Can an Anthropocene Series be defined and recognized?

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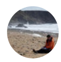

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Notes

Can an Anthropocene Series be defined and recognized?

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Abstract: We consider the Anthropocene as a physical, chronostratigraphic unit across terrestrial and marine sedimentary facies, from both a present and a far future perspective, provisionally using an approximately 1950 CE base that approximates with the 'Great Acceleration', worldwide sedimentary incorporation of A-bomb-derived radionuclides and light nitrogen isotopes linked to the growth in fertilizer use, and other markers. More or less effective recognition of such a unit today (with annual/decadal resolution) is facies-dependent and variably compromised by the disturbance of stratigraphic superposition that commonly occurs at geologically brief temporal scales, and that particularly affects soils, deep marine deposits and the pre-1950 parts of current urban areas. The Anthropocene, thus, more than any other geological time unit, is locally affected by such blurring of its chronostratigraphic boundary with Holocene strata. Nevertheless, clearly separable representatives of an Anthropocene Series may be found in lakes, land ice, certain river/delta systems, in the widespread dredged parts of shallow-marine systems on continental shelves and slopes, and in those parts of deep-water systems where human-rafted debris is common. From a far future perspective, the boundary is likely to appear geologically instantaneous and stratigraphically significant.

The concept that we may be living in an Anthropocene geological time interval has attracted considerable interest and scrutiny since its latest restatement by Crutzen & Stoermer (2000) and Crutzen (2002) (see also Revkin 1992). These authors effectively regarded the Holocene as having terminated because of the scale and significance of human impact upon the Earth system. In this view, a new and distinct phase of Earth history has already begun, and Crutzen (2002) regarded the beginning of the Industrial Revolution as marking the beginning of profound global change.

Formalizing this concept within the Geological Time Scale (Zalasiewicz *et al.* 2008, 2011, 2012) would result in the creation of an Anthropocene Epoch. Higher levels (e.g. Period, Era) might be considered because of the lack of precedent in Earth history for some of the component stratigraphical signals, such as the lithostratigraphical signal in urban regions (Price *et al.* 2011; Ford *et al.* 2014), and the scale and character of the biotic change (Barnosky 2008, 2013; Barnosky *et al.* 2011, 2012). Lower hierarchical levels are possible too (e.g. an Anthropocene Age as subdivision of the Holocene Epoch), and this would result in less modification of the Geological Time Scale. However, we continue to discuss the Anthropocene in terms of the hierarchical level of Epoch, not least because it brings clear focus on the important scientific question of whether or not the Earth system now lies outside of the 'Holocene envelope' of stratigraphically significant environmental conditions (cf. Rockström *et al.* 2009; Steffen *et al.* 2011).

Anthropocene boundary level

To carry out the analysis below, we must provisionally select a start date for the Anthropocene. Potential dates for the beginning of this phenomenon have fallen into three categories. First, dates a few to several millennia back within the Holocene (Certini & Scalenghe 2011; Ruddiman 2013) have been suggested, reflecting the growing evidence for widespread, low-intensity human modification of the terrestrial environment (Ellis 2011; Kaplan *et al.* 2011) and, more controversially (Ruddiman 2003, 2013; cf. Elsig *et al.* 2009), resultant release of sufficient greenhouse gases to maintain the Holocene within stable conditions of climate and sea level. Secondly, the beginning of the Anthropocene at around 1800 CE, as originally suggested by Crutzen (2002): that is, around the beginning of the Industrial Revolution when the rapid increase in human numbers, energy use and atmospheric carbon dioxide levels began (Zalasiewicz *et al.* 2008, fig. 1). Thirdly, approximately 1950 CE, the beginning of the post-war 'Great Acceleration' of economic activity (Steffen *et al.* 2007).

We regard the latter two as the more suitable candidates because of the clear break between

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Holocene global stability (or the very slow change), and the more rapid and geologically striking changes of the last two centuries (e.g. Zalasiewicz *et al.* 2008, fig. 1; Steffen *et al.* 2011, fig. 1). The Anthropocene does not represent the detectable incoming of human influence (which in any case is clearly diachronous: e.g. Kaplan *et al.* 2011) but major change to the Earth system that happens to be currently driven by human forcing, and which may geologically soon be more significantly controlled by a number of secondary positive feedbacks, such as methane release from permafrost and ice-albedo changes (e.g. Hay 2013, pp. 897–939).

For the purposes of this exercise we choose the later, approximately 1950 CE date. This level coincides with changes to lacustrine dynamics and sedimentation worldwide (expressly linked to a potential Holocene–Anthropocene boundary by Wolfe *et al.* 2013, and partly reflecting a worldwide shift in nitrogen isotopes associated with the increase in global fertilizer use: Holtgrieve *et al.* 2011). It also coincides with the beginning of the nuclear age and the spread of artificial radionuclides into contemporary sediments worldwide, and both biotic (Barnosky 2013; Wilkinson *et al.* 2014) and physical (Ford *et al.* 2014) stratigraphical signals that seem to be stratigraphically sharp (to *c.* decadal level) and globally widespread. These changes are traceable by scientists living today, and not just by hypothetical 'far-future' geologists. They represent a significant and permanent shift in the Earth system, although probably not the greatest changes, that will almost certainly take place in the coming centuries and millennia (Barnosky *et al.* 2011, 2012; New *et al.* 2011).

Thus, while it is still too early to make a formal recommendation, the approximately 1950 level currently seems to provide sharper stratigraphic definition than the relatively more diffuse and diachronous signals associated with the Industrial Revolution (e.g. the shift in carbon isotopes from the increase in fossil fuel burning: Al-Rousan *et al.* 2004).

We do not here examine the question of whether the boundary should be defined by a Global Standard Stratigraphic Age (GSSA or more simply a numerical age) or Global Stratigraphic Section and Point (GSSP = 'golden spike'). For practical purposes in current use, we consider that either would be effective. By whichever means defined, this approximately 1950 CE level might be regarded as stratigraphically challenging, in encompassing (to date) the geologically almost infinitesimally brief interval of about 65 years: over three orders of magnitude shorter than the Holocene and over five orders of magnitude shorter than the average epoch in the Cenozoic (Fig. 1).

The Anthropocene in geochronology and chronostratigraphy

Given current stratigraphic practice, we must consider the Anthropocene as a potential formal stratigraphic unit in not one but two meanings.

First, it is a potential *geochronological* unit – that is, one of geological time – over which a variety of events have taken place on Earth. An Anthropocene Epoch, as an Earth-based time unit, would (as with the Holocene Epoch and all other geochronological units) hence be used as temporal reference for events in the Earth's deep interior as much as those at the surface.

Separate geological timescales have been set up for other bodies, such as the Moon and Mars (Tanaka & Hartmann 2012), and so an Anthropocene Epoch would be limited to this planet, as holds currently true for other terrestrial geochronological units. The limits on Earth extend from the core to the atmosphere and arguably to the region of space immediately dominated by the Earth's gravitational field, although excluding the Moon, which has a separate stratigraphic scheme (Tanaka & Hartmann 2012). However, we note that it is now beginning to be possible to correlate the Anthropocene across space, in what might be regarded as the first interplanetary stratigraphic marker since the products of the Late Heavy Bombardment of the late Archaean. Infinitesimally smaller in bulk, although very much more synchronously distributed, human-projected spacecraft and associated debris have now left physical traces on and around several planets and moons of this solar system.

For all past geological units, with the exception of the later part of the Holocene Epoch (that we still, formally, live in), all of our knowledge of the history of the Earth is derived from the rock record. From the beginning of a human written record, this proxy record began to be augmented by human observations of terrestrial events. This human observation has developed, today, to the extent that many terrestrial processes are now routinely monitored, recorded and analysed; this means that geological proxy data of the Anthropocene, being captured within rock currently forming, can now be directly compared with the geological events themselves.

The Anthropocene, in tandem with other geological units, should also be considered as a material rock unit of chronostratigraphy (commonly referred to as 'time-rock'). Chronostratigraphic units are commonly regarded as the material 'rock' record of geological time, and thus the physical embodiment of (and evidence for) the passage of time. Thus, the Jurassic System comprises all of the strata formed during the Jurassic Period, while the

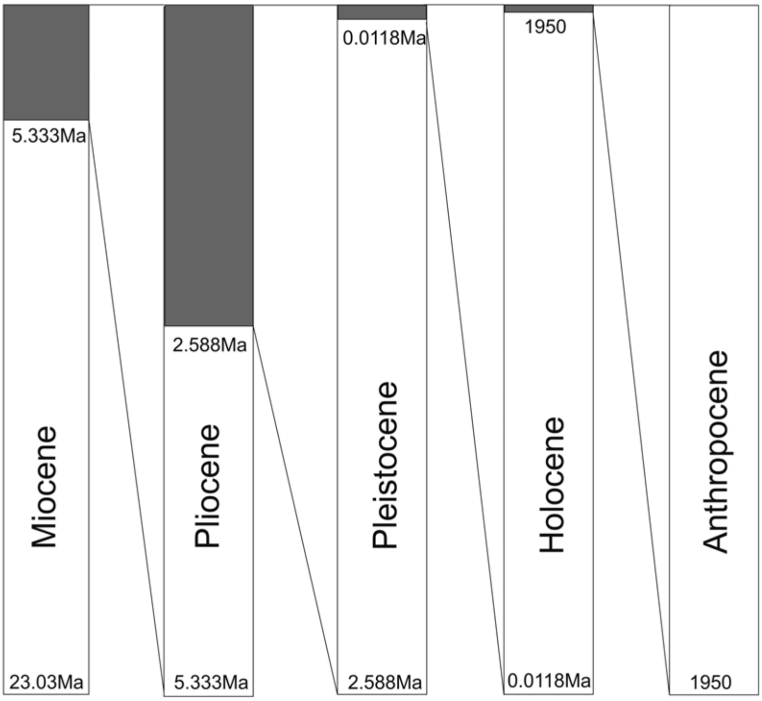

Fig. 1. Comparison of lengths of epochs from the mid-Cenozoic to the present, showing progressive shortening in time span. Dates from Gradstein *et al.* (2012).

Pleistocene Series is the equivalent rock record of the Pleistocene Epoch. There is hence a hierarchical system of chronostratigraphical terms, exactly parallel to those of geochronology. The Anthropocene, if considered as an Epoch, should also be considered as a Series.

Chronostratigraphy, scale-dependence and the Anthropocene

Not all geologists consider chronostratigraphy to be a necessary and fundamental part of the Geological Time Scale (e.g. Zalasiewicz *et al.* 2004, 2007; Carter 2007). In such an interpretation there need not be both a Pleistocene Epoch and a Pleistocene Series, but simply an Epoch, to which the material record is referred descriptively (thus: strata formed during the Pleistocene Epoch, or more simply 'Pleistocene strata'). Currently, though, most stratigraphers, as represented by voting members of the International Commission on Stratigraphy, prefer to use the dual hierarchy of geochronology + chronostratigraphy (Zalasiewicz *et al.* 2013*a*), and so we here regard consideration of an Anthropocene Series as an integral part of the analysis of the Anthropocene concept.

Chronostratigraphy in practice only effectively applies to stratified rocks, where superposition applies, and hence 'lower' equals 'older' and 'upper' equals 'younger' (Zalasiewicz *et al.* 2013*a*). Single hand specimens of igneous and (especially) metamorphic rocks commonly include a number of intermeshing fabrics of distinctly different ages (that can be dated and placed within a geochronological framework), and so 'upper' and 'lower' have no meaning, and the rock itself cannot be regarded as having 'formed' at a particular moment in time. Thus, a putative Anthropocene Series encompasses only stratified deposits currently accumulating and not (say) mineral assemblages now crystallizing (i.e. during the Anthropocene Epoch) in the roots of current mountain belts.

Chronostratigraphy is also scale-dependent (Zalasiewicz *et al.* 2007). That is, on short time-scales, the superpositional fabrics of sedimentary stratification may be disrupted by such processes as bioturbation (in marine deposits especially: Anderson 2001) or by soil-forming processes (Bacon *et al.* 2012), giving disrupted sedimentary fabrics in which temporal information has been mixed or homogenized. This process commonly affects time units of durations of some thousands of years (Anderson 2001) but it can also act over timescales of millions of years (e.g. Bacon *et al.* 2012) and length scales of kilometres in the case of subsurface sedimentary diapirism (e.g. Shoulders & Cartwright 2004).

For most stratigraphic units in the deep time record, this scale-dependence effect may be neglected, given that currently achievable levels of time resolution are typically measured in fractions of millions of years. However, the duration of epochs, both actual (Holocene) and potential (Anthropocene), becomes much shorter towards the present day (Fig. 1). Thus, for Pleistocene and (especially) for Holocene strata, the scale dependence effect becomes significant, and for the Anthropocene (where decadal time resolution may reasonably be sought) it becomes an important factor in chronostratigraphic definition.

Components of an Anthropocene Series

Despite the complications noted above, an attempt to define an Anthropocene Series is both part of formal stratigraphic analysis and, independently of this, is useful in helping to understand the Anthropocene phenomenon (formal or informal) as a part of Earth history.

What might an Anthropocene Series, and its various material stratigraphic components, comprise? We consider the strata that accumulate in a range of geographical settings, from terrestrial (in the sense of 'land-based') to deep marine, and discuss how they might be recognized and characterized. We reiterate that the Anthropocene here is a time boundary, and not a boundary between anthropogenic 'artificial' and 'natural' sedimentary facies. Hence, an Anthropocene Series (and, indeed, pre-Anthropocene deposits) will include both of these facies, the boundary between them being diachronous. Nevertheless, the extent of facies diachroneity will vary, both geographically and between different types of stratigraphic signal, and this might offer the possibility of effective discrimination of an Anthropocene Series.

These strata include a number of proxies for time – not least fossils, a form of evidence that remains key to the subdivision of Phanerozoic strata (Gradstein *et al.* 2012) and that has the potential to help characterize an Anthropocene interval (Barnosky 2013; Wilkinson *et al.* 2014) when used in combination with other stratigraphic indicators (Waters *et al.* 2014).

Terrestrial settings

Geologically, the terrestrial realm may be divided into areas of erosion, particularly of older rock, and areas of deposition. The former in stratigraphy may be considered as unconformity surfaces, only to be preserved at the transition between phases of erosion and subsequent sedimentation. Although such erosion surfaces may be studied by techniques such as Terrestrial Cosmogenic Nuclide (TCN) dating (e.g. Gosse & Phillips 2001), we will not consider them further here, except via the indirect record they leave via the sedimentary deposits eroded from them. These may be broadly categorized as the following.

Soils

Soils are, perhaps, the most widespread terrestrial sedimentary facies, forming on both erosional and depositional surfaces, and having deep time equivalents, palaeosols, when preserved on depositional surfaces.

The alteration of soils by anthropogenic activities is widespread, striking and increasingly well documented (Richter 2007). However, the spread of anthropogenic soils has been strongly diachronous through the Holocene, and reflects the spread of agriculture across the globe (Ellis *et al.* 2012). At present, therefore: which soils are Holocene and which are Anthropocene?

One approach here has been to take a major phase of soil expansion 2000 years ago across northern Europe (Certini & Scalenghe 2011) and suggest that the base of that may be taken as a 'golden spike' to mark the base of the Anthropocene. This is an intriguing and imaginative suggestion, but is not without problems (Gale & Hoare 2012). First, the base of a soil upon older regolith is gradational and cannot capture a boundary with the resolution required for the Anthropocene. Secondly, and more generally, soils exemplify the 'scale-dependence' phenomenon noted above, being continually reworked by both natural and anthropogenic processes as long as they are at the Earth's surface. Hence, it may in some ways be more appropriate to place *all* surface soils in the Anthropocene because they are continually being modified, even though many of them have fabrics and components that range back for thousands and, in some cases (Bacon *et al.* 2012), for millions of years. This ongoing modification is arguably greatest for agricultural soils because of the intensive nature of human reworking. Owing to the breakdown of superposition, soils are generally problematic to classify chronostratigraphically at the very high levels of temporal resolution required for the Anthropocene. Thirdly, the criteria for definition of a 'golden spike' recommends that a section be used in which there is a continuous succession, where observed gaps in deposition are absent or at a minimum. In existing chronostratographical units, palaeosols are considered to represent time gaps and would be avoided as a basis on which to define a chronostratigraphical boundary (Remane *et al.* 1996).

Lacustrine deposits

Lake deposits are, perhaps, the most straightforward to deal with stratigraphically. Their deposits commonly form ordered strata, which – especially in those lakes with low-oxygen bottom waters – tend not to be seriously disrupted by bioturbation. The resulting high-resolution stratigraphic archives can show a clear signal of the environmental changes that may potentially characterize an approximately 1950 CE Anthropocene Series base, such as widespread, marked N isotope (Holtgrieve *et al.* 2011) and palaeontological (Wolfe *et al.* 2013) signals in northern lakes far from urban centres, while the incoming of A-bomb test-related radionuclides provides another marker (Yan *et al.* 2002; Appleby 2008; Hancock *et al.* 2011, 2014). If it was decided to define the Anthropocene boundary via a physical reference level or GSSP ('golden spike') rather than a designated numerical date GSSA (see the Discussion later), then lake deposits will figure strongly as settings for candidate stratotypes. Lacustrine sediments, though, include anthropogenic signals of other ages too, some markedly diachronous, such as sediment influxes associated with land-use changes (Edwards & Whittington 2001).

Fluvial deposits

The human management of rivers, and consequent alteration of their patterns of sedimentation and erosion, has a long history, and the consequent spread of indirect anthropogenic deposits has been marked (e.g. Syvitski & Kettner 2011; Merritts *et al.* 2011; Brown *et al.* 2013), multi-faceted (e.g. the nineteenth century modification of fluvial sedimentation in north America, as numbers of beavers – and, hence, beaver dams – fell sharply as a result of hunting: Kramer *et al.* 2011) and strikingly diachronous across the world, and even in part on a regional scale within the UK (Lewin 2012). Indeed, the difficulty of consistently recognizing an Anthropocene boundary in modern fluvial deposits was regarded by Autin & Holbrook (2012) as one reason to reject the concept of a formalized Anthropocene.

However, globally, the rate of fluvial transformation saw significant rises that coincided with the two main inflections in human economic activity at about 1800 and 1950 (Syvitski & Kettner 2011), both of which are candidate dates for the beginning of the Anthropocene. To what extent these may be generally 'traceable' within the sedimentary record seems still to be an open question. Locally, at least, major, distinct Anthropocene bodies of sediment are building up behind the major dams that in recent decades have been constructed on nearly all major rivers of the world (Syvitski & Kettner 2011), with rates of sediment supply commonly increased by deforestation and related processes (Wilkinson 2005). For instance, most sediment that used to be transported down to the Nile Delta is now trapped behind the Aswan Dam (producing a substantial, and rapidly growing Anthropocene sediment body) or held within artificially multiplied (for irrigation) distributaries within a system that has been completely altered by human activity (Stanley 1996).

Significant future rise in sea level would be expected to result in development of transgressive estuarine–marine deposits in the distal parts of river systems. However, the interplay of associated changes in precipitation, vegetation and human forcing would certainly be complex, making patterns of sedimentation hard to predict.

Aeolian deposits

Windblown deposits occur both within the major sand seas of the world, such as the ergs of the Sahara desert, as more localized dune fields, such as those associated with coastal areas, and also as far-travelled loess and related deposits. All are sensitive to local climate and to vegetation cover, and to human activity, in particular through overgrazing, overcultivation, unsustainable irrigation techniques and deforestation, which has strongly influenced the generation of loess through desertification, and whose effects include increases in dust flux (Goudie 2009). There is evidence of an increase of a factor of 2 in background dust loads over the Antlantic since the mid-1960s, the likely product of desertification caused by the doubling of the population in the Sahel region over the past 40 years (Moulin & Chiapello 2006). The extent to which these might translate into an Anthropocene Series boundary is uncertain. It seems likely that within contemporary large, long-lived dune fields, at least, the shifting sands will render a boundary difficult to locate and trace precisely – although in this the Anthropocene is not alone in facing difficulties of chronostratigraphic classification (see below).

Glacial deposits

Glacial deposits are sensitive recorders of changes in ice volume and extent, and many present-day glacial valleys in Europe include terminal moraines reflecting the greater extent of ice during the Little Ice Age of the sixteenth–mid-ninteenth centuries (Mann 2002). Similarly, the shrinking of most mountain glaciers since the 1850s, with regional variations in both retreat and advance during the mid-twentieth century and large-scale retreats since the 1980s (IPCC 2001, fig. 2.18), linked to global temperature increases, has exposed morainic deposits that may be clearly identified and mapped as of Anthropocene age, particularly where detailed cartographic and photographic records occur of glacier extents earlier in the twentieth century (e.g. Kulkarni *et al.* 2007). Associated deposits include those laid down catastrophically by dam-bursts, as increased volumes of meltwater have accumulated behind and destabilized morainic dams and wasting morainic ice cores (Nayar 2009).

Ice

This is also a terrestrial sedimentary deposit that is found on all the continents (except in Australia, and probably not for much longer in Africa, where it is represented only by rapidly thawing Kilimanjaro). Ice sheets record snow layers extending back many thousands of years, and encapsulating (in the Arctic and Antarctic) the entire interval of human history, including levels that can be identified for 1800 and 1950, and which provide data on rising CO_2 intervals. Snow layers record human pollutants from the atmosphere back to classical times (e.g. lead aerosols derived from Roman smelting). Following this, there is a succession of recorded events that might provide geochemical criteria to identify either an approximate 1800 CE or 1950 CE level. This includes the CO_2 levels preserved in air pockets (although this is compromised by the 'lock-in' time for air post-dating the deposition of the snow). However, events such as the appearance of nitrogen derived from the Haber–Bosch process (cf. Holtgrieve *et al.* 2011), the change in lead isotopes reflecting the use and then abandonment of lead additives in petrol (Bollhöfer & Rosman 2000), and the incorporation of artificial radionuclides provide useful global stratigraphic markers. The range of palaeoenvironmental proxies recorded in this medium and the annual resolution make selection of a GSSP within a snow/ice core a potential option, as for the Pleistocene–Holocene boundary (cf. Walker *et al.* 2009).

Artificial deposits

The transformation of primary raw materials (sand and gravel, limestone, mudrock, metal ores) into the fabric of urban areas represents the creation of a novel and substantial type of stratum in which the buildings themselves and the associated landscape changes (the latter mapped as various types of Artificial Ground on British Geological Survey maps, for instance: Price *et al.* 2011; Ford *et al.* 2014) provide something that combines features of a lithostratigraphic unit and of an extraordinarily large trace fossil system.

The resulting deposit is clearly anthropogenic but, because towns and cities have been a feature of human civilization since the Epi-palaeolithic (Mesolithic) at about 9000 BC (see Edgeworth 2013), also clearly diachronous. We may discuss two features of relevance here.

First, the extraordinary post-war growth of cities and megacities allows, by simply mapping the historical growth of urban areas, a distinction between post-1950 CE artificial deposits and those that predate them (Fig. 2). Prior to the 1950s, large cities tended to be located close to natural resources or be suitable coastal locations for the import/export of these resources. The post-1950s evolution of megacities has relied upon the contained population of the megacity to be the key resource, and these cities have been a centre for the inward influx of natural resources sourced from rural areas and transported to the cities to fuel industry and construction. This change can be seen as a product of improvement of transport networks and greater efficiencies in the mass transport of bulk materials during the late twentieth century (Haff 2013; see also Williams *et al.* 2013). This creation of laterally continuous but temporally distinct deposits may be compared with, say, those created naturally during the progradation (outgrowth) of a delta system.

Secondly, even within the older parts of existing cities, the continuous replacement of the urban fabric, both above and below ground, means that these artificial deposits comprise complex mixtures of pre-Anthropocene and Anthropocene rocks and minerals (and, locally, indeed fossils). The presence of novel materials and minerals in both direct and, to a lesser extent, indirect anthropogenic deposits (Zalasiewicz *et al.* 2013*b*; Ford *et al.* 2014) provides an approach to dating these deposits to decadal level, a resolution far beyond that applicable for previous epochs. This is a rather coarser-grained equivalent of the situation noted above with soils, and again underscores the awkwardness of chronostratigraphy in dealing with short timescales, and complex sedimentary processes and geometries. It is only towns and cities abandoned pre-1950 that may be said to comprise wholly pre-Anthropocene representatives of this deposit type.

Below ground, artificial ground locally deeply extends into underlying strata via the many mineshafts and boreholes sunk to extract resources, with considerable 'halo' effects via such as hydrocarbon extraction (and now, injection of fluids and sand for shale gas extraction). Geologically, this is something of a hybrid, combining features of burrowing, albeit on an enormous scale, with those of

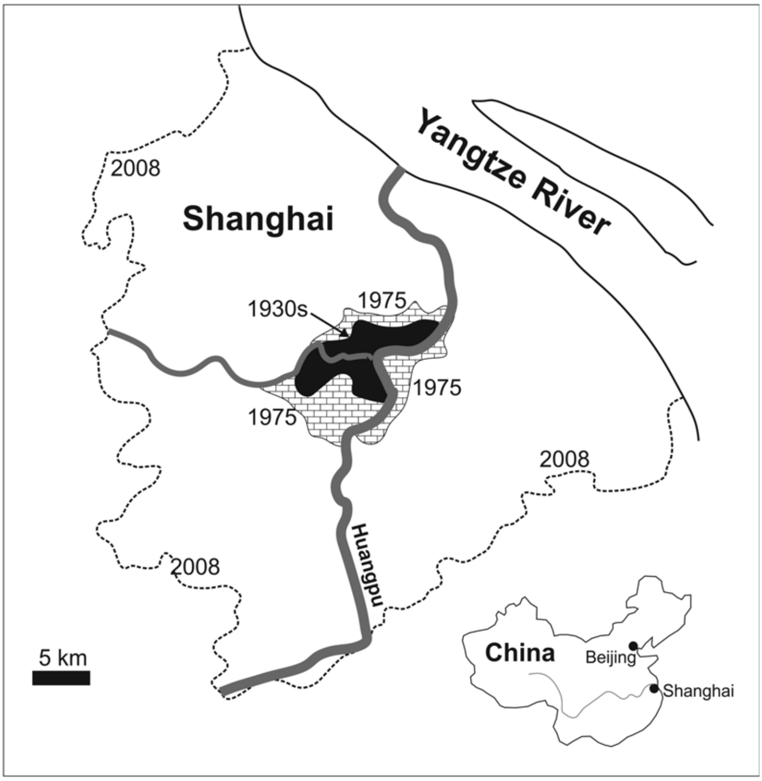

Fig. 2. The rapid mid-twentieth century growth of Shanghai, as an example of the formation of a distinct, extensive sedimentary facies that may be referred to a putative Anthropocene Series. Information from Larmer (2010) and Map of Central Shanghai, printed by the British War Office/US Army Map Service in 1935.

intrusive bodies, showing cross-cutting relationships and even of diagenetic alteration. Neither of the last two phenomena are generally classified within chronostratigraphic units (as they do not show superpositional relationships), as their history may be protracted and only related in general terms to processes acting at the Earth's surface (Ford *et al.* 2014). The subsurface anthropogenic phenomena, by contrast, are very much related to surface activities (and can also impact on the surface, as for instance with aquaculture-related subsidence on the Yellow River delta in China which now reaches 250 mm a^{-1}: Higgins *et al.* 2013). They clearly form a pronounced and temporally constrained event, given the post-war surge in drilling and mining (Ford *et al.* 2014).

Marine settings

Coastal systems

These systems include beaches, tidal flats and deltas. Throughout much of the latter half of the Holocene, these have been commonly progradational, as sediment eroded from the land has accumulated around a coastline more or less fixed as sea level stabilized following its post-glacial rise. Where sediment has built up and built out in this way, then distinct stratal packets that relate to industrialization and land-use change have been recognized and suggested as Anthropocene markers (e.g. Poirier *et al.* 2011). Some are distinctive through their content of heavy metals, organic chemicals and so on (e.g. Allen 1988; Marshall *et al.* 2007; Vane *et al.* 2011; Gałuszka *et al.* 2013), with eutrophication of coastal environments due to influx of excess nitrogen, and these may also be used to help identify an Anthropocene–Holocene boundary. Globally, the overall facies changes are diachronous, but within them some signals (such as distinct chemical markers related to particular industrial processes: Kruge 1999) may provide more or less synchronous marker levels.

Within the last couple of centuries – and, particularly, the last several decades, many coastal systems have seen large-scale change that is clearly relevant to the historical characterization of the Anthropocene, but that complicates the simple progradational picture. For instance, as rivers have been dammed, sediment is temporally stored behind the dams (see above) and does not nourish growing deltas, some of which have as a consequence shrunk back (e.g. Nile, Mississippi: Törnqvist *et al.* 2008). Related phenomena include the draining of coastal wetlands for farmland, resulting in the large-scale loss of such strata as surface peat deposits through desiccation, deflation and oxidation. For instance, some 2000 km^2 of peat up to 4 m thick in the English Fenland alone has disappeared since the eighteenth century, resulting in the exposure of the underlying geology, now itself compacted and oxidized (Smith *et al.* 2010). Attempts at stabilization of coastal erosion rates through construction of coastal defences produces artificial deposits, while impacting upon sediment flux and erosion rates adjacent to protected regions. The Anthropocene boundary here approximates to a regional sedimentary hiatus and disconformity – likely to be buried beneath new coastal sedimentary deposits, a century or two hence, as only a geologically trivial sea-level rise will suffice to trigger marine transgression across such areas.

The expression of the Anthropocene in the environmentally sensitive coastal systems, therefore, represents a diverse patchwork of deposits and lacunae that reflect local interplays of natural and anthropogenic forces.

Shelf/slope marine systems

Human impact on open marine systems has, in general, substantially lagged those on land. The marine fisheries in northern Europe began in earnest in Medieval times, perhaps as a result of technological improvements (e.g. effective drift nets), and their spread across the world has been charted by Roberts (2007). The concomitant, diachronous decline in fish stocks through overfishing changed the structure of marine ecosystems, although impacts on the kind of organisms (e.g. foraminifera, dinoflagellates – much lower in the food chain) used in biostratigraphy have probably been small, even with the dramatic fish declines reported (e.g. Myers & Worm 2003).

More profound physical and chemical impacts on recent marine strata are associated with the industrial age, from about 1800 CE. The greatest physical impact on sediments has been the physical disruption caused by sea-bottom trawling. This is not a modern technique: the fourteenth century saw a petition to regulate the use of the 'wondyrechaun' – essentially a wooden beam trawl used in shallow coastal waters (Roberts 2007) – but open-sea trawling came with steam-powered ships, and has continued to expand markedly in recent decades, moving into slope settings in waters approaching a depth of 1 km.

Sea-bottom trawling now affects some 15×10^6 km^2 each year (Gattuso *et al.* 2009) – representing most of the world's continental shelf area and also including significant areas of deep-water slope (Puig *et al.* 2012) and seamount surface. The process in effect ploughs the seafloor, producing a coarsening-upwards sedimentary signature (Palanques *et al.* 2001; M. Coughlan pers. comm.), with mud swept up into an expanded nepheloid layer and transported more distally, and nutrients redistributed (Dounas *et al.* 2007). Benthic assemblages are altered (Malakoff 2002) and some sensitive ones (e.g. deep-water coral systems) effectively destroyed (Sheppard 2006). Topographical effects may be substantial, with evident smoothing of topographical contours (Puig *et al.* 2012).

More recent extension of 'Worked Ground' into a marine setting can be seen with increased extraction of mineral resources including hydrocarbons and aggregates. It is only since the 1940s that technology and economics has made offshore extraction of hydrocarbons feasible, and it has grown to the point where it currently accounts for about 30% of total global output. Aggregate extraction significantly modifies the marine landscape, causes habitat modification and impacts on benthic communities both within, and downcurrent, of extraction sites, and can significantly change sediment fluxes, potentially starving supplies of sand to coastal areas. Similar concerns are being raised about offshore wind turbine construction, an even more recent and expanding innovation.

Within tropical waters, bleaching of coral reefs in response to rising sea temperatures, in addition to other stressors, such as increased turbidity of marine waters due to runoff, the fishing process of dynamiting reefs and, ultimately, decreasing ocean pH (Tyrrell 2011), may lead to the extinction of whole reef systems, resulting in a drowned reef horizon.

In aggrading sedimentary systems, the resultant facies should have considerable preservation potential. It is of limited diachroneity, given the marked post-1950 expansion of many of the processes involved.

Deep sea

This is usually considered as those areas where water is >200 m deep (i.e. largely below wave base and off the continental shelf edge) and might be simplified into two main systems: the clastic wedges of turbidite fans and contourite drifts that fringe the continental masses; and the slowly accumulating deep-sea oozes that lie beyond. Both systems have been and continue to be affected by physical disturbance (e.g. by trawling, offshore mineral extraction), by input of particulate material ('litter') varying from micron to metre scale in size (and locally indeed larger, in the case of shipwrecks), by chemical contamination with both organic and inorganic substances, by effects associated with atmospheric CO_2 increase and warming (such as variations in pH and dissolved oxygen content), and by biological changes driven by all of the above processes, either directly or indirectly. The extent of these effects – all of which can affect the nature of sediments being deposited – have been qualitatively described but not yet rigorously mapped (Ramirez-Llodra *et al.* 2011). The stratigraphic signal is patchy but locally may be striking. As with the effects of urbanization, local signals go back millennia. Major expansions of activity and, hence, extent of stratigraphic imprint were associated with the Industrial Revolution at around 1800 CE and with the ongoing 'Great Acceleration' that started at about 1950 CE.

The accumulation of litter – material dropped overboard – has reached the level where it rivals the extent of ice-rafted debris (IRD) in scale (Ramirez-Llodra *et al.* 2011), and is now seen in most surveys of the seafloor, where it is easily distinct from the surrounding (mostly very-fine-grained) sediment. We suggest hence terming this material, sedimentologically, as human-rafted debris (HRD) to help characterize a deep-water facies of a putative Anthropocene Series. Given technical progress, it shows the kind of extremely high-resolution 'biostratigraphy' of human artefacts and products also seen on land (Ford *et al.* 2014). Hence, spreads of clinker (combustion products from the coal that powered steam ships) that were universally dumped on the seafloor in the period from about 1800 CE to 1950 CE – now colonized by a specific biota – might be regarded as immediately pre-Anthropocene in our provisional definition, while those with plastics, aluminium and other such more modern materials largely date from after 1950 CE (Ramirez-Llodra *et al.* 2011). In the distal, naturally slow-accumulating parts of the seafloor, such HRD from different centuries will, in effect, fall within and contribute to the same physical layer.

More broadly, within the clastic wedges, the pattern of turbidite/contourite deposition seems not yet to have been substantially affected by human activity; it is not clear that changes in sediment supply caused by large-scale anthropogenic modification of river systems (e.g. Syvitski & Kettner 2011) have yet filtered down to cause substantial change to deep-sea clastic systems, although we regard significant longer-term change as likely (see below). However, local effects include the triggering of turbidity currents (that may also rework HRD into concentrations: Ramirez-Llodra *et al.* 2011) by bottom trawling (Puig *et al.* 2012). In the longer-term, clastic shut-off caused by sea-level rise may be envisaged.

The slowly accumulating deep-ocean oozes beyond will, in addition to such accumulations, be influenced by anthropogenic change, via such signals as a lighter carbon isotopic content in foraminifera shells, from the burning of fossil fuels. Additional chemical signals such as those from anthropogenic organic pollutants or artificial radionuclides are rapidly (e.g. Robison *et al.* 2005) if unevenly (Buesseler *et al.* 2007) transported to the sea via aggregated sinking planktonic debris. However, the very slow accumulation rate over most of this realm means that this material is thoroughly intermixed, by bioturbation, with pre-Anthropocene sediment, precluding recognition at such scale of a distinct Anthropocene Series. Only in regions of significantly more rapid deposition (e.g. Al-Rousan *et al.* 2004) does such a potential Series emerge as a distinct entity with coherent upper (sedimenting) and lower surfaces. However, potential changes to ocean chemistry may result in more extensive anoxia, with eutrophic bottom conditions limiting bioturbation, and changes to the elevation of the Calcite Compensation Depth in response to reduced oceanic pH (Tyrrell 2011), producing a carbonate dissolution layer. In addition, the types of deep-sea mineral extraction planned, if put into practice (of manganese nodules, for instance), will cause widespread and distinct physical and biological modification.

Duration of the Anthropocene: the long-term perspective

The complexities of diachronous event and process boundaries, and scale-dependence effects, visible today, will largely or wholly disappear in any consideration of far future perspective.

We do not consider the Anthropocene as a short transitional phase to some kind of post-Anthropocene interval, even were there to be a catastrophic decrease in the global human population in the near future. Rather, we consider that the future course of geological evolution, with both natural and human feedbacks, will inevitably be shaped by the anthropogenic perturbations that have taken place to date. Thus, the Anthropocene has only just begun and will play out over geological rather than human timescales. The Toarcian and Paleocene–Eocene Thermal Maximum (PETM) (Zachos *et al.* 2005; Cohen *et al.* 2007) events may be regarded as comparable, with an initial perturbation of the carbon cycle, amplification by natural feedbacks including massive carbon release from ground to air, modulated by astronomical pacing (Kemp *et al.* 2005), and slow recovery over the order of 0.1–0.2 Myr. Although each of these events in detail represents a succession of distinct phases, each may also be (and are, in practice) regarded as a whole.

In detail, the Anthropocene departs from the Toarcian and PETM models in a number of ways. It is an incipient 'hyperthermal' in an icehouse rather than greenhouse world, and so the ultimate sea-level rise (barely begun) should give a stronger transgressive signal (Rahmstorf 2007) than that in an essentially ice-free world. Indeed, if the glacial–interglacial cycle is significantly perturbed (Tyrrell 2011) with ice loss that exceeds Quaternary norms, then the geologically rapid transgression that followed the collapse of the end-Ordovician glaciation (Brenchley *et al.* 1994) might be considered as a closer analogue (Zalasiewicz & Williams 2013).

The Anthropocene also has a biotic pattern where perturbations (habitat clearance, predation, transglobal rather than local species invasions) are not simply forced by climate and ocean chemistry; as with previous biotic revolutions, these will be geologically long-lasting quantitatively (i.e. regarding diversity measures) and effectively permanent qualitatively (with new lineages arising from survivors and invaders) (see also Barnosky 2013). This pattern is also unique in modification by unpredictable but likely important feedbacks, both planned and unplanned, within the perturbatory human system (Kellie-Smith & Cox 2011).

One might compare the scale of effects with those recently proposed (the 8.2 and 4.2 kyr events) to subdivide the Holocene Epoch into Ages (Walker *et al.* 2012; see also Gibbard & Walker 2013). As regards global climate, current effects (a $<1\ ^{\circ}C$ global temperature rise since the beginning of the twentieth century) might not be regarded as yet comparing with the 8.2 and 4.2 kyr events in magnitude. However, near-future temperature rises are projected to considerably exceed these (IPCC 2001, 2007), given the unprecedented and ongoing rise in greenhouse gas levels. Other signals (lithostratigraphic, biostratigraphic, chemostratigraphic), though, are already pronounced and, as an ensemble, have no parallel in Earth's stratigraphic history. Debate over the current formal significance of the Anthropocene will need to assess the importance of all the relevant signals, and this is not a trivial task.

Nevertheless, the unprecedented rate of change in its early stages (within a small part of a single interglacial phase) means that the lower boundary to deposits of Anthropocene facies will appear synchronous globally. One may develop the 'super-interglacial' concept of Broecker (1987) by envisaging a variety of stratigraphic signals that vary from 'event beds' (e.g. the urban lithostratigraphic signal), to longer-lasting perturbations of chemical cycles and related effects on global temperature and sea level, to the effectively permanent changes to the course of the Earth's biotic evolution.

Discussion

How might the Anthropocene be characterized? Clearly, it is not simply by the appearance of anthropogenic signals in the stratigraphic record, as these are diachronous, locally dating back to earlier parts of the Holocene and, indeed, into pre-Holocene deposits. Such early records have been used in favour of an 'early Anthropocene' hypothesis that encompasses much of the Holocene (e.g. Ruddiman 2003, 2013) and also in criticism of the attempt to define an Anthropocene unit in stratigraphy at all (e.g. Gale & Hoare 2012; Gibbard & Walker 2013).

The key question seems to be whether the present-day Earth system now has been changed (by whatever agent) sufficiently in scale and permanence to justify a new geological time interval. If that is the case, one also may accept that the change from a putative pre-Anthropocene to an Anthropocene state has taken place non-instantaneously and diachronously. Most changes to the Earth system in our planet's history have been neither instantaneous nor globally synchronous (e.g. Williams *et al.* 2013), and most established geological time boundaries have been compromises – generally vigorously debated – of one sort or another.

The task then becomes one of finding the most effective – or, if one prefers, the least worst – criteria for defining a boundary. Then, one has to decide whether a boundary so defined can function effectively to define both a unit of time (an Anthropocene Epoch) and a body of strata (an Anthropocene Series). This is the question we examine here. We note that the further test for a formal Anthropocene – its use to both geological and arguably wider (Nature 2011; Vidas 2011; Zalasiewicz 2013) communities – falls outside the scope of this paper, as does the question – see above and Zalasiewicz *et al.* (2008, 2011, 2012) and Wolfe *et al.* (2013) – over whether a boundary, if agreed, is best defined by GSSP ('golden spike') or GSSA (numerical date).

It is clear that the material record of a putative Anthropocene Series, even considered with an approximately 1950 CE boundary, is locally distinctive and substantial – a feature reflecting the globally enhanced rates of erosion and sedimentation caused by humans (Hooke 2000; Wilkinson 2005;

Price *et al.* 2011; Syvitski & Kettner 2011). It is in many places also effectively distinguishable from pre-Anthropocene strata, on a decadal or even annual scale of resolution.

Elsewhere, however, the distinction of Anthropocene from pre-Anthropocene strata is less obvious. This may be because there are no significant markers or facies changes (as in desert dune strata, for instance). Or, it might reflect widespread irresolvable mixing of Anthropocene and pre-Anthropocene strata, through non-human bioturbation and other mixing processes (as in the deep ocean). Or there may have been protracted, complex human reworking of the ground (as in long-inhabited cities). Such phenomena prevent the clear, unambiguous and consistent delineation of a laterally continuous 'Anthropocene Series'. We may discuss them in turn as regards comparison with older chronostratigraphic units.

The local inability to unambiguously assign particular units of strata to chronostratigraphic units is a problem as old as is geology. One may take the case of the 'Permo-Triassic', long used as a descriptive bucket label given the difficulty of locating a boundary between Permian and Triassic deposits in 'red bed' deposits that lack fossils, even if it is as sharp and catastrophically founded as that between the Permian and Triassic systems (and between the Palaeozoic and Mesozoic erathems). Even in less stratigraphically opaque strata, chronostratigraphic boundaries, away from the reference 'golden spike' section, can rarely be located within an error bar of less than a few hundred thousand years (Zalasiewicz *et al.* 2013*a*). Most stratigraphic research is based upon the most informative and correlatable sections, but between these there are many stratal units within which major chronostratigraphic boundaries are located only approximately.

Similar uncertainty will certainly apply to an 'Anthropocene Series', with boundaries (now being placed at a decadal/annual scale) being effectively locatable in some places and more uncertainly placed in others. Hence, at least qualitatively, the Anthropocene shares the correlation problems attached to chronostratigraphic units generally, and it is not yet clear whether it possesses these kinds of uncertainties in greater measure than do the established units of the Geological Time Scale.

The problem of the disruption of superposition is rather different. This arises in part out of the exceedingly short timescale of the Anthropocene (to date) and in part out of complex, intermingled sedimentary geometries commonly created by human activity, where clear principles of superposition cannot be applied. This creates situations that archaeologists, for instance, are more familiar with, in discriminating numerous successive historical events within geometrically complex deposits (Edgeworth 2013) and on palimpsest surfaces (where the evidence from different phases of human history is preserved upon essentially two-dimensional surfaces).

The practice of basing chronostratigraphic subdivision upon the principle of superposition reflects the tendency on Earth for thick successions of strata to have built up, virtually since the origin of the planet. For most of the geological record it is an effective means to build and operate the geological timescale, and in older rocks, where stratigraphic uncertainties are measured in millions of years, the superpositional blurring through bioturbation and allied processes may be regarded as negligible. In such circumstances, chronostratigraphy and geochronology have operated in parallel, in their long-established 'dual hierarchy'.

However, at brief geological timescales and/or when extremely fine temporal resolution is sought, disruption of superpositional relationships may become a practical, rather than theoretical problem. This is already the case in the discrimination of high-resolution climate histories from deep seafloor deposits, where those strata with the highest sedimentation rates (and therefore least prone to bioturbational mixing) are actively sought. This phenomenon is, hence, most acutely expressed in the Anthropocene, with its extremely short timescale exacerbated by its peculiarly human-made complex stratal geometries. It might be regarded as a problem as much inherent of chronostratigraphic practice as it is of the Anthropocene.

Nevertheless, despite the complicating effects of these various processes, we propose that a reasonably consistent Holocene–Anthropocene boundary placed at around 1950 CE might be effectively traceable over large areas in both marine and non-marine settings. Attempts to consistently trace and delineate such a unit would reveal the extent to which this proposal is true. They would also help in the understanding of the extraordinary episode of history – whether formalized in stratigraphy or not – which the Earth is currently experiencing.

Conclusions

- A material 'Anthropocene Series' might be defined with a historically recent boundary at approximately 1950 CE, characterized by time proxies such as artificial radionuclides, biostratigraphic changes and human-made novel materials (e.g. plastics and uncombined aluminium). It locally forms substantial, distinct and correlatable sediment bodies in both terrestrial and marine realms.
- Locally, too, Anthropocene deposits so defined are difficult to recognize and correlate for want

of appropriate time markers to fix the boundary. These are analogous to stratigraphically indeterminate deposits in the older stratigraphic record.

- Commonly, also, Anthropocene deposits are difficult to separately recognize as distinct units because of intermixing, for instance by human or non-human bioturbation, reflecting the very short duration of the Anthropocene. This may be regarded as a problem inherent in very high-resolution chronostratigraphy as much as one of the Anthropocene.
- Attempts to better delineate and analyse the material expression of the Anthropocene will increase our understanding of the phenomenon as a whole.

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