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Stratigraphy of the Anthropocene

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The Anthropocene, an informal term used to signal the impact of collective human activity on biological, physical and chemical processes on the Earth system, is assessed using stratigraphic criteria. It is complex in time, space and process, and may be considered in terms of the scale, relative timing, duration and novelty of its various phenomena. The lithostratigraphic signal includes both direct components, such as urban constructions and man-made deposits, and indirect ones, such as sediment

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flux changes. Already widespread, these are producing a significant 'event layer', locally with considerable long-term preservation potential. Chemostratigraphic signals include new organic compounds, but are likely to be dominated by the effects of CO_2 release, particularly via acidification in the marine realm, and man-made radionuclides. The sequence stratigraphic signal is negligible to date, but may become geologically significant over centennial/millennial time scales. The rapidly growing biostratigraphic signal includes geologically novel aspects (the scale of globally transferred species) and geologically will have permanent effects.

Keywords: Anthropocene; geological time; stratigraphy; biodiversity; climate; anthropogenic deposits

1. Introduction

The term Anthropocene [1,2] is the latest iteration of a concept to signal the impact of collective human activity on biological, physical and chemical processes at and around the Earth's surface. Earlier versions of this concept (e.g. [3]) were widely, if intermittently, discussed in both scientific and philosophical terms. However, they were not seriously considered as potential additions to the geological time scale; this was partly because of the extremely brief duration of human civilization—from a geological perspective—and partly because the effects of human modification of Earth's surface processes were widely viewed, by geoscientists, as small by comparison with those resulting from natural processes acting over relatively long geological time spans [4].

However, the Anthropocene, virtually from the time of its suggestion, had a considerably more positive reception, and has been widely (and is increasingly) used in the scientific literature (e.g. [5–7]). This reflects a widespread realization among Earth and environmental scientists that some types of anthropogenic changes may now be compared with those of 'the great forces of Nature' [8].

Nevertheless, the significance of the Anthropocene from a stratigraphic perspective has been little debated. If we consider that the degree of environmental change is significant enough to formally recognize a separate time stratigraphic unit, then what best defines the Anthropocene, and where and how might we recognize its boundary with the previous stratigraphic interval, the Holocene? In this paper, we explore the history of evolution of the geological time scale and the techniques used by geologists to distinguish and establish time stratigraphic units. We also debate the extent and pace of change in the Anthropocene relative to earlier event-defining boundaries in the geological past.

2. The geological time scale

The 4.56 Gyr of Earth's geological record [9,10] is subdivided into aeons that represent hundreds of millions or indeed billions of years, which are further hierarchically subdivided into eras, periods, epochs and ages that represent successively smaller units of time. These time (or geochronological) units traditionally have parallels in chronostratigraphic (or 'time–rock') units (eonothems, eras, systems, series, stages) that represent the rock record formed during those time units ([11]; though see discussion in [12]). This subdivision of the geological time scale is pragmatic. In the Phanerozoic aeon, representing the last 542 Myr characterized by an abundant macrofossil (e.g. shelly fauna) record, the time units at any of the hierarchical levels are not of the same duration, and nor are the equivalent chronostratigraphic units of similar thickness. Rather, the boundaries between the units are decided on fundamental changes in the Earth system, recorded in the rock record. The most widely known of these is the Cretaceous–Palaeogene boundary, associated with a mass extinction that included the dinosaurs at 65.5 Ma [13]. In defining boundaries, reference points are chosen at key levels within strata at specified localities (Global Boundary Stratotype Sections and Points (GSSPs) or 'golden spikes'), and these simultaneously mark the boundaries between both a time unit and its equivalent time–rock unit. For most Precambrian strata, macrofossils are absent and hence precise subdivision and correlation have so far proved difficult: in this instance, a Global Standard Stratigraphic Age (GSSA) is designated (e.g. the Archaean–Proterozoic Aeon boundary at 2500 Ma). The beginning of the (formally) current epoch, the Holocene, also used to be defined by a GSSA (10 000 radiocarbon years before present) until very recently, when this boundary was supplanted by a GSSP (located within an ice core from Greenland [14]) that records a date of 11 700 years before AD 2000 [10].

The nomenclature of the geological time scale has been evolving for 200 years, the most recent major addition being the Ediacaran Period, ratified in 2004 [15]. Initially, the boundaries between units (in the Phanerozoic) were based on changes in the fossil content reflecting extinction and evolutionary radiation events. Only in the latter part of the twentieth century were these biotic changes complemented by physical and chemical, including isotopic, data, and these in turn were linked with fundamental changes in the Earth system influenced by both extrinsic (e.g. bolide impacts, orbital effects such as Milankovitch cycles) and intrinsic (e.g. continental configuration, ocean circulation) factors (e.g. [10,16]).

The ages of rock units and the histories they represent are thus deduced virtually entirely from tangible evidence obtained from the rock record. Rocks are subdivided on a number of criteria, such as their physical character (lithostratigraphy), fossil content (biostratigraphy), chemical properties (chemostratigraphy), magnetic properties (magnetostratigraphy) and patterns within them related to sea-level change (sequence stratigraphy). The sum total of this evidence is used in the dating and correlation of rock successions, and in continued refinement of the geological time scale. Thus, if the Anthropocene is to take its place alongside other temporal divisions of the Phanerozoic, it should be expressed in the rock record with unequivocal and characteristic stratigraphic signals. We suggest that these are comparable with, although distinctively different from, those that apply to all time divisions after the Ediacaran, and summarize the evidence below.

3. Lithostratigraphy

Anthropogenic modification of sedimentary patterns comprises both modifications to natural sedimentary environments (such as the damming or straightening of rivers and coastal reclamation) and the creation of novel sedimentary environments and structures (such as the construction of cities and anthropogenic deposits); these are not entirely separate categories, but are to some extent inter-gradational. In detail, they are diachronous, reflecting the spread of human activity across the Earth (e.g. [17]). Additional related phenomena, especially those that are sequence stratigraphic, are discussed separately in §5 below.

(*a*) *Modifications of sediment patterns*

This category comprises changes to natural sediment patterns and pathways caused by human activity. These include the diversion and impoundment of sediment associated with the building of dams and the engineered modification of rivers and coastlines [18] that locally have led to a dramatic change, as in the desiccation of the Aral Sea [19]; the changes in terrestrial sediment dispersion caused by agricultural and urban development (including the effects of deforestation; e.g. [20]); and, offshore, the changes to sea-floor sediments and biota by bottom trawling (e.g. [21]).

The sum effect of anthropogenic soil, rock and sediment movement in the terrestrial realm has been estimated to exceed, currently, those from natural processes, perhaps by an order of magnitude [22,23]. In the marine realm, the area scraped and churned by bottom trawling, a practice described by the oceanographer Sylvia Earle as the equivalent of bulldozing the countryside to harvest squirrels, has been estimated at approximately $20 \times 10^6\,\mathrm{km}^2$ and hence probably includes most of the continental shelf, which covers some $26 \times 10^6\,\mathrm{km}^2$, or about 7 per cent of the surface area of the oceans [24]. This represents a novel form of bioturbation that in its physical effects most closely approximates to the scouring of high-latitude shallow sea floors by iceberg keels [25]. Similarly, the destruction of coral reefs through detonating explosives for coral ‘mining’ and illegal fishing is producing new sediment, albeit at the loss of important marine ecosystems [26].

(*b*) *Novel strata*

This category may be regarded as both lithostratigraphical and biostratigraphical, for it comprises the built environment (a kind of trace fossil system in the making) that humans have created, particularly in urban areas [27]. These are robust, largely made of modified geological materials (e.g. sand, gravel, limestone, mudstone, oil shale, coal and mineral spoil, and hard rock), together with more or less novel materials (plastics, metal alloys, glass). The built environment, in turn, commonly rests on the compacted materials of earlier settlement, and in any event will include substantial subsurface constructions (foundations, pilings, pipelines and so on) that collectively may be shown as a separate deposit on a geological map (as ‘artificial deposits’—formerly ‘made ground’—on maps of the British Geological Survey, for example, that complements the ‘worked ground’ of pits and quarries [28]) (see [27] for a detailed classification of artificial deposits). This layer is highly variable in thickness and composition, but may be several metres thick beneath towns and cities, and has a more patchy, though still extensive, distribution in populated rural areas. For example, in the ‘Black Country’ (the English West Midlands), a major centre of mining and industrialization in the eighteenth, nineteenth and early twentieth centuries, anthropogenic deposits between 2 and 10 m thick cover an area of up to $90\,\mathrm{km}^2$

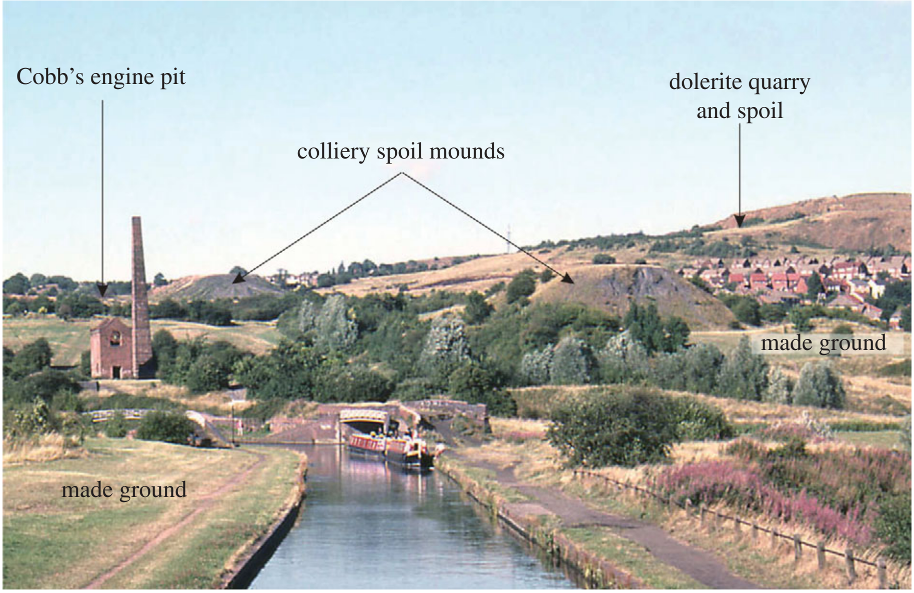

Figure 1. Two hundred years of anthropogenic deposits in the Netherton Area, West Midlands, UK. Cobb's engine pit was built around 1831 to extract water from the Windmill End Colliery coal mine workings, and continued in operation until 1928. The underground mining operations produced large volumes of spoil, stored as pit mounds, still visible. The coal was transported via canal barges, the canals themselves associated with areas of general made ground deposits. Rough Hill, to the right of the photo, is formed from a dolerite intrusion that has been extensively quarried, an operation that also has generated large volumes of spoil. Photo taken by C.N. Waters (reproduced with permission from the Director, British Geological Survey © NERC). (Online version in colour.)

([29,30]; figure 1). Although largely terrestrial, anthropogenic deposits are also common along coastal zones and include constructions—associated with oil platforms, for instance—that extend into the sea floor, and material dumped offshore, such as coal mine waste from the Northumberland and Durham coalfields in the UK.

Related modifications of existing rock, which might be regarded as mechanically assisted bioturbation, comprise structures such as boreholes, wells, deep tunnels and mineshafts, which may extend for hundreds or thousands of metres underground, and which are commonly associated with significant anthropogenic stratal modification (such as the removal of mineral, including hydrocarbon and water, accumulations). These occur in both terrestrial and marine settings, and are found in considerable number: the British Geological Survey's (extensive, but incomplete) database contains nearly a million records of such structures in the UK (that hence average approx. $4\,\mathrm{km}^{-2}$), albeit their distribution is highly variable, with considerable concentrations in urban areas.

4. Chemostratigraphy

Increasingly, geologists use chemostratigraphic markers to define geological boundaries, the most famous of these being the iridium anomaly of the

Cretaceous–Palaeogene boundary, thought to have resulted from the impact of an extraterrestrial bolide [31,32]. Perhaps the most widely used chemostratigraphic markers are carbon isotope excursions (the ratio of ^{13}C to ^{12}C) recognized in organic-rich and inorganic C-rich sediments, which reflect, among other factors, ocean productivity and massive carbon burial or release. Carbon isotope excursions are recognized throughout the Phanerozoic (and earlier), and are typically associated with biotic change, as, for example, in the Cambrian (e.g. [33]), the Late Ordovician (e.g. [34]) or at the Palaeocene–Eocene boundary [35]. They are often excellent stratigraphic markers for major geological boundaries. Other chemostratigraphic indicators include strontium ([36]: although this reflects long-term weathering changes likely to be of limited relevance to the Anthropocene) and osmium isotopes (reflecting shorter-term changes in terrestrial weathering intensity [37]).

Human perturbation of some global geochemical cycles is now on a sufficient scale to leave clear markers in contemporary sediments, both as regards their immediate effects and in terms of their effects on other systems—particularly biological impact. Furthermore, these perturbations are locally triggering significant feedbacks, both positive and negative, the magnitude of which may ultimately exceed that of the original perturbation.

The chemical perturbation of carbon is probably the most important, because of its potentially far-reaching, long-term and cascading consequences for the whole Earth system. Thus, against a context in which atmospheric CO_2 concentrations have oscillated between approximately 180 and 260–280 ppm in glacial and interglacial phases of the Quaternary, respectively [38,39], the Holocene has seen a slow rise from approximately 260 to 280 ppm between the early part of this interglacial and about AD 1800. This has been attributed, controversially, to effects of early agriculture and inferred as a factor in the longevity of Holocene warmth [40,41]. The rapid subsequent rise in $p\mathrm{CO}_2$ levels, from approximately 280 ppm prior to the Industrial Revolution to approximately 390 ppm in 2010 (and rising at 2–3 ppm per annum) is projected to reach between approximately 550 and 950 ppm by 2100 [42]. Another expression of the perturbation of the carbon cycle is an approximate doubling of the levels of methane (a yet more potent, though shorter-lived greenhouse gas) relative to pre-industrial levels [42].

Other significant chemical perturbations include: a twofold increase in the amounts of reactive nitrogen at the Earth's surface and in the oceans, mainly as a consequence of the Haber process and the production of nitrogen-based fertilizers; increases in the amounts of particulate reactive iron (from fly ash), lead, soluble mercury and petroleum-based products as either spills or combustion residues; the introduction of a number of (largely novel) compounds associated with pesticides, flame retardants and other industrial products ([43] and references therein; see also [44]); and radionuclides associated with fall-out from nuclear explosions.

Some direct signals of these changes may be observed within sediments. For instance, anthropogenic carbon emissions produce measurable changes in carbon isotope ratios within marine calcareous shells [45]; increases in lead deposition (dating back to Roman times) have been detected in ice cores and alluvial sediments; organic pollutants can produce characteristic spectroscopic signatures in sediments [46]; and anthropogenic nuclear fission products are now widely detectable in post-1945 strata worldwide [47].

However, it is through the indirect effects of these chemical changes that the stratigraphic signals will be most clearly expressed, although these will show various offsets in timing and scale with respect to the original perturbation. These include, for CO_2 and CH_4, a projected global mean surface temperature rise of between 1.1°C and 6.4°C relative to 1980–1999 [42] and a decrease of between 0.14 and 0.35 units in ocean pH (compared with currently elapsed amounts of approx. 0.6°C—though up to 3°C in some high-latitude regions—and 0.1 pH units, respectively). Biotic consequences are already detectable and threaten to become severe within decades [48,49], while temperature-related sea-level changes, which have barely commenced, may, when finally equilibrated (on multi-millennial time scales) amount to tens of metres [50], although constraints remain poor on the timing, rate and ultimate magnitude of these changes [51].

5. Sequence stratigraphy

The Earth's stratigraphic record is characterized by evidence of many global sea-level changes, associated with both period-scale (e.g. beginning of the Silurian and Jurassic) and epoch-level (e.g. beginning of the Oligocene and Holocene) boundaries. Episodes of global warming are typically associated with sea-level rise, which may mainly result from thermal expansion of sea water in times of low global ice volume (e.g. at the Palaeocene–Eocene boundary) or from ice melt in 'icehouse' times (e.g. end of the Ordovician [52]). Reflection of this as lithofacies changes occurs in both shallow- and deep-water settings, as both clastic and carbonate sedimentary systems respond variously to the sea-level change [53].

Consideration of past (Late Tertiary to Quaternary) sea-level changes indicates, empirically, 10–30 m of ultimate glacio-eustatic change per 1°C change [50]. If so, and given median Intergovernmental Panel on Climate Change (IPCC) global temperature projections, maximum sea levels of the Anthropocene event might reach a few to several tens of metres above present levels, implying melting of a substantial part of the Earth's cryosphere. Such sea-level change lags behind climate change by millennia. In the Early Holocene, while temperatures rose rapidly to normal interglacial levels (a few decades in the case of the Northern Hemisphere; see [54] and references therein), the sea-level response of approximately 120 m rise took approximately 4000 years [55]; the rate of sea-level rise was non-uniform, but included 'jumps' of up to several metres [56]. Sea-level change thus far has been stratigraphically negligible (approx. 30 cm in the twentieth century), and may be stratigraphically slight by the end of this century (estimated at 0.5 ± 0.4 m by [57]). However, in the long term, if global warming continues unabated, the rise might conceivably match or exceed the approximately 6 m above present-day levels of the last interglacial MIS 5e [58, p. 23].

6. Biostratigraphy

The diverse fossil biota preserved in rocks of the last half billion years means that, for Phanerozoic rocks, most day-to-day practical age-dating and stratigraphic correlation is done on the basis of fossils. Significant chronostratigraphic boundaries are typically associated with distinct faunal turnovers and enhanced extinction/evolutionary radiation events, linked with changes in atmospheric and ocean chemistry. These are in turn associated with drivers such as continental reconfiguration, cryosphere evolution, enhanced volcanism and changes in solar insolation (e.g. [16]), or more exotically by bolide impacts [59]. The Earth's biota thus, historically, has acted as a complex and sensitive recorder of the environmental process.

However, in practice, biostratigraphy does not aim at a consideration of the entirety of past life. Being utilitarian, it focuses on those groups that are most commonly and widely (geographically) found preserved in rock strata and that record enhanced rates of extinction and evolutionary radiation events. Throughout most of the Phanerozoic, there is focus on groups that show the most rapid rates of evolution (i.e. originations and extinctions) of recognizable morphotaxa; for instance, in the Jurassic, the finest biozonation is provided by the ammonites (e.g. [60]), and in the Silurian by the graptolites (e.g. [61]). Other bioevents can be exploited, such as local immigrations and emigrations of plant and animal species. This is particularly the case in the Quaternary, where individual interglacials may be 'fingerprinted' by particular patterns of immigration and emigration of trees or insects (e.g. [62,63]). Similar events may be exploited in earlier time intervals, such as the rapid abundance increase and migration to higher latitudes of the tropical dinoflagellate genus *Apectodinium* during the Palaeocene–Eocene Thermal Maximum, producing a clear global marker for this event in marine strata [64].

The Earth today is undergoing what is generally agreed to be an interval of ongoing and accelerating biological change. The anthropogenic drivers of this change are due to several inter-related phenomena, partly linked to the global physical and chemical changes described above. Among these are:

— human consumption of other species, mostly organized and mechanized on land via farming, and mostly still a form of hunting–gathering, albeit highly mechanized, at sea. On land, this has converted natural biodiversity patterns into one highly skewed in favour of the relatively small number of taxa that we artificially maintain at very high levels for food. At sea, some favoured prey species, mostly fish near the top of the food chain, have been severely reduced by over-fishing (e.g. [65]), locally beyond tipping points as taxa reach population abundances too low to easily recover (e.g. Atlantic cod fisheries off the Grand Banks, Newfoundland), and other taxa usurp their place in the trophic web. Other species are squeezed out, particularly on land, but also with changes in benthic marine communities from the effects of, for instance, bottom trawling. Trawling alters the structure of the benthic communities, in particular by reducing or removing larger [66] and sedentary [67] taxa, with possible longer-term biotic effects (e.g. via changes in recruitment patterns).

— the effects of chemical perturbations, most notably the effects of increased CO_2 (and CH_4) levels. These have begun to increase ambient global temperatures, particularly at high latitudes, and measurably affect biological communities (e.g. [68]), particularly at sea, where species tend to have narrower temperature tolerances [69]. The acidification effects of enhanced CO_2, already noticeable, will probably be profound in coming decades [70–73]. Near-coast sea-floor oxygenation has been locally reduced by N and P emissions to produce (mostly seasonal) 'dead zones' [74], while more generally marine oxygen and nutrient stresses will increase in a warmer world with more highly stratified oceans, with consequences for biota [75].

The question is how this change may compare—and how in measurable terms it may be compared with—the records of past biodiversity change preserved within strata. The rapidity and geologically brief duration of modern change hinders analysis, not least in simple problems of stratigraphic integrity. For instance, nearly all marine sediments are mixed through bioturbation to depths of centimetres to decimetres, effectively homogenizing signals that in deep-sea environments typically represent many centuries (e.g. [76]); thus disentangling the nineteenth/twentieth-century signal from earlier ones needs either the more rare high-resolution records (e.g. more rapidly accumulated strata) or the use of, say, plankton traps. Nevertheless, the following phenomena are among those that are producing signals in sediments forming today, of the kind that may be compared with the deep-time stratigraphic record.

(*a*) *Extinction events*

Only about 10 per cent of species have been documented taxonomically, hampering attempts to estimate the current degree of biodiversity loss [77] that, nevertheless, may be considerable [78]. Comparison of the scale of present extinction with past extinction events is also rendered difficult by the different methodologies applied by biologists and palaeontologists. The assessment of extinction today focuses on individual species, and the various means of assessing them as endangered, 'critically endangered' and 'extinct', depending on sightings (or the lack of them) by appropriate specialists (e.g. the International Union for Conservation of Nature and Natural Resources (IUCN) Red List at http://www.iucnredlist.org/). Most focus has been on organisms (e.g. birds, mammals) for which the approximate size of the species pool is well established, but these are not typically groups that form key biostratigraphic indicators in the fossil record. Nevertheless, analysis of individual groups, such as Australian mammals, shows alarming rates of extinction or endangerment (e.g. [79]). Syntheses of global change should be facilitated in coming years by the newly created Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES), a body created to parallel the work of the IPCC for biodiversity.

In contrast, the major extinction events of the past are typically assessed at higher taxonomic levels—e.g. at family level [80] with extrapolation to indicate levels of species loss. Furthermore, and in marked contrast to the present, past extinction events are largely constrained from the marine record, which is much better preserved than that from terrestrial environments. Finally, the temporal scale between present and past is vastly different. Nevertheless, within individual fossil groups, species-level patterns of extinctions and appearances are recorded in great detail (as, for example, with the graptolites in the Lower Palaeozoic [61]; or Mesozoic–Cenozoic calcareous nanoplankton [81]), typically by making the recording of presence/absence data at multiple levels within selected stratal successions. It is, therefore, possible to analyse the rates of extinction (and recovery) between individual fossil groups, and this fossil record of extinction may therefore be useful for estimating the path of future biodiversity loss (see also [77]).

(*b*) *Assemblage changes and migrations*

Clearer stratigraphic signals result from changes in proportions of taxa and communities that arise directly or indirectly from human forcing. While such changes may be associated with increased extinction risk among the 'losing' species, here we focus on the relative balance of component taxa within assemblages

On land, the scale and rate of change in communities consequent upon the spread of agriculture and industry have been demonstrated, the terrestrial biosphere making the transition from mostly wild to mostly settled early in the twentieth century [82]. Hence, natural communities are variably replaced (commonly by agricultural crops), modified and fragmented. Stratigraphically, these changes are most easily expressed via changes in pollen spectra, with pollen representing natural vegetation cover being replaced by pollen representing disturbed ground and crop plants, the latter of systematically decreasing diversity as a handful of high-yielding varieties of rice, wheat, maize and so on have come to dominate human food supply [83]. This change is most akin to the kind of climatically driven vegetation change seen in Quaternary glacial–interglacial terrestrial successions, but includes novel aspects such as extensive forest loss at low and mid-latitudes at a time of warming.

In the oceans, the scale and extent of change are more poorly constrained than that on land, because of the relative difficulty of exploration of this environment for humans. However, significant change has been detected [75], particularly at high latitudes [84]. Consideration of changes in dominant and or habitat-forming organisms such as reef corals, kelp and mangroves, all currently in decline [75], probably comprise the best parallels with biostratigraphic changes based on common taxa observed in deep time. Thus, around the West Antarctic Peninsula, recent declines in sea ice have led to phytoplankton decreases, which in turn have led to increases in salp populations at the expense of krill, with changes at higher trophic levels likely as a result [84]. A more general trend (as on land) is a drastic reduction of top predators, such as sharks, affecting the food web lower down [85].

In the fossil record, temperature-related changes are expressed at individual locations as stratigraphic appearances and disappearances of taxa, as in, for example, the forest successions shown in terrestrial glacial–interglacial alternations, and plankton successions at the onset of the Palaeocene–Eocene Thermal Maximum [86]. These local changes represent migrations, as the taxa moved to stay within their temperature tolerances as climate changed. Quaternary migrations were overall a successful tactic, as Pleistocene extinction rates were low (e.g. [63]). However, given likely warming trends exceeding previous Quaternary limits, and substantial barriers to migration posed by markedly anthropogenically fragmented habitats, considerably higher extinction rates are projected [49]. Furthermore, during the Quaternary, the continued existence of plants and animals that now inhabit high-latitude and mountain habitats was conditioned in previous interglacials by the occurrence of refugia (e.g. [87]). Today, humans have destroyed or severely modified these refugial areas. Thus, as climate deteriorates once more—as it probably will once Earth systems have readjusted—the continued survival of many taxa will be compromised.

(c) *Invasive species*

A geologically novel biotic change is the extent and rate of transfer of animals and plants from one region to another, both on land and in the sea. While species migration has been extensively documented in the deep-time record, major changes on land have been typically associated with environmental change (e.g. during the glacial–interglacial transitions of the Quaternary), wherever sufficient geographical continuity exists, or where new geographical connections between previously isolated landmasses have been made, the classic example being the great American interchange of 3 Ma [88]. However, the current simultaneous mass cross-transfer of species between each major and minor landmass, the Antarctic being the exception, is geologically unprecedented. This is a large-scale phenomenon, extending well beyond classic examples such as the grey squirrel in Britain and the rabbit in Australia. In North America, north of Mexico, over 50 000 species are considered invasive and are regarded as causing environmental damage on the scale of 120 billion US dollars per year [89]. While, in Europe, nearly 11 000 invasive species have been identified (DAISIE website, accessed July 2010, http://www.europe-aliens.org/). Among these are taxa that are easily fossilizable and now abundant in their new territories. For instance, the freshwater mollusc *Corbicula fluminea*, originally southeast Asian, now extends in abundance throughout European waters (to the extent that it can render river gravels unusable as aggregate), while the marine littoral bivalve *Brachidontes phoronis* now commonly displaces the Mediterranean mytilid *Mytilaster minimus* (http://www.europe-aliens.org/). Some invaders are causes of mass extinctions by predation or displacement (Nile perch and cichlid fish; Hawaiian land snails), while others are palaeontologically invisible but may have profound impact (the chytrid fungus currently affecting amphibian populations worldwide).

Eradication efforts are likely to be partially successful, at best, and offset by continued invasions. Thus, this substantial modification of the world's biota will have permanent repercussions in that, even as the invasive taxa themselves eventually become extinct, many will probably give rise to descendent species.

7. Discussion

The various types of anthropogenic change may be considered in terms of different parameters.

(*a*) *Scale*

Firstly, there is the *scale* of change engendered to date, relative to long-term natural processes. Here, for instance, the change in terrestrial land cover has been substantial, with natural vegetation and soils being replaced by agricultural and urban land over 39 per cent of the ice-free land surface, with an almost equivalent amount of land being 'embedded' within such transformed areas [82], while most shallow marine sea floors have been impacted by bottom trawling. This is even now a considerable perturbation, and one that, where preserved (largely on subsiding coastal areas, deltas and low-lying floodplains), will result in a lithologically unique event bed that, in the case of urban areas, may reach several metres in thickness.

(*b*) *Duration*

There is also the duration of the different types of anthropogenic perturbation to consider. Landscape modification will only persist as long as human land management persists; there will be a lag time, probably of a few centuries (for dams to cease being sediment traps, rivers to free themselves of embankments and so on). After this, sedimentary processes will revert to approximately natural: there would be a geologically rapid return to natural sedimentation. Nevertheless, given the scale of the perturbation, the 'event layer', where preserved, may locally form a considerable deposit. It will exceed in thickness and facies complexity the modest and discontinuous unit that might be expected from simple consideration of the geologically almost infinitesimally small time-span of industrial human civilization. It will thus be more extensive and more distinctive as regards lithofacies than the preserved remains of any previous Quaternary interglacial phase. From a more contemporary and anthropocentric perspective—given that stratigraphy is a human construct intended for practical ends—this event layer, at least on land, also represents the habitat of most humans living today in urban conurbations.

In contrast, part of the biotic change associated with biodiversity loss and species translocations will be effectively permanent. Future evolution in any part of the world will take place from the species remaining on Earth, both surviving and translocated. Thus, the pattern of future evolutionary change—that is, future biostratigraphy—will be altered proportionately to the scale of the perturbation. Even if species do not become extinct, dropping instead to very low numbers (as is the case for many organisms now classified as 'endangered' upon the IUCN Red List), the ensuing restructuring of the ecosystem will probably be a barrier to simple reversion to the *status quo* once anthropogenic pressure is removed. For example, there has been little recovery yet in the cod population off Newfoundland, following their crash through over-fishing, other animals having (to date) taken their place in the food web [90]. Thus, biodiversity recovers, but into a new pattern as different taxa fill niches. The striking disparity between Palaeozoic, Mesozoic and Cenozoic fossil assemblages reflects such restructuring following the extinction events that mark the boundaries between these eras. (Another component of modern biotic change, by contrast—the agricultural monocultures that are widespread today—are only maintained through continuous human intervention, and will last only as long as anthropogenic pressure persists.)

Chemical perturbations seem to be of intermediate duration. Most notably, the pulse of CO_2 injected into the atmosphere–ocean system (including acidification effects, though not including feedbacks) can be modelled [91]. This pulse will eventually be neutralized by silicate weathering, a new equilibrium being reached after some tens of millennia. Such modelling is consistent with the duration of previous carbon-release events such as in the Early Toarcian (*ca* 182 Ma) and at the Palaeocene–Eocene boundary (*ca* 55.8 Ma) [92,93]. Direct biotic consequences will follow a similar course in part: as temperatures and pH eventually change back towards present levels, the 'species migration' part of the resulting biostratigraphic signal will diminish or disappear (i.e. surviving taxa will migrate back), while the 'species extinction' part will comprise permanent biostratigraphic change.

(*c*) *Relative timing*

Anthropogenic perturbations have varied in time and space. Thus, modification of terrestrial landscapes and biota (as regards large-mammal populations) essentially began at the beginning of the Holocene, and was diachronous across the Earth, following the spread of agriculture. Global-scale effects to the marine realm, in contrast, are more recent phenomena, from the Industrial Revolution onwards. Biotic effects of CO_2-forced warming and acidification are in their early stages, and are thus delayed by comparison with biotic change resulting from habitat loss and invasive species. In contrast, warming-related sea-level change to date has been minimal; at some 0.3 m rise, this is simply too small to be deciphered in any far-future sedimentary record; the course of future sea-level rise resulting from present/near-future warming is likely to be more pronounced, though its rate, scale and mode through the centuries and millennia to come remain uncertain [51].

(*d*) *Novel phenomena*

A feature of the Anthropocene is entirely new phenomena (counting only those geological phenomena with reasonable potential for preservation in the geological record) that are unprecedented in the 4.5 Gyr history of this planet. In this category are the manufactured constructions (in effect, sophisticated and human-designed trace fossils) and anthropogenic deposits within the lithostratigraphic event layer; the removal of top predators other than humans and (in its scale) the invasive species phenomenon on land and in the sea; and, arguably, the rate of change to the carbon and nitrogen cycles.

8. Built-in future change and human feedbacks

Further considerations are the extent to which the course, scale and effects of anthropogenic change can be sensibly predicted and causally linked, and the nature of the lag time between current disturbance and future effects. Thus, current CO_2 levels are approximately 390 ppm, up by 30 per cent from pre-industrial levels. The warming to date has been 0.6°C, and that which is 'built-in', and is predicted to take place even if no further increase takes place, is 0.3–0.9°C over the next century ([94]; but see [95]). The future rate and scale of anthropogenic CO_2 increase are not predictable with any precision, but levels are unlikely to be below 560 ppm by 2100 [42], not counting modification by natural feedbacks (e.g. changes in mass fluxes between atmosphere and terrestrial/ocean reservoirs).

Some of the further effects are more or less directly predictable. Change in ocean pH will directly track $p\mathrm{CO}_2$ levels, so that decreases in aragonite and calcite saturation state can be modelled with some robustness [71]. Thus, even with $p\mathrm{CO}_2$ levels rising along the lower part of the range of predicted trajectories, most ocean water will be below aragonite saturation levels by 2100. The biotic response is more complex, as different calcium carbonate-secreting organisms have different physiological responses to such stresses [96], but ongoing experiments may go some way to constraining these uncertainties.

The effect on temperature may be more complex. There is considerable consensus that warming will take place, but the precise course and time scale of that warming will probably be determined by multiple feedbacks, such as a possible slowdown in global warming over the last few years, attributable to increases in stratospheric water vapour effects [97]. When examined at very high levels of resolution, global warming events in deep time, such as that which occurred during the Toarcian, show a complex course at a millennial level that includes both reversals and rapid increases [98]. The course of Anthropocene climate is likely to be no less complex.

The course of the Anthropocene will be modified by human feedbacks, too, as society attempts to mitigate and to adapt to global change. Mitigation efforts need to be collective to be effective: for instance, conservation policies aimed at reducing biodiversity loss, or carbon reductions as a brake on climate change. Even if implemented, such actions will probably leave their own geological footprint, as (say) alternative energy sources are constructed, or large-scale carbon sequestration is initiated. Adaptation will be to local effects, but may leave a considerable stratigraphic signal (e.g. building sea defences or translocating infrastructure) and perhaps involve increased energy use and carbon emissions. Thus, an evolving web of feedbacks, involving combinations of local and global human reactions in various realms including that of finance [99], will further influence, and be another geologically unique feature of, this time interval.

9. A lower boundary to the Anthropocene

The degree of environmental change wrought by humans may be considered sufficient for a formal chronostratigraphic definition of the Anthropocene epoch. While human effects may be detected in deposits thousands of years old (e.g. [41]), major, unequivocal global change is of more recent date (e.g. [100]; figure 1 [101]). It is the scale and rate of change that are relevant here, rather than the agent of change (in this case, humans).

The boundary may be defined by a GSSP, or it may be defined numerically with a GSSA for its inception, which is then ratified by the International Commission on Stratigraphy (ICS). Potential GSSPs and ages should allow stratigraphic resolution to the annual level. One may consider using the rise of $p\mathrm{CO}_2$ levels above background levels as a marker, roughly at the beginning of the Industrial Revolution in the West (following Crutzen [1]), or the stable carbon isotope changes reflecting the influx of anthropogenic carbon [45]. However, although abrupt on centennial/millennial time scales, these changes are too gradual to provide useful markers at an annual or a decadal level (while the CO_2 record in ice cores, also, is offset from that of the enclosing ice layers by the time taken to isolate the air bubbles from the atmosphere during compaction of the snow). From a practical viewpoint, a globally identifiable level is provided by the global spread of radioactive isotopes from the atomic bomb tests of the 1950s [102], but this event is considerably later than the onset of increased levels of anthropogenic atmospheric gases resulting from industrial processes. Any candidate boundary based on the deposit (i.e. future rock) record, such as the base of furnace slag, colliery waste and so on in, say, the Ironbridge Gorge, Coalbrookdale, regarded as the cradle of the Industrial Revolution, will be diachronous as industrialization spread throughout western Europe, the Americas and latterly to the Far East. In the case of the Anthropocene though, it is clear from the preceding discussion that—for current practical purposes—a GSSP may not be immediately necessary. At the level of resolution sought, and at this temporal distance, simply selecting a numerical age, such as the beginning of 1800 in the Christian Gregorian calendar, may be an equally effective practical measure. This would allow (for the present and near future) simple and unambiguous correlation of the stratigraphical and historical records and give consistent utility and meaning to this as-yet informal (but increasingly used) term. Nevertheless, the choice of a date should not necessarily reflect a western perspective: the 1st of June 1800 equates to the 9th of Muharram, 1215, in the Islamic calendar (Kingdom of Saudi Arabia, Ministry of Islamic Affairs, Endowments, Da'wah and Guidance at http://prayer.al-islam.com/convert.asp?l=eng).

10. Summary remarks

It seems clear that the Anthropocene is an event that, despite its brief duration to date, is significant on the scale of Earth history. However, providing a clearer and more quantitative description of it will be a necessary prerequisite to consideration of formalization. This will mean providing a better integrated 'total' Earth history (with due attention to episodes of relative stasis as well as of rapid change), which can be translated into 'modern' terms that the wider scientific community can deal with. Conversely, summary data on modern processes must be translated into stratigraphic terms (i.e. what would their product be, if preserved in strata) for effective comparison to be made. The former process will be facilitated by initiatives such as the time scale creator [103] in which past physical, chemical and biological phenomena are plotted on to a uniform geological time scale, while the latter will be enabled by the kind of integrations of data achieved by the IPCC and now by the IPBES. There remains much work to do.

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