



## The stratigraphic basis of the Anthropocene Event

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### ABSTRACT

This paper outlines the stratigraphic basis of a proposed Anthropocene Event. It considers a diachronous event framework to be more appropriate for understanding the Anthropocene than treating it as a new geological series/epoch. Four general categories of material evidence are identified as of particular relevance: 'artificial' strata with natural constituents; humanly modified ground; legacy sediments; and 'natural' geo-deposits containing artefactual material. All these arise from the interaction and mixing of human, natural, and hybrid human-natural forces. Taken together, such stratigraphic evidence supports the case for recognising the Anthropocene as an unfolding event.

### 1. Introduction

The case for designating the Anthropocene as a new unit of series/epoch status within the International Geological Timescale (GTS) is well documented by numerous articles and books (Zalasiewicz et al., 2008, 2019; Head et al., 2022; Waters et al., 2014, 2016, 2018). Furthermore, the Anthropocene Working Group (AWG) of the Subcommittee for Quaternary Stratigraphy has communicated its position effectively to the general public through internet and other media articles. It is no longer necessary for every paper on the subject of the Anthropocene to summarize the case for the proposed new series/epoch and its suggested start in the mid-20th century, or to outline the whole history of the Anthropocene concept.

Instead, this paper takes as its starting point recent work which reconfigures the Anthropocene from a proposed geological epoch to an emergent, unfolding, intensifying event (Gibbard et al., 2022a, 2022b; Bauer et al., 2021, Edwards et al., 2022). This work proposes that the Anthropocene concept would be most useful to science if it continues to be regarded as an informal time unit alongside the GTS (cf. Swindles et al., 2023). Unlike formally defined epochs, geological events can

encompass spatial and temporal heterogeneity and the diverse processes that interact to produce global environmental changes (Bauer et al., 2021).

Many sources of evidence from within the social sciences and humanities, as well as the natural sciences, support the case for an Anthropocene Event. This paper, however, is focused specifically on physical stratigraphic evidence, and thus draws mostly from disciplines that deal with strata and use stratigraphic methods, including geology, archaeology, soil science, and fluvial sedimentology.

When the term 'stratigraphy' is used in this paper, it refers to the study of strata - namely the rocks, deposits and soils in the ground, interfaces and discontinuities between them, patterns of layering, chemical signatures, profusion or absence of certain kinds of natural fossils or other evidence on either side of material boundaries, rather than conceptual boundaries and timelines. It may also refer to tree-rings (Jacoby and D'Arrigo, 1997) and stratigraphic evidence preserved within ice cores (Orombelli et al., 2010) - providing a record of atmospheric and climate changes (e.g. Walker et al., 2009).

The aim is to characterize, at least in broad terms, the stratigraphic basis of the Anthropocene Event.

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## 2. Diachronous onset and development

Until the publications of [Gibbard et al. \(2022a, 2022b\)](#), it was generally assumed that the Anthropocene must have a single start as a point within a sedimentary sequence or in the form of a numerical date. The question of ‘when did the Anthropocene begin?’ has been the subject of much discussion, with numerous dates of onset proposed (see [Erlandson and Braje, 2013a, 2013b](#); [Smith and Zeder, 2013](#); [Lewis and Maslin, 2015](#) for summaries). Initially it was suggested that the late 18th century was an appropriate start date, reflecting the onset of industrialisation in western Europe ([Crutzen and Stoermer, 2000](#); [Crutzen, 2002](#); [Crutzen and Steffen, 2003](#); [Zalasiewicz et al., 2008](#)), but the mid-20th century is currently the favoured date of the AWG ([Waters et al., 2016](#); [Zalasiewicz et al., 2019](#); [Head et al., 2022](#)).

With the Anthropocene thought of as an ongoing event, however, it is not just the mid-20th century start date that is questioned, but also the assumption that the Anthropocene must have a precisely specified start, following previous critiques that point to neglected earlier evidence ([Ruddiman et al., 2015](#)) and question the suitability of the chronostratigraphic method for framing the Anthropocene ([Edgeworth et al., 2019](#)). The Anthropocene Event is conceptualized, instead, as an emergent set of processes that increase in transformational intensity through time. It has been defined as ‘*aggregated effects of human activities that are transforming the Earth system and altering biodiversity, producing a substantial record in sedimentary strata and in human-modified ground*’ ([Gibbard et al., 2022a](#), 350).

As this definition implies, human-influenced transformations of the Earth system are considered to accumulate, intensify and compound as the Anthropocene Event unfolds. This is different from maintaining that an instantaneous transition from one epoch to another has occurred. The beginnings of emergent Anthropocene phenomena and processes are spatially and temporally variable, impossible to pin down to a single point in time.

Note that the definition of the Anthropocene Event refers also to the sedimentary strata and humanly modified ground that constitute the material record. There is an essential correspondence between the concept and its stratigraphic basis. That is not the case with the epoch (i. e. numerical age) argument. Epoch proponents draw their main evidence for the start from non-stratigraphic sources, and in particular from the many indicators of accelerated planetary change characterised as the ‘Great Acceleration’ ([Steffen et al., 2015](#)). Some of these indicators – such as increases in nitrogen and carbon cycles and other geochemical signals – can be identified in the physical stratigraphic record (see [Zalasiewicz and Williams, 2020](#) for summary), but specifying a precise start date (1950CE) on the basis of such evidence remains problematic. This is because the Great Acceleration is an acceleration of existing trends. It did not occur from a standing start, but rather as the continuation and intensification of processes already in motion ([Stephens et al., 2019](#)). As a set of unfolding diachronous processes with roots in the more distant past, and speeding up dramatically from roughly the 1950s on, it is the latest part of the larger unfolding Anthropocene Event. It does not have a single moment of start any more than the Anthropocene as a whole does.

There is strong support for a Great Acceleration in physical stratigraphic evidence, in the form of the exponential growth and spread of humanly modified ground in recent times (though this is largely unused by epoch proponents, on account of its high degree of diachroneity). More geological material is now being moved around the planet by humans and their machines than by rivers or other geomorphological forces ([Hooke, 1994, 2000](#); [Syvitski et al., 2005](#), [Wilkinson, 2005](#); [Wilkinson and McElroy, 2007](#); [Hooke and Martín-Duque, 2012](#); [Reusser et al., 2015](#)), producing new humanly-modified stratal formations on an unprecedented scale, with rate of growth increasing every year. But this surge in production of humanly-modified ground is a continuation of processes of accumulation of material already well underway, building up in stratified sequences over centuries, sometimes millennia ([Braje](#)

[and Erlandson, 2013](#)). Contemporary and recently formed anthropogenic deposits are integral parts of the same successions as more ancient material. On the basis of such evidence, the Great Acceleration is more readily understood as the recent acceleration of (the impacts and effects of) the larger Anthropocene Event.

Even the radiogenic signal in strata (derived from nuclear weapons fallout) that is now cited as a marker of the start of the Anthropocene epoch (e.g. [Waters et al., 2015](#)) is diachronous. The first atomic Trinity test in 1945 in New Mexico can be dated to the nearest hundredth of a second ([Zalasiewicz et al., 2015](#)) - but that is not a stratigraphic signal. Over five hundred above-ground nuclear detonations occurred between 1945 and 1963, since when most testing has taken place underground. Distribution of radiogenic isotopes from these explosions via the atmosphere was spread out over years, and particles did not arrive everywhere on the Earth’s surface to find their way into strata at the same moment. In general, the further away from sites of nuclear testing the longer it took for radiogenic isotopes to get there, subject to vagaries of air currents and other climate patterns. Since most of the testing was done in the Northern Hemisphere, there was delay in particles reaching large parts of the Southern Hemisphere ([Severi et al., 2023](#)). Wind direction and strength and rates of precipitation were important factors, as were ocean currents and depth of water, as particles falling into the ocean do not sink immediately to the seabed but may be held and transported by water for considerable periods of time. For the radiogenic signal to be incorporated into shells, bones of vertebrates, etc, and for these in turn to become embedded in strata, more time-lags are involved.

Further complications concern the re-mobilization of radiogenic particles once these reach the ground/lake bed/seafloor, especially over large parts of the Earth’s surface affected by human activity (e.g. ploughing of cultivated soils, disturbance of the sea bed through industrial-scale deep trawling, etc). Particles may migrate vertically from the layer in which deposited to older and deeper layers through bioturbation and anthroturbation processes; they may also be carried downward by groundwater, picked up by crops and transferred into the human food chain, or removed completely through soil erosion by wind or water to be deposited in sediment elsewhere. Urban and suburban ground surfaces are extensively armoured with stone, concrete and tarmac, or covered with buildings. Locations in built-up areas where radiogenic particles might freely enter soil directly are gardens and parks, or zones where buildings have been cleared, such as Karlsplatz in Vienna ([Wagreich et al., 2022](#)). For the most part, particles falling in urban contexts are likely to be redirected by rainfall into drains and sewers before even reaching the soil, to be swept from there into rivers and ocean. All this constitutes a time-transgressive stratigraphic signal, spread over decades.

Plastics ([Zalasiewicz et al., 2016](#)), often cited as a secondary marker, likewise did not suddenly appear in strata in 1950. Bakelite, an early form of synthetic plastic, appears in small amounts in UK landfills from about the late 1920s onwards. Production of modern plastics may have surged in the mid-20th century, as epoch proponents argue, but this took some time to register in the stratigraphic record. Plastics on the ocean surface were first detected in 1971 ([Carpenter and Smith, 1972](#)) though it is uncertain when these were first incorporated into sediment on the sea floor. Large amounts of modern types of plastic were being deliberately buried in landfill from about the 1960s on ([Rathje and Murphy, 1992](#)). However, like radiogenic particles, plastics are highly mobile, and do not necessarily stay in the layers where deposited, as shown by evidence of the downward migration of plastics in lake sediments ([Dimante-Deimantovica et al., 2022](#)) and the leaking of buried plastics from eroding coastal landfills inundated by rising sea levels ([Spencer and O’Shea, 2014](#); [Edgeworth, 2023](#)). Movement within sediment sequences may arise as a consequence of post-depositional bioturbation, loading, etc. Plastic particles have only recently been detected in Antarctic snow ([Aves et al., 2022](#)), so have yet to become fully integrated into ice-core stratigraphic archives. The stratigraphic signal of plastics is

a highly dynamic and diachronous one. As such, it constitutes evidence more for the unfolding Anthropocene Event than the proposed new geological epoch.

### 3. A spectrum of stratigraphic evidence

There is a wide range of stratigraphic evidence available that is relevant to the study of the Anthropocene Event. All of it arises from different levels and degrees of human-natural interactions. This evidence reflects the fact that the Earth system has, over the course of time, become a human-natural hybrid system characterised by an entanglement of human and natural forces, sometimes merging to work together and sometimes operating in opposition to each other. As already noted, this did not happen instantaneously in the mid-20th century, as implied by the epoch paradigm, as if the Earth flipped from a natural state to humanly-dominated state to fit the requirements of chronostratigraphy for a globally isochronous stratigraphic boundary. Rather it developed over thousands of years, with the extent of human influence increasing and speeding up over time, leading up to and including the Great Acceleration (Steffen et al., 2015), and still unfolding at the present moment.

There is no hard and fast division between the various types of evidence outlined below; they grade into and overlap with each other. Moreover, they may be found interleaved in various combinations in the same vertical stratigraphic successions, which makes their mapping through surface manifestations alone impractical. A rigid classification system is inappropriate here. Rather, it is better to envisage a broad spectrum of types of stratal evidence, ranging from 'artificial' strata containing natural constituents at one end to 'natural' geological deposits with inclusions derived from the human world at the other. In all, we recognise four general categories of deposit that characterize the Anthropocene Event: 'artificial' strata with natural constituents; humanly-modified ground; legacy sediments; and 'natural' geo-deposits containing artefactual material.

#### 3.1. 'Artificial' strata with natural constituents

Layers of concrete, road surfaces, hardcore, industrial ash, building and demolition rubble, and other biologically inert and sterile deposits and dumps, often extracted, transported and deposited with earth-moving machines, are all what might be termed 'artificial' strata. These typically contain redeposited natural material or reconstituted natural components. The overall shape of stratigraphic formations that result is largely the product of intentional human geological agency, and often exhibits clear elements of design.

Some reclaimed land composed of redeposited spoil from quarrying or tunnelling might be placed in this general category. An example is Wallasea mudflats on the coast of Essex in Eastern England, now the largest human-made wetland and wildlife reserve in England, which was sculpted mainly from material extracted during tunnelling for the new Crossrail underground metro line under London. The material is mostly London Clay, originally deposited about 55 million years ago at the bottom of a shallow sea. It contains an abundance of marine fossils from that time. Excavated by tunnel boring machine, raised to the surface and transported down the river on barges, it was then unloaded by crane and spread by bulldozers.

Another example is provided by the 'artificial' islands largely made of sand off the coast of Dubai, in the shallow waters of the Persian Gulf. These include large palm-shaped islands protected by a storm barrier, and about 300 small islands grouped together to resemble a map of the Earth, designed to be visible from space and on programmes such as Google Earth. Islands are formed by dredging sand from the seabed and spraying it from ships into a designed shape. The loose grainy material is held in place with rocks and compacted with compressors which use water pressure and gravity to pack the grains together, thereby effectively solidifying it in order to provide a firm foundation for building

construction to take place.

Although advances in earth-moving technology are speeding up the creation of new land for urban expansion, including the formation of artificial islands, this is not in any sense a new phenomenon. It needs to be seen as a continuation and acceleration of trends in processes of land reclamation that have been going on for thousands of years in coastal and river cities throughout the world (Hudson, 1996; Masoud, 2021), with pace of development increasing as the Anthropocene Event continues to unfold.

Similar terraforming techniques are deployed widely in the Netherlands, where large quantities of sand are dredged up from the North Sea floor and pumped onto the land to replenish beaches and provide material for embankments and dykes (Noordzeeloket website). The Sand Motor project on the coast of Delfland recently extracted 21.5 million cubic metres of sand from the seabed 10 km offshore and deposited it to form one large hook-shaped peninsular, letting 'natural' forces of wind and waves distribute it along the coast (Heerema, 2021). It is estimated that over 65% of land in The Netherlands would be underwater at high tide today if it were not for such interventions, which have their roots in the long history of Dutch land reclamation (Hoeksema, 2007).

The rationale of 'building with nature' at the heart of the Sand Motor project is presented as a modern concept but is actually a defining principle of much landscape transformation over several thousand years. Hillsides throughout parts of Asia, southern Europe, South America and other parts of the world have been terraformed by the creation of terraces (Brown et al., 2021), often enlisting the force of gravity to move material downslope, trapping this 'hill wash' against terrace walls to form a descending series of flat fields (Fig. 1).

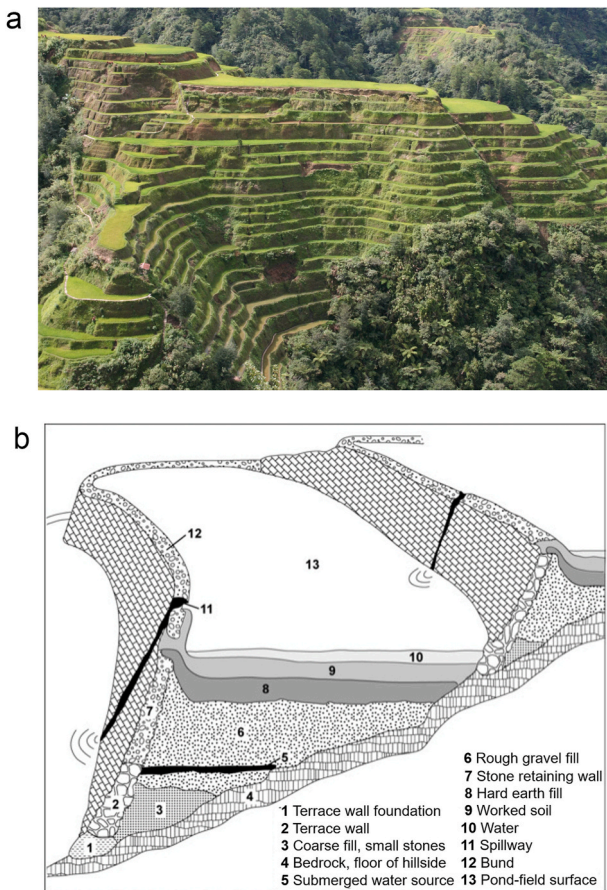
Such landscapes are formed as much through human-controlled and human-channelled geomorphological process as through direct human agency on its own. Though classified here as artificial structures, they typically accumulate multiple stratigraphic traces of human action and are subject to numerous biological and geomorphological and transformations over many generations of use and maintenance (Tarolli et al., 2014). As such they might be better described as archaeological earthworks/landscapes, and hence placed in category 2.

It is worth re-emphasising that there is often no clear distinction between these different categories of evidence. Over time, reclaimed land (classed here as category 1), no matter how artificial and sterile to begin with, or how heavily designed, is increasingly impacted by natural and hybrid human-natural geomorphological forces, becoming more biologically active and transforming into what might more accurately be described as humanly-modified ground (category 2). Some deposits will be subject to liquefaction by erosive forces and material will be redistributed to become part of legacy sediments (category 3) or 'natural' geo-deposits such as those left behind on land in the wake of tsunamis (category 4).

#### 3.2. Humanly-modified ground

The term humanly-modified ground refers to archaeological strata, earthworks, landfills, cultivation soils, landfills, cuts and fills of features such as quarries, pits and ditches, service trenches containing buried infrastructure, and other ground which humans have played a large part, together with natural geomorphological forces (Brown et al., 2017), in creating or shaping - often as the unintentional by-product or material residue of human activities. All these constitute the 'archaeosphere' (Edgeworth, 2014, 2017, 2018). Formations of it have been growing for thousands of years, in isolated patches at first (e.g. Erlandson, 2013), but now spreading rapidly across formerly untouched parts of the ice-free land surfaces of Earth to constitute in its entirety a stratigraphic entity of global scale, and still very much in the process of formation today. More humanly-modified ground is being created now than ever before, adding to existing accumulations of more ancient material (Fig. 2). As already noted, the surge in its growth over the last 70 years could itself





**Fig. 1.** Terraforming of hillsides by agricultural terracing, Luzon, Philippines (a) Banaue rice terraces and complex irrigation system, on the foothills of the Cordillera mountains, Luzon, Philippines. Still in use by Ifugao traditional wet-rice farmers, vast areas of hillsides have been terraced incrementally over many generations, starting at the base of slopes and working up. Each terrace is part of a larger hillside system, which in turn is an interwoven part of yet larger systems comprising many such terraced hillsides. Photo by Roundtheworld, 2009). CC-BY-SA 2.0. (b) Schematic section through one of the terraced pond-fields, giving an idea of the depth of archaeological successions. Depending on gradient of slope, the height of stone terrace walls (and depth of stratigraphy in the field above) averages 2–6 m, with width of the field varying accordingly. Water is channelled down stepped fields from managed rain forest higher in the mountains through systems of dams, sluices, channels and spillways. Drawing by Philip Stickler, adapted from [Acabado \(2009\)](#), [Conklin \(1980\)](#).

be used as a stratigraphic indicator of the Great Acceleration ([Steffen et al., 2015](#)).

Humanly-modified ground can be observed and recorded at different scales. It can for example be mapped as a single layer, as Eduard Suess did in Vienna in the 1860s ([Suess, 1862](#)) and Robert Sherlock did in London in the 1920s ([Sherlock, 1922](#)). More recently, geoarchaeologists in Pisa ([Bini et al., 2017](#)), Rome ([Luberti, 2018](#)) and Sao Paulo, Brazil ([Peloggia et al., 2017](#)) have also treated it as a single unified deposit. But it actually comprises multiple stratigraphic units of various scales such as cuts, fills, dumps, layers, lenses, etc, sometimes occurring together in complex stratified successions. Archaeology has developed and honed methods to deal with unravelling, sequencing, dating and correlating such deposits ([Harris, 1989](#); [Roskams, 2001](#); [Lucas, 2012](#)). Each layer, fill or feature in the sequence may contain environmental material such as pollen, seeds, insects, animal bones, and other organic materials as well as human artefacts – the total assemblage providing valuable information about, climate, animal and plant populations, human-natural processes at work at the time the layer was laid down or the feature formed, and other palaeoecological aspects. These inclusions can also

provide information about age, whether from comparison of artefact form with artefacts of known date from other sites, or the application of more precise scientific methods such as radiometric dating (e.g. radiocarbon; luminescence) and other techniques (such as dendrochronology) which give specific ages in years before present ([Walker, 2005](#)). But the relative dating afforded by the order of cuts and deposits in stratigraphic sequences is the principal means by which archaeological knowledge of the order of events in the past is constructed.

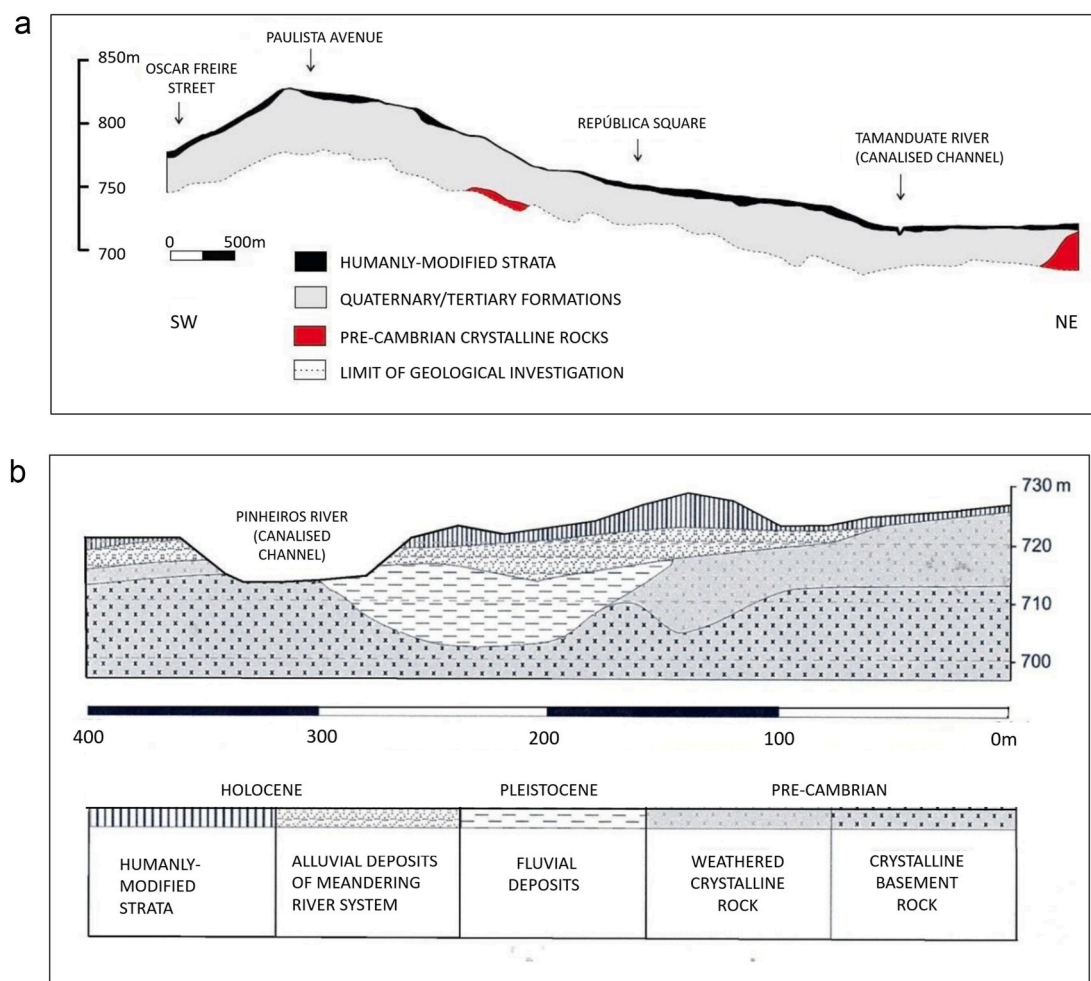
Of considerable relevance is the fact that humanly modified ground often has a clear lower bounding surface. This is a material interface between human-natural layers above and natural geological layers below, and is formed as a compound entity from multiple cuts, truncations and bedding planes. Routinely encountered by field archaeologists, it is informally referred to as the ‘surface of the natural’. This is a real material boundary that can be seen and touched and followed along, associated with distinct biostratigraphical signals. The bounding surface is considered by the AWG to be of little relevance to the Anthropocene conceived of as epoch, due to its high degree of diachroneity and the fact that parts of it are of pre-1950 date (though in reality a large proportion of it has formed since 1950, as a result of the recent accelerated spread of humanly modified ground over previously untouched areas). Described in more detail as ‘Boundary A’ in [Edgeworth et al. \(2015\)](#), and marked as such on [Fig. 3](#), it may prove to be of considerable value in investigating the stratigraphic basis of the Anthropocene Event.

Chronologies derived from highly diachronous humanly modified ground are necessarily different from those of chronostratigraphy, partly because the timescales deployed are of different magnitudes. Time boundaries in archaeology move temporally from place to place instead of being globally isochronous. For example, the start of the Neolithic (involving the emergence of agriculture, the domestication of many species of animals and plants, the adoption of settled ways of life, etc) is thousands of years earlier in the Fertile Crescent area than in, say, Northern Europe. Technological developments take time to disseminate and spread to different parts of the world. The start of the Iron Age in Hungary, as a further example, is different from that in East Africa, which is different in turn from that in Australia. This is entirely in keeping with the stratigraphic evidence of the unfolding character of the Anthropocene Event on human timescales.

Within stratified sequences of humanly-modified ground are some striking diachronous biostratigraphic signals unprecedented in natural geological layers below. Just two are considered here. The first is the manifest profusion of artefacts and novel materials, increasing in abundance and diversity through time. No novel materials at all are found in entirely natural geological strata. Ceramics are a common inclusion in rubbish pits of the European Neolithic. In rubbish pits of the European Iron Age, ceramics are often found with other novel materials such as glass or metal alloys. These prehistoric depositional contexts can be compared with the relative abundance and sheer diversity of novel materials, from ceramics to concrete to fibre glass to plastics and so on, contained in 20th century landfill deposits ([Rathje and Murphy, 1992](#)). Taken overall, this is a multi-scalar signal, not only in the sense that it starts small and gets bigger over time, but also in that the evidence of larger events and processes (the development of novel materials taken as a whole) may have evidence of smaller events and processes (say, the recent development of plastics, or specific types of plastic) nested within.

The second is the presence of exceptionally large numbers of unusually well-preserved skeletal remains of a single species: human beings. In a manner unprecedented in natural geological deposits, these are often grouped together into communal burial grounds, sometimes contained within coffins or (in the case of cremations) in pottery vessels, and placed within burial pits, frequently arranged in rows or other geometric formations and often stacked vertically in the same reused and recut burial spot. This deliberate and systematic burial – the intentional placement of potential fossil remains into strata – means skeletal remains are much better preserved than would otherwise be the





**Fig. 2.** Urban geology, São Paulo, Brazil a) Geological profile of ground in the central part of the city of São Paulo, showing humanly-modified strata as forming the latest geological deposit. This started accumulating in the centre of the city during colonial times from the 16th century on, spread rapidly outwards from the late 19th century, with rates of growth increasing again from the 1940s to the present (Peloggia et al., 2017). Adapted from drawing by Alex Peloggia. b) Schematic section showing sediments of the Pinheiros River in relation to the humanly-modified ground above, the formation of which was connected with transformation of the many rivers in the city. The meandering channel of the Pinheiros was straightened into an artificial canal. The old floodplain was covered with landfill, the former river terraces replaced by artificial levels on which houses, tower blocks and other urban structures were built. Flow was reversed to supply a hydropower plant. Adapted from drawing by Alex Peloggia, based on original in Luz & Rodrigues (2015).

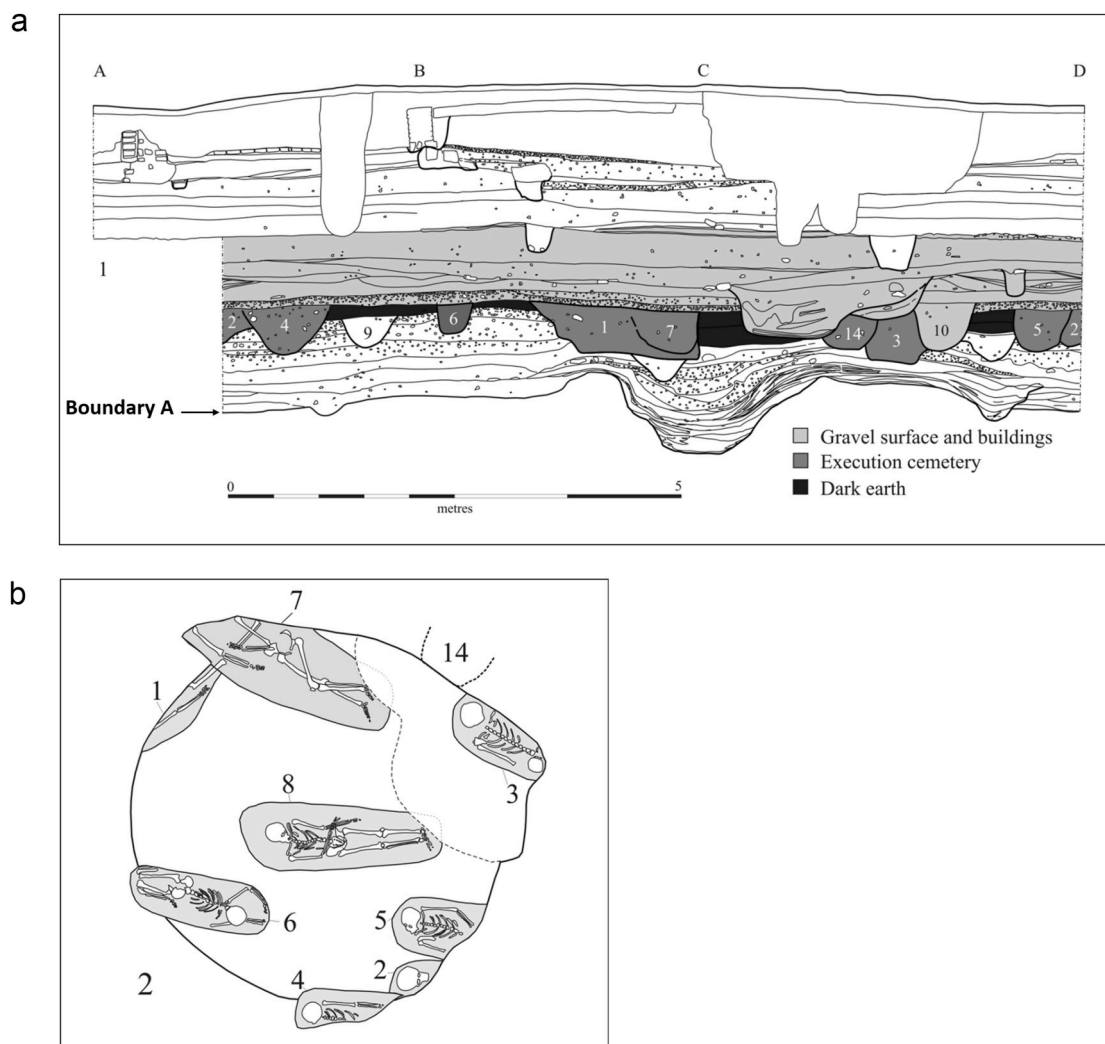
case. There are tens of thousands of burial grounds of various sizes and dates throughout the world, containing hundreds of millions of individual sets of remains, with numbers growing all the time. While pre-historic cemeteries are relatively small, a single cemetery in London may contain a hundred thousand bodies or more buried in extremely tight three-dimensional stratigraphic formations. The largest cemetery in the world, the Islamic cemetery in the holy city of Najaf, Iraq, is said to contain several million buried bodies, with tens of thousands more added every year. Considered on a global scale, this is an unparalleled diachronous biostratigraphic signal of human population growth through time. Far from being a homogenous signal that takes the same form everywhere, however, it takes multiple forms – the traces of culturally diverse burial practices. The signal also changes and develops over time. Like many things to do with the Anthropocene Event, it grows in intensity and size through processes of accumulation.

Humans are not the only species to be deliberately buried in humanly modified strata, and thus to have vastly improved chances of entering the fossil record. When outbreaks of avian flu sweep across continents, millions of carcasses of exterminated broiler chickens and other factory-reared birds, with bone-structure shaped by centuries of human selection, are disposed of en-masse deep in landfills throughout the world - constituting a durable stratigraphic signal of a biosphere reconfigured

by human activity (Bennett et al., 2019).

Some cities such as Toronto and Houston have networks of tunnels known as ‘underground cities’ (de Mulder et al., 2014) following earlier traditions of sub-surface urban spaces such those of Cappadocia in Turkey (Yamaç, 2022). Many have extensive systems of metro (underground railway) tunnels and shafts extending down into deep strata far below the city streets, providing a durable stratigraphic signal of rapid urban population growth and energy consumption over the last century and a half (Williams et al., 2020). Evidence of the growth of metros in cities, starting from small beginnings and spreading outwards and downwards almost like a root system, and spreading also from city to city, is difficult to assimilate within the concept of the Anthropocene when conceived of as an epoch - not just because in many cities such as London and New York processes of metro construction started well before 1950, but also because the stratigraphic evidence of continued and ongoing developments is so time transgressive. Such evidence fits comfortably, however, into the conceptual frame of the unfolding Anthropocene Event.

It is not just urban landscapes that have stratigraphic depth. Agricultural landscapes also have thicknesses of humanly-modified ground. Some agricultural soils such as plaggens, built up through the regular addition of animal bedding and manure (Blume and Leinweber, 2004),



**Fig. 3.** A stratigraphic succession of humanly-modified ground, Cambridge, UK (a) This vertical section drawing records the side of a cylindrical sewer shaft excavated through urban ground by the Cambridge Archaeological Unit. It illustrates the complexity and richness of humanly-modified ground. Below Boundary A are natural clays and silts. Above Boundary A are Roman layers (unshaded), including evidence of a road and roadside ditch. Sealing the Roman levels is a layer of dark earth, into which are cut inhumation graves (numbered) of a 7th-9th century Saxon execution cemetery. These in turn are overlaid by a gravel layer, the internal floor of a possible church, with a single burial cut through it. Above is a succession of further floor surfaces, through which a large pit has been cut. Over a thousand sherds of pottery were found as inclusions in the (shaded) Saxon and Saxo-Norman layers alone, together with environmental evidence such as carbonized grain. Proceeding upwards from there, a series of floors (unshaded) of medieval domestic buildings contained a hoard of 1805 silver and 9 gold coins dating to 1350, with occupation layers of post-medieval houses, with brick walls and fireplace above. A late feature is a cellar which cuts through earlier layers. The layer at the very top is the modern tarmac surface of the present road (Cessford et al., 2007). The label for Boundary A has been added. (b) The Saxon execution cemetery shown in plan, as it was encountered mid-way through the excavation. It comprises shallow burial pits, oriented roughly east-west, containing human skeletons, with cut marks on them indicating execution. These graves, numbered, are also visible in the section, as embedded parts of the stratigraphic succession (Cessford et al., 2007). Images reproduced courtesy of Craig Cessford and Matt Brudenell of the Cambridge Archaeological Unit, and Taylor and Francis.

can be several metres deep. The extent of agricultural soils in terms of surface area covered is well-mapped (e.g. Ellis and Ramankutty, 2008), but measurements of depth are required to work out volume and quantity. Soil science is only just coming to terms with the realisation that a large proportion of soils have been transformed by human activities (Richter, 2007). Much urban waste is now dumped in the countryside, creating extensive new strata composed of landfill material. Supposedly natural environments such as the Amazon rain forest may have deposits of artefact-rich anthropogenic soils known as dark earth or *terra preta* produced by traditional horticultural practices of indigenous peoples (Neves et al., 2004), or large numbers of previously unsuspected earthworks (de Souza et al., 2018).

Although people and their technologies are the principal geological agency involved in the production and transformation of humanly-modified ground, other non-human agencies such as earthworms,

insects, burrowing mammals, rivers, domestic animals and plants, tree roots, micro-bacteria, etc, all play significant parts. Some of these might be described as hybrid human-natural agencies. The stratigraphic formations of cemeteries and landfills provide good examples of human and non-human forces working together. Formation of strata and settling of ground in both settings involves a symbiotic working relationship between humans and micro-organisms in decomposing bodies and waste material. Such 'dark ecologies' exemplify the human-nature interactions evident in so much of the stratigraphy of the Anthropocene Event.

### 3.3. Legacy sediment

'Legacy sediment' is a term that describes sediments that are the indirect and often unintentional outcome of human activities, such as

over-cultivation of soils, deforestation, dam and reservoir construction, straightening of rivers, etc. Such activities cause increased amounts of material to be eroded, transported, deposited and reworked by wind and water, or by slippage of materials down hillsides (James, 2013). Rivers in particular are subject to human-induced changes in sediment flux (Syvitski et al., 2005). A compilation of more than 4000 rates of alluvial sediment accumulation for North America revealed that rates of sedimentation increased by more than an order of magnitude since European colonization and associated agricultural expansion and river modification (Kemp et al., 2020). Much earlier archaeological evidence of anthropogenic activity influencing sedimentation rates in rivers can be found in other parts of the world such as China, as for example on the Huang He or Yellow River (Zhuang and Kidder, 2014).

Increasing amounts of material eroded and carried by a river can result in greater amounts deposited on floodplains and in deltas, and in corresponding changes to morphologies of river channels. However, the construction of dams creates impediments which slow and block the flow of material transported by a river. Legacy sediments that would otherwise have been deposited in deltas accumulate behind dams on river corridors, preventing transport of sediment downstream, with many delta areas now sinking as a result (Syvitski and Kettner, 2011). The sediment trapped by dams impacts their efficiency, and in many cases results in their eventual abandonment, with multiple knock-on effects on river development if or when the dam is eventually breached, leading to the kind of transformations in river form documented by Walter and Merritts (2008) and Merritts et al. (2011).

Abandonment of terraced hillsides in many parts of Asia, South America and southern Europe leads to extensive soil erosion and to build-up of colluvial material (Tarolli et al., 2014). There is a direct analogy here with dams on rivers. Terrace walls can be seen as the land equivalent of dams, except that the material flows being controlled are solid materials moving down slope. When the walls fall into disrepair, gully erosion occurs which massively increases the risk of landslides and the amount of colluvial material accumulating at the base of the slope.

It is important not to assume a direct one-directional causal link from human activity to environmental legacy effects. Situations are more complex and entangled than that. Thus the erosion of soils by wind in the Dust Bowl of the Southern Great Plains of North America, and related deposition of eroded material, was not solely due to over-cultivation, though that was crucial, but to a combination of economic, social, agricultural, climatic, and other environmental factors. It was a 'synergy of multiple natural and anthropogenic extreme events' that created the Dust Bowl (Lee and Gill, 2015, 16).

Mining waste legacy sediments (Fig. 4) can be extremely toxic, with many rivers and floodplain deposits badly contaminated by heavy metals such as lead and zinc (Pavlovsky et al., 2017) or mercury (Fornasaro et al., 2022). Extraction of ore generates huge quantities of waste material often spread over large areas, transforming landscapes (Lawrence et al., 2023) and their ecologies. In such cases, the term 'legacy sediment' is especially appropriate because of its double meaning. On the one hand it refers to the sediment itself as the legacy of human activities which indirectly caused its deposition; on the other hand it refers to the legacy it will leave for the future in the form of knock-on effects on the wider environment, its material flows and biological inhabitants.

All of this suggests the need for a general rethinking of the established view of stratigraphic evidence as merely providing a material record of past events. As well as the product or effect of past geological agencies, the types of evidence discussed here reflect a material set of active forces which generate effects on other things and on the wider environment, destroying some habitats and creating others, and impacting heavily on the biosphere, atmosphere and hydrosphere (for examples of effects on each, see Edgeworth, 2018). In the unfolding Anthropocene Event, it is no longer just the direct effects of human activities that are influencing transformations of the Earth system, but also the indirect legacy effects of the accumulated material residues of those activities.



Fig. 4. Legacy sediment showing lighter brown mine tailings overlying darker pre-European floodplain deposits, River Loddon, Victoria, Australia.

The Loddon River system was subject to extensive erosion of creeks and gullies as a result of 19th century goldmining activities, leading to mobilization of sediments that spread as toxic sludge over floodplains on higher-order streams, burying former river landscapes under considerable depths of contaminated material. After sedimentation diminished, incised channels exposed the accumulated sediment and the original floodplain deposits in high vertical banks (Lawrence et al., 2023). Photograph by Susan Lawrence, La Trobe University. Image reproduced courtesy of Peter Davies and John Wiley and Sons.

Legacy sediments may be interleaved with deposits of humanly-modified ground. For example, the cultural occupation layers of settlements on river floodplains are often interleaved with alluvial flood sediments. Colluvial material from eroded terraces may cover over layers of humanly-modified ground at the foot of a slope, and then itself be overlaid or cut into by further layers or features resulting from human activity. Many more examples could be given. This interleaving of layers again testifies to the interaction and mixing of human, natural, and hybrid human-natural forces.

#### 3.4. 'Natural' geo-deposits containing artefactual material

There are some deposits that seem to be clearly the results of wholly natural geological processes yet may still contain inclusions of human artefacts and structures, or chemical signals indicative of human activities. Examples are volcanic ash falls, pyroclastic flows, lava flows, lahar deposits, sand dune formations, flood deposits, landslides triggered by earthquakes, tsunami deposits, turbidite flows spread across the sea floor as the result of ocean currents, and so on. Although human activities may have effects on some of these (e.g. minor earthquakes caused by fracking or reservoir construction), for the most part these are not human-influenced nor human-induced.

Lahar deposits (the results of volcanically induced mudflows, landslides and debris flows) sometimes engulf human settlements and landscapes, picking up fenceposts, barbed wire, telegraph poles, communication lines, bricks, parts of buildings, automobiles, human and animal bodies, and so on, all of which are retained as inclusions. In 1985, for example, much of the town of Armero in Colombia was buried under several metres of mud as the result of a lahar flow caused by the eruption of the volcano Nevado del Ruiz in the Cordillera Central mountain range, 50 km away, with the loss of 20,000 lives (Naranjo et al., 1986).

Similarly, tsunamis flowing across land cause much devastation and pick up wreckage from human settlements and surface infrastructure,



which are likewise retained as inclusions in the tsunami flow deposits that are left behind (Fig. 5). Artefacts effectively become sedimentary particles, and may be found stacked against each other in imbrication patterns, indicating direction of flow at time of deposition. Such deposits can be dated by the artefacts and other material contained within, in the same manner as archaeological deposits.

While Fig. 5 shows an ancient example, modern tsunami deposits may contain the full range of artefacts and modern materials characteristic of recent humanly-modified ground. Even such objects as cars may become sedimentary particles (Romans, 2011) and be deposited in imbrication patterns. As well as gathering objects from the surface, tsunamis can inundate and liquify landfill deposits, effectively gouging out and remobilizing the artefact-rich and often heavily contaminated contents. This happened for example with coastal landfills around Banda Aceh, Sumatra during the Indian Ocean tsunami of December 2004 (Srinivas, 2015). Such material may be swept out to sea as backwash to contribute to marine pollution or become incorporated as inclusions within tsunami flow deposits.

Natural events such as earthquakes can lead to the accumulation of large amounts of rubble containing artefacts and all the novel materials in general use at the time. Much of this material ends up in the stratigraphic record - some remaining in situ, some cleared and redeposited elsewhere by people. The same applies to war rubble (although this is

not the outcome of natural events) such as that which resulted from the bombing of cities in World War Two, or the obliteration of Carthage by the Roman army in 146 BC, both represented by substantial 'destruction layers' within larger successions of humanly-modified strata.

Humans do have some influence, albeit small, on movement of lava and its subsequent solidification into rock. Lava dams have been successfully constructed to divert lava away from settlements and infrastructure in Sicily, Hawaii and Iceland. The artificial structures of dams (category 1), often 5–6 m high, made of earth and other materials compacted by earthmoving machines, may come to be at least half-embedded and sometimes completely buried in igneous rock formations.

Volcanic deposits can be very useful in dating stratigraphic successions of mixed humanly modified and natural strata. In Iceland, archaeological horizons are often interspersed by layers of tephra (volcanic ash, small rock fragments, large boulders, etc) traceable through chemical signature to historical eruptions (e.g. Harning et al., 2018). Because tephra is widely dispersed, layers on different sites can be correlated with each other and with a known and dated volcanic event. This obviously helps in dating settlement layers above and below the tephra in stratigraphic successions (Byock, 2001).

In addition to the stratigraphic products of violent geological events, naturally forming sediments on the sea floors and lake beds are increasingly becoming the recipient deposits for plastics and



**Fig. 5.** Tsunami deposit containing artefacts, Palaikaastro, Crete (a) This tsunami deposit from the promontory near the former Minoan town of Palaikaastro on the northeast coast of Crete contains a chaotic mix of natural and artefactual objects/materials: pot sherds, tiles, wall plaster, domestic animal bones, marine shells, natural rounded pebbles, volcanic ash (tephra) reworked by water. Three forms of dating are possible using these inclusions. Volcanic ash can be dated through analysis of its chemical signature; cattle bones and marine shells can be radiocarbon dated; and pot sherds dated archaeologically on the basis of pottery types and styles (correlated with layers containing similar sherds in stratigraphic successions from the excavated town nearby, and from other sites as far away as Egypt). All these combined enable the tsunami deposit to be associated with an eruption of the Santorini Volcano in the eastern Mediterranean Sea roughly 120 km north of Crete in about 1600 BCE (Bruins et al., 2008). (b) General view of the setting of the tsunami deposit on the shoreline and the position of Section 1, which is shown in the close-up image in (a). Note the walls (W) that are emerging from the cliff through erosion, partly covered by the tsunami deposit: these are elements of buildings connected with the Minoan town nearby (Bruins et al., 2008).

Images reproduced courtesy of Hendrick Bruins and Elsevier.

microplastic particles. As already noted, plastic particles were recently identified in Antarctic snow (Aves et al., 2022), and will at some point register in ice core archives. Surface soils on land and upper layers of sediment in lakes and oceans, and layers of ice in polar regions, are likewise recipient deposits for radiogenic particles from the fallout from nuclear detonations.

Stratigraphic evidence from ice cores may indicate changes in the composition of the atmosphere that are partly induced by human activities. But this should not be regarded as completely separate from the evidence of humanly-modified ground. Because terrestrial processes are connected to those in the atmosphere, with the tilling of soil removing carbon and releasing carbon dioxide into the air (Reicosky, 2005), and rice production and livestock farming producing methane and other greenhouse gases, information on the composition of the atmosphere obtained from ice cores can sometimes be correlated with stratigraphic evidence from the ground (Fuller et al., 2011; Ruddiman et al., 2016).

The 'natural archives' (Waters et al., 2018) which seem to be the preferred type of deposit for the AWG constitute a small subset of category 4 evidence. Much less attention is directed by the AWG towards the far more substantial evidence in categories 1–3. This emphasis on natural archives at the expense of anthropogenic evidence is somewhat paradoxical when characterizing a time unit partly defined in terms of human geological agency. If the significance of the Anthropocene is to be better understood, then the stratigraphic evidence produced by human and hybrid human-natural forms of agency, as well as that generated by natural geological agencies, should surely be acknowledged and treated as equally valid.

#### 4. Conclusions

The Anthropocene Event leaves a substantial material record in the form of stratigraphic evidence. It has a strong stratigraphic basis, testifying to transformations of the Earth's surface and the Earth system as these develop over time, including the intensification of processes of change during the Great Acceleration. In taking account of this evidence, the overall view of the Anthropocene, as conceptualized over the past two decades or so, inevitably changes. Instead of a 'Human Age' it might be conceived of more as a time of increasing or accelerating effects of human-natural interactions on the Earth system, with numerous hybrid forces producing new stratigraphic forms and leaving a substantial, rich and growing stratigraphic signature. The Great Acceleration is understood to be an intrinsic and integral part of the larger unfolding Anthropocene Event, as an acceleration of processes which have roots in the more distant past.

The idea that human involvement in Earth system change can be adequately represented by a geological series/epoch with shallow temporal depth and a fixed and precisely defined start date, implying a near-instantaneous and recent shift from a natural to human-dominated world, is manifestly oversimplistic. Such a view can only be sustained by overlooking or putting to one side substantial bodies of relevant stratigraphic evidence – whether because too diachronous, pre-1950s in date, or not fitting into the category of 'natural archives'. This paper has drawn attention to some of that neglected material, pointing out its significance and relevance. From the much broader stratigraphic record outlined here (and in Gibbard et al., 2022a, 2022b) the picture emerges not so much of a new geological epoch with sudden date of onset that can be precisely defined, but of a more time-extended, diachronous, emergent, transformative, entangled, multi-scalar, intensifying, unfolding Anthropocene Event.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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