 2015), at the beginning of the main global "bomb spike" in the early 1950s (Waters et al., 2015), or at its peak in 1964 (Lewis & Maslin, 2015). If one of these is chosen, then the decision will reflect the total ensemble of stratigraphic signals at least as much as the precise pattern of the radioactive signal itself.

Biostratigraphy

The use of the complex evolution of organisms, both single-celled and multicellular, has provided the main means of defining and using the geological time scale in the Phanerozoic, within the strata of which fossils are generally abundant. However, in applying this technique to the Anthropocene, there are a number of reasons why "classical" biostratigraphy is difficult to apply. First, there is the short time scale of the Anthropocene, measured in thousands of years at most, compared with the millions of years over which normal processes of evolution and extinction take place. Then, there is the difficulty in comparing data collected by biologists and ecologists regarding the recent and current history of Earth's biota, with the kind of criteria used by palaeontologists, who mainly deal with skeletal remains only. And, there are some quite novel aspects in Earth's biological history that need to be taken into account in this analysis.

As regards gaining an idea of the Earth prior to human modification, a baseline state might be best represented by the last interglacial phase, 125,000 years ago. Considering the baseline state is not simple, as overall the Quaternary has been a ~2.6-million-year interval of considerable oscillatory climate change between glacial and interglacial states, with the glacial phases in particular (that make up the bulk of the time) showing complex and dynamic change. Nevertheless, it is notable that most of the Quaternary does not show a particularly elevated rate of either extinctions or evolution, suggesting that life overall had adapted to repeated climate change. It is only late in the Pleistocene that significant biotic change appears, suggesting that the human factor became significant from this time.

Extinctions

Following the unremarkable evolutionary pattern of most of the Quaternary, the late Pleistocene, from ~50,000 years ago to the early Holocene saw waves of extinctions of large mammal species, with most species (other than those in Africa) becoming extinct (Barnosky et al., 2011). The species affected included such as the mammoth, sabre-tooth cat, ground sloth, woolly rhinoceros, and there has been considerable debate about whether climate/environmental change or human hunting was the cause. However, there was commonly a close link between the arrival of humans to any geographic region and subsequent extinctions, suggesting that “overkill” by humans often played a large or crucial role.

Following this, extinction continued through the Holocene, although not on such a dramatic scale. Nevertheless, it is clear that many species became extinct (particularly on hitherto isolated islands) in part because of predation by humans, in part because of competition from or predation by associated invasive species (see below) such as rats and cats and in part because of habitat loss as natural habitat was converted to farmland or urban areas.

Extinctions have accelerated in recent decades, and there has been considerable debate about whether the Earth is entering, or has entered another major mass extinction (it would be the sixth recognized) in Earth history (Barnosky et al., 2011). The consensus seems to be that this mass extinction has not yet happened as, in most major groups of organisms, the number of species known to be extinct is of the order of 1 percent. However, current rates of extinction are far above background levels (perhaps by up to three orders of magnitude) and also the number of species known to be endangered or critically endangered (i.e., in very low numbers) is, within many different major groups, of the order of a few to several tens of percent. With current “business as usual” trends of predation and habitat loss, a mass extinction on the scale of the “big five” is thought likely within two to three hundred years, (Barnosky et al., 2011) even without considering the additional effects of climate change.

Species invasions

While species extinctions are not yet on a major scale, other biological changes are on a considerably greater scale. Species invasions, for instance (also termed neobiota), already comprise a widespread and (uniquely, in Earth history) global phenomenon. *Homo sapiens*, of course, is the invasive species par excellence, living on every continent—even Antarctica—and having reached, and mostly occupied, virtually every island on the planet. With humans have come a range of other species, either by design (pigs, goats, cats, rabbits) or accidentally (most famously, rats). For vascular plants, although native losses are great over at least half of the ice-free land surface, plant species have been enriched mostly because species invasions exceed native losses (Ellis, Antill, & Kreft, 2012). Species have now been translocated between every continent and every ocean, and invasive species now commonly form up to a half (locally more) of the species complements of many regions—with particularly successful invasives often dominating assemblages (the name Homogenocene having been suggested by John Curnutt to reflect this phenomenon). The global character of this process is unique, as previous invasions were confined to continents that became geographically conjoined (notably, the Americas some 7 million years ago)—or a landmass separated to allow the species from the oceans on either side to mingle. Such invasions can increase local biodiversity (as well as reducing it, by causing native species to become extinct), even while the total biodiversity of the Earth is undergoing reduction. As with extinctions, the effects are essentially permanent, as it is the successfully translocated and surviving species that will comprise the biology (and the palaeontology) of the future.

Population/assemblage changes

Part of the reason that so many species are in low numbers is the appropriation of a large proportion (currently ~40%) of primary productivity to support our own species. This is another unique signal of the Anthropocene. The distortion to the pre-human ecological pattern may be exemplified by land vertebrates. Prior to the late Quaternary megafaunal extinctions, resources were shared among some 350 large vertebrate species. Currently, about

180 of these still exist. Among these—considering just body mass—humans now make about one-third. Most of the other two-thirds is distributed among those few vertebrate species that we keep to eat—cows, pigs, sheep, goats, and so on—and these have been heavily modified by selective breeding. Less than 5%—and probably less than 3%—is distributed among the wild large vertebrates of the world: elephants, rhinoceri, hippopotami, lions and tigers, and others. In a further distortion, the total large vertebrate mass has been increased by about an order of magnitude over geological baseline levels, because of agriculturally hyper-fertilized primary productivity (via nitrogen, phosphorus especially—see above) that is now fed efficiently to our preferred prey species.

Researchers examining overall plant and animal communities speak of them in terms of biomes: large areas with particular patterns of ecosystems determined largely by climate. The increasing human influence on terrestrial areas has led to the concept of anthromes (Ellis et al., 2012), where these primary patterns have been transformed into human-dominated agricultural (dominated by a few selectively bred and genetically modified primary crops) and urban systems (of which the nonhuman biology is often largely invasive). The extent of this transformation means that it is no longer accurate to say that humans have created a variety of anthromes that are nested within the regional biomes; rather, with only a few percent of pristine landscape left, it is more appropriate to say that there are now patches of more or less undisturbed biome left within anthrome-dominated terrestrial biology.

Humans, uniquely among land vertebrates, have also changed the trophic structure of the oceans. Increasingly effective and widely applied fishing methods have reduced the numbers of top predators and those just below them in the food web—whales, sharks, tuna, and others—with most populations now decreased by one to two orders of magnitude, and some (such as the Newfoundland cod) having undergone even greater population crashes. With the main targets thus diminished, fishing effort is becoming focused on lower levels of the trophic structure—"fishing down the food chain."

Within nearshore settings, including lagoon and estuaries, microflora, such as diatoms and dinoflagellates, and microfauna such as foraminifera and ostracods respond dramatically to human-driven stresses (Wilkinson, Poirier, Head, Sayer, & Tibby, 2014). The changes locally occur at a range of dates, but when viewed globally the population and assemblage changes are most prominent from 1940 to 1945, influenced by increases in the release of toxins and pollutants, increased runoff of agricultural fertilizers and input of sewage, changes to water acidity and oxygen levels, increased water turbidity, and salinization. However, in areas where stresses on microbiota have reduced through environmental controls, populations show signs of recovery.

Human trace fossils—technofossils and the technosphere

Many animals leave not only body fossils, mainly of hard parts such as bones and shells, but also trace fossils, such as worm burrows and footprints. Some animals create more complex structures that are also capable of being fossilized: the casings of caddis fly larvae, or the nests of both solitary and colonial insects, some being extraordinarily sophisticated, such as termite nests. The structures created by humans—houses and factories, roads and cars, tools ranging from knives to computers, are also commonly potentially preservable, and may also be considered to be trace fossils. They have been termed technofossils (Zalasiewicz, Williams, Waters, Barnosky, & Haff, 2014), and have some unique attributes: their remarkable diversity (very many millions of types have been made, compared with the usual maximum of three or four traces made by any other species in the animal kingdom); and their rapid evolution, now on a scale of decades and years (sometimes less) which is now also completely decoupled from the biological evolution of the trace-maker.

They all, in one way or another, embody technology, and without this technology the Earth would not be able to support more than a small fraction of the present human population. The technology is produced by humans, but humans, being dependent on that technology, must also maintain it, and the entire technological system is now globally connected. The entire system has been termed the technosphere (Haff, 2014), an emergent system comprising both the technological objects (“hardware”) and its human organizational systems (“software”). It currently needs a great deal of energy to power it, largely from fossil fuels. It has developed from, and is perhaps now in part parasitic upon, the biosphere. It is the system behind all the environmental changes of the Anthropocene, and the future of this time interval will be determined by the nature of its further evolution. It currently has some considerable instabilities—for instance it is extremely poor at recycling its constituent materials compared with the biosphere, and so risks being poisoned by its own waste products. But, it is evolving rapidly, so time will tell.

Climate Change and the Anthropocene

There has been rapid rise in major climate drivers (for example, carbon dioxide and methane), as noted above, and these are now outside Quaternary norms. With atmospheric carbon dioxide currently at ~400 ppm, it is at levels likely broadly typical of the Pliocene Epoch, 3 to 5 million years ago, when temperatures were 2–3 °C higher than today and sea levels 10–20 m higher.

However, there has so far only been a small rise in global average temperature, of ~0.8 °C globally over the past century. This is likely due to global lag effects, together with the storage of heat in oceans (which are much larger stores of heat compared with the atmosphere, and are measurably becoming warmer in their upper layers, with up to half of the last century’s rise in sea level of ~30 cm being due to thermal expansion). Currently, therefore, the Earth is still well within envelope of interglacial conditions as regards global temperature and sea level. Indeed, in the last interglacial, peak temperatures and sea levels were a little higher than today, without anthropogenic forcing. Nevertheless, evidence of the beginning of anthropogenic warming and climate destabilization is now clear, with the temperature rise so far virtually certain to be the result of the rise of greenhouse gases in the atmosphere. There have been clear signs too, over the last couple of decades of increased ice melt and freshening of seawater around both Greenland and Antarctica, with ice mass loss now a few hundred billion tons each year.

Thus, unless human energy supplies rapidly become decarbonized, there will over the coming decades and centuries be rises of global temperature and then sea level that will take the Earth system out of Quaternary interglacial norms and into conditions more resembling the pre-Quaternary Cenozoic. The temperature changes in themselves will lead to many extinctions as species are forced out of their habitable ranges. Hence, as regards the global climate and (especially) sea level signal, of the Anthropocene currently remains weak, but will likely increase considerably over future decades and centuries.

Synthesis, Definition, and Wider Significance

The evidence summarized above suggests that the Anthropocene hypothesis is founded upon a robust array of data indicating a major change in the Earth system (even if still larger changes lie ahead), also recorded as changes to strata, similar to signatures recorded in the geological past.

Hence, if the Anthropocene is real—how should it be defined? The boundaries of geological time units simply represent a temporal framework which captures, as well as possible, the main features of a complex and often protracted change from one state of the Earth system to another.

Three main candidate levels have been suggested for the beginning (or chronostratigraphic base) of the Anthropocene:

Firstly, an "early Anthropocene" or "Palaeoanthropocene" (Foley et al., 2013) that reflects early events, with ideas ranging from the great megafaunal extinctions to, more commonly quoted, events associated with the beginning and spread of agriculture in the early to mid Holocene, which produced significant changes to the landscape, though only marginal changes to the marine realm. Controversially, these landscape changes may have led to the slow rise in atmospheric carbon dioxide levels (from 260 to 280 ppm) through the pre-industrial Holocene, and may have prevented the slide back into a glacial phase.

Secondly, at the beginning of the Industrial Revolution, human population exceeded a billion (Steffen et al., 2015), and the development of large-scale coal burning, steam engines and industry that began the rise in atmospheric carbon dioxide levels that continues to this day. This spread from Britain to Europe to North America between the late 17th and late 18th century, and subsequently more widely (Waters et al., 2014). It was this option that was favored during early descriptions of the Anthropocene by Crutzen and Stoermer (2000) and Crutzen (2002).

Thirdly, from the mid-20th century, there came a "Great Acceleration" in the scale and rate of population growth, energy use, manufacture, habitat/biotic change, and widespread change beginning in the marine realm (Steffen et al., 2015). This was the start of the oil economy and the beginning of nuclear age (Zalasiewicz et al., 2015; Waters et al., 2015) and of globalization, with rapid growth and sophistication of the technosphere (Haff., 2014). Most of the anthropogenic rise in atmospheric carbon dioxide took place in this interval.

Other levels have been proposed, including the 16th and early 17th centuries (e.g., Lewis & Maslin, 2015)—and also a future level, once climate has warmed and sea level has risen further (Wolff, 2014), but those three remain the main candidates. Of them, the "early Anthropocene" is historically highly significant—but the processes, and stratigraphic signals, were diachronous, taking millennia to spread across those parts of the globe they affected (Edgeworth et al., 2015). The same, in a more compressed form, may be said about the Industrial Revolution. It is the mid-20th century "Great Acceleration" that represents the most widespread and synchronous or near-synchronous signals, and also the greatest changes (so far) to the Earth system, and it is likely therefore that a level some time in the mid-20th century will become accepted as the beginning of the Anthropocene (Zalasiewicz et al., 2015), whether this new time term is formalized or not.

As regards hierarchical level, the Anthropocene is currently being considered as a potential epoch, although other levels are possible. Given that it combines features that are geologically striking and completely novel (for example the whole-planet species invasions and technofossils), with others that are still trivial (e.g., sea level change), this is probably a reasonable compromise—especially given that yet larger changes seem likely.

The question of formalization of the Anthropocene will hinge as much on the perceived usefulness of having this unit on the Geological Time Scale (and for whom it is useful, given the wide interest in this concept) as on its geological reality. This is a complex question, the answer to which is hard to predict.

Nevertheless, whether formal or informal, this term and this concept has succeeded in conveying something of the overall rate and scale of global change in the context of all of Earth history, and thus helping in the analysis—and dealing with the human consequences—of this change. Moreover, it has helped refashion the relationship between humans and nature—in effect intertwining them so that one now cannot change without affecting the other. Thus it has also brought the sciences and humanities closer, as inquiry from both sides will be necessary to fully understand—and perhaps even direct the course of—the Anthropocene. Geologists, looking at past major phases of change to the Earth, are used to analyzing driving forces such as major volcanic outbursts and comet strikes. Here it is humans currently driving change to the Earth system—a far more difficult, and more unpredictable, phenomenon.

References

Barnosky, A. D., Matzke, N., Tomiya, S., Wogan, G. O. U., Swartz, B., Quental, T. B., et al. (2011). Has the Earth/'s sixth mass extinction already arrived? [http://dx.doi.org/10.1038/nature09678]. Nature, 471(7336), 51-–57.

Crutzen, P. J., & Stoermer, E. F. (2000). The Anthropocene. International Geosphere-Biosphere Programme Newsletter, 41, 17–18. http://www.igbp.net/download/18.316f18321323470177580001401/1376383088452/NL41.pdf.

Crutzen, P. J. (2002). Geology of Mankind. Nature, 415, p. 23. http://www.nature.com/nature/journal/v415/n6867/full/415023a.html.

Edgeworth, M., Richter, D. DeB., Waters, C. N., Haff, P., Neal, C., & Price, S. J. (2015). Diachronous beginnings of the Anthropocene: The lower bounding surface of anthropogenic deposits. Anthropocene Review, 2 (1) 33–581–26. doi:10.1177/2053019614565394. http://anr.sagepub.com/content/2/1/33.

Ellis, E. C., Antill, E. C., & Kreft, H. (2012). All Is Not Loss: Plant Biodiversity in the Anthropocene. PLoS ONE, 7(1), e30535. http://dx.doi.org/: 10.1371/journal.pone.0030535.

Foley, S., Gronenborn, D., Andreae, M., Kadereit, J., Esper, J., Scholz, D., et al. (2013). The Palaeoanthropocene—The beginnings of anthropogenic environmental change. Anthropocene 3, 83−88. http://www.sciencedirect.com/science/article/pii/S2213305413000404.

Ford, J. R., Price, S. J., Cooper, A. H., & Waters, C. N. (2014). An assessment of lithostratigraphy for anthropogenic deposits. In C. N. Waters, J. Zalasiewicz, M. Williams, M. A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (Special Publication 395, pp. 55–89). http://dx.doi.org/:10.1144/SP395.12.

Gałuszka, A., Migaszewski, Z. M., & Zalasiewicz, J. (2014). Assessing the Anthropocene with geochemical methods. In C. N. Waters, J. Zalasiewicz, M. Williams, M. A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (Special Publication 395, pp. 221–238). http://dx.doi.org/:10.1144/SP395.5.

Haff, P. K. (2014). Technology as a geological phenomenon: implications Implications for human well-being. In C. . N. Waters, J. Zalasiewicz, M. Williams, M. A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (Special Publication 395, pp. 301–309). London: Geological Society. http://dx.doi.org/:10.1144/SP395.4.

Lewis, S. L., & Maslin, M. A. (2015). Defining the Anthropocene. Nature, 519, 171–180. http://dx.doi.org/:10.1038/nature14258.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C.et al. (2015). The trajectory of the Anthropocene: the The Great Acceleration. The Anthropocene Review, 2(1): 81–98. http://anr.sagepub.com/content/2/1/81.

Syvitski, J. P. M., & Kettner, A. J. (2011). Sediment flux and the Anthropocene. Philosophical Transactions of the Royal Society, A2011(369), 957–975. http://dx.doi.org/:10.1098/rsta.2010.0329.

Tyrrell, T. (2011). Anthropogenic modification of the oceans. Philosophical Transactions of the Royal Society, A369, 887–908.

Waters, C. N., Zalasiewicz, J., Williams, M., Ellis, M. A., & Snelling, A. (Eds.) (2014). A Stratigraphical Basis for the Anthropocene? (Special Publication 395, pp. 321). London: Geological Society. http://sp.lyellcollection.org/content/395/.

Waters, C. N., Syvitski, J. P. M., Gałuszka, A., Hancock, G. J, Zalasiewicz, J., Cearreta, A., Grinevald, J., McNeill, J. R., Summerhayes, C., submitted2015. Can environmental radiogenic signatures define the beginning of the Anthropocene Epoch? Bulletin of Atomic Scientists, 71(3) 46–57.

Wilkinson, I. P., Poirier, C., Head, M. J., Sayer, C. D., & Tibby, J. (2014). Micropalaeontological signatures of the Anthropocene. In C. . N. Waters, J. Zalasiewicz, M. Williams, M. . A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (Vol. Special Publications 395, pp. 185–219). London: Geological Society.

Williams, M., Zalasiewicz, J., Haywood, A., & Ellis, M. (Eds.) (2011). The Anthropocene: a A new epoch of geological time? (Vol. 369A, 833–1112). Philosophical Transactions of the Royal Society.

Williams, M., Zalasiewicz, J., Waters, C. N., & Landing, E. (2014). Is the fossil record of complex animal behaviour a stratigraphical analogue for the Anthropocene? In C. . N. Waters, J. Zalasiewicz, M. Williams, M. A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (Special Publication 395, pp. 143–148). London: Geological Society. http://rsta.royalsocietypublishing.org/content/369/1938.

Wolfe, A. P., Hobbs, W. O., Birks, H. H., Briner, J. P., Holmgren, S. U., Ingólfsson, Ó., et al. (2013). Stratigraphic expressions of the Holocene–Anthropocene transition revealed in sediments from remote lakes. Earth-Science Reviews, 116, 17–34. http://dx.doi.org/: http://dx.doi.org/10.1016/j.earscirev.2012.11.001.

Wolff, E. W. (2014). Ice Sheets and the Anthropocene. In C. N. Waters, J. Zalasiewicz, M. Williams, M. A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (Vol. Special Publications 395, pp. 255–263). London: Geological Society.

Zalasiewicz, J., Kryza, R., & Williams, M. (2014a). The mineral signature of the Anthropocene. In C. N. Waters, J. Zalasiewicz, M. Williams, M. A. Ellis, & A. Snelling (Eds.), A Stratigraphical Basis for the Anthropocene (pp. 109–117). London: Geological Society.

Zalasiewicz, J., Waters, C. N., & Williams, M. (2014b). Human bioturbation, and the subterranean landscape of the Anthropocene. Anthropocene , 6, 3–9http://dx.doi.org/:10.1016/j.ancene.2014.07.002.

Zalasiewicz, J., Waters, C. N., Williams, M., et al. (2015). When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. Quaternary International. http://dx.doi.org/10.1016/j.quaint.2014.11.045.

Zalasiewicz, J., Williams, M., Smith, A., Barry, T. L., Coe, A. . L., Bown, P. R., et al. (2008). Are we now living in the Anthropocene? Geological Society of America Today, 18(2), 4–8.

Zalasiewicz, J., Williams, M., Waters, C. N., Barnosky, A. D., & Haff, P. (2014c). The technofossil record of humans. Anthropocene Review 1, 34–43. http://dx.doi.org/:10.1177/2053019613514953.