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When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal

Jan Zalasiewicz [a], Colin N. Waters [b,*], Mark Williams [a], Anthony D. Barnosky [c], Alejandro Cearreta [d], Paul Crutzen [e], Erle Ellis [f], Michael A. Ellis [b], Ian J. Fairchild [g], Jacques Grinevald [h], Peter K. Haff [i], Irka Hajdas [j], Reinhold Leinfelder [k], John McNeill [l], Eric O. Odada [m], Clément Poirier [n], Daniel Richter [o], Will Steffen [p], Colin Summerhayes [q], James P.M. Syvitski [r], Davor Vidas [s], Michael Wagreich [t], Scott L. Wing [u], Alexander P. Wolfe [v], An Zhisheng [w], Naomi Oreskes [x]

[a] *Department of Geology, University of Leicester, University Road, Leicester LE1 7RH, UK*
[b] *British Geological Survey, Keyworth, Nottingham NG12 5GG, UK*
[c] *Dept. of Integrative Biology, Museum of Paleontology, Museum of Vertebrate Zoology, University of California, Berkeley, CA 94720, USA*
[d] *Departamento de Estratigrafía y Paleontología, Facultad de Ciencia y Tecnología, Universidad del País Vasco UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[e] *Max-Planck-Institute for Chemistry, Department of Atmospheric Chemistry, PO Box 3060, D-55020 Mainz, Germany*
[f] *Department of Geography and Environmental Systems, University of Maryland Baltimore County, Baltimore, MD 21250, USA*
[g] *School of Geography, Earth and Environmental Sciences, University of Birmingham, B15 2TT, UK*
[h] *IHEID, Chemin Eugène Rigot 2, 1211 Genève 11, Switzerland*
[i] *Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Box 90233, Durham, NC 27516, USA*
[j] *ETH Zurich, Laboratory of Ion Beam Physics, HPK H27, Otto-Stern-Weg 5, CH-8093 Zürich, Switzerland*
[k] *Department of Geological Sciences, Freie Universität Berlin, Malteserstr. 74-100/D, 12249 Berlin, Germany*
[l] *Georgetown University, Washington, DC, USA*
[m] *Department of Geology, University of Nairobi, Kenya*
[n] *Morphodynamique Continentale et Côtière, Université de Caen Basse Normandie, CNRS, 24 rue des Tilleuls, F-14000 Caen, France*
[o] *Nicholas School of the Environment, Duke University, Durham, NC, USA*
[p] *The Australian National University, Canberra, ACT 0200, Australia*
[q] *Scott Polar Research Institute, Cambridge University, Lensfield Road, Cambridge CB2 1ER, UK*
[r] *University of Colorado-Boulder Campus, Box 545, Boulder, CO 80309-0545, USA*
[s] *Marine Affairs and Law of the Sea Programme, The Fridtjof Nansen Institute, Norway*
[t] *Department of Geodynamics and Sedimentology, University of Vienna, A-1090 Vienna, Austria*
[u] *Dept. of Paleobiology, NHB121, PO Box 37012, Museum of Natural History, Smithsonian Institution, Washington, DC, USA*
[v] *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada*
[w] *The Institute of the Earth Environment, Chinese Academy of Sciences, 10 Fenghui South Road, Xi'an High-Tech Zone, Xi'an 710075, China*
[x] *Department of the History of Science, Harvard University, Cambridge, MA 02138, USA*

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ABSTRACT

We evaluate the boundary of the Anthropocene geological time interval as an epoch, since it is useful to have a consistent temporal definition for this increasingly used unit, whether the presently informal term is eventually formalized or not. Of the three main levels suggested – an 'early Anthropocene' level some thousands of years ago; the beginning of the Industrial Revolution at ~1800 CE (Common Era); and the 'Great Acceleration' of the mid-twentieth century – current evidence suggests that the last of these has the most pronounced and globally synchronous signal. A boundary at this time need not have a Global Boundary Stratotype Section and Point (GSSP or 'golden spike') but can be defined by a Global Standard Stratigraphic Age (GSSA), i.e. a point in time of the human calendar. We propose an appropriate boundary level here to be the time of the world's first nuclear bomb explosion, on July 16th 1945 at Alamogordo, New Mexico; additional bombs were detonated at the average rate of one every 9.6 days until 1988 with attendant worldwide fallout easily identifiable in the chemostratigraphic record. Hence, Anthropocene deposits would be those that may include the globally distributed primary artificial

* Corresponding author.
E-mail address: jaz1@leicester.ac.uk (J. Zalasiewicz).

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radionuclide signal, while also being recognized using a wide range of other stratigraphic criteria. This suggestion for the Holocene–Anthropocene boundary may ultimately be superseded, as the Anthropocene is only in its early phases, but it should remain practical and effective for use by at least the current generation of scientists.

1. Introduction

The advent of the Anthropocene concept has brought with it the question of where its boundary should be. The term was first suggested to reflect the perturbation of surface Earth processes by human activities (Crutzen and Stoermer, 2000; Crutzen, 2002) and very soon became widely used (e.g. Steffen et al., 2007). Following initial consideration by the Stratigraphy Commission of the Geological Society of London (Zalasiewicz et al., 2008), it is now being formally examined as a potential new unit within the International Chronostratigraphic Chart by an Anthropocene Working Group of the Subcommission on Quaternary Stratigraphy, in turn a component body of the International Commission on Stratigraphy. Some of the first studies have already been published (e.g. Williams et al., 2011; Waters et al., 2014a). These studies were aimed at examining whether the Anthropocene is geologically justifiable, whether its formalization is useful, and how it might be characterized and defined. Here, we evaluate when the Anthropocene might be considered to have begun, as sufficient relevant studies have already been published (notably, those concerned with stratigraphic examination of the Anthropocene in Waters et al., 2014a) for interim assessment of this question.

We emphasize that resolution of this question is *separate* from whether the Anthropocene should be formalized or not (see e.g. Finney, 2014; Gibbard and Walker, 2014). There are some widely used yet unofficial stratigraphic time terms (e.g. Precambrian, Tertiary) of which, nevertheless, the durations are fixed and consistently used, avoiding ambiguity in communication. Nor are we here addressing the question of the hierarchical level of the Anthropocene: that is, whether it should be considered (or potentially formalized) at Epoch level.

In suggesting a boundary, we do not imply that the time intervals before (the deposits below) that boundary become insignificant to studies of the Anthropocene – or that younger times and higher deposits become irrelevant to the Holocene, if the boundary is considered at epoch level. The division of geological time units is chosen as much (or more) for practical effectiveness of stratigraphic correlation as for geohistorical significance, and indicators of these two factors are not necessarily precisely coincident (see below). Understanding the driving processes in any major global transition necessarily involves study of events across any chosen time boundary, irrespective of where it might happen to have been placed. A stratigraphic time boundary, however arbitrary, needs as far as possible to be singular, globally synchronous and commonly understood. We consider the means by which this widely used term may acquire a stable and consistent meaning as regards its stratigraphic duration and inception and propose, for wider discussion, a specific boundary level.

1.1. The International Chronostratigraphic Chart and the Anthropocene

The International Chronostratigraphic Chart of the International Commission on Stratigraphy (Cohen et al., 2013, updated) is essentially the same as the Geological Time Scale as widely understood. It is arguably the single most important construction for geologists, as it establishes the time framework by which the Earth's 4.6 billion year history – and all of the rocks that formed within it, might be categorized and analysed. In defining any unit within the International Chronostratigraphic Chart, perhaps the most important single aspect is the fixing of its boundary – by convention, its lower boundary within strata, or its beginning within time – so that it provides, as far as is possible, a synchronous and effectively correlatable level within strata worldwide.

The emphasis on strata is significant. Earth history, as formalized in the International Chronostratigraphic Chart, has a dual hierarchy of time units. One, known as the geochronological time scale, is simply of time itself; for instance, using this, one speaks of the Cambrian Period. The second, parallel scale is of chronostratigraphy; the equivalent unit here is the Cambrian System, which comprises all of the strata deposited during the Cambrian Period (see Zalasiewicz et al., 2013 for discussion and further explanation). Thus, in consideration of the Anthropocene, one may speak of its history within the Anthropocene Epoch, and also of its material record represented within the deposits of an Anthropocene Series. Given the brevity of the Anthropocene, one might question the formal need for the latter. However, the anthropogenic acceleration of processes of erosion and sedimentation has led to the physical record of the Anthropocene being substantial (e.g. Price et al., 2011; Hooke et al., 2012; Ford et al., 2014), and large parts of this record are also distinctive, given the geological novelty of many human-driven processes. While the geometrical and temporal complexity of Anthropocene deposits clearly present some unusual challenges, an Anthropocene chronostratigraphical unit may be recognized (Zalasiewicz et al., 2014a) and this is significant to the choice of a boundary for this unit.

An effective geochronological and chronostratigraphical boundary often reflects a substantial change in the Earth system, so that the physical and chemical nature of the deposits, and their fossil contents, are recognizably different above and below the boundary. For example, the beginning of the Cambrian Period (and simultaneously of the Palaeozoic Era and the Phanerozoic Eon, or base of the Cambrian System) has been placed at the appearance of a distinctive trace fossil assemblage that reflects a change in behaviour associated with the earliest burrowing bilaterian animals (emerging during the ‘Cambrian explosion’ of metazoan animals), and so the beginning of an abundant fossil record within strata (Landing, 1994). To take another example, the boundary between the Ordovician and Silurian periods reflects a brief, intense glacial phase that triggered one of the ‘Big Five’ mass extinction events, and hence profoundly altered the biota (and fossil record) of the Earth (Sheehan, 2001). Likewise, each of the Cenozoic epochs is characterized by distinctive assemblages of fossil life, with the biotic changes that help define their boundaries being rapid relative to the constancy of the biota that lasts through each epoch (Barnosky, 2014).

Within this overall framework, there comes the question of the *precise* placing of the boundary. This is meant to represent a single time surface, a precisely synchronous level that can be traced all around the Earth. In practice this ideal situation is never encountered: even with the Cretaceous-Paleogene boundary, coincident

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with a large meteorite strike, global fallout of iridium-rich debris and geologically instantaneous extinctions (Schulte et al., 2010), there have been debates about the exact placement of the K/T boundary in some places (e.g. Keller et al., 2003). With most boundaries, there is the need to select the optimal (or 'least poor') of a range of possible boundary indicators – and then to use this as the primary marker, while in practice the boundary is located by using all the evidence available.

Thus, in the Cambrian example there was a wide choice of candidate indicators spanning a range of ~15 million years. The appearance of a distinctive type of animal burrow, *Treptichnus*, and its first record at the Global Boundary Stratotype Section and Point (GSSP) site at Mistaken Point, Newfoundland, was used to fix the boundary level (see discussion in Williams et al., 2014 and the current questioning of this level as an effective GSSP by Babcock et al., 2014). For the Ordovician–Silurian boundary, the precise indicator chosen was the apparently simultaneous appearance of the graptolite species *Akidograptus ascensus* and *Parakidograptus acuminatus praematurus* at the GSSP site of Dob's Linn, Scotland – a relatively trivial event in terms of global environmental change, but one that was regarded as close to the main changes in time and as widely correlatable, at least in deep marine strata (see Melchin et al., 2012; Zalasiewicz and Williams, 2014). And for most of the Cenozoic epochs, the boundaries coincide with first appearances of various invertebrate marine species (Hilgen et al., 2012; Vandenberghe et al., 2012).

If a boundary is drawn at a level that ultimately proves not to provide effective global correlation, then there may be an initiative to place it at a different level. Recently, after about 50 years of debate, the beginning of the Quaternary Period was changed from a level at ca 1.81 Ma to one at ~2.6 Ma (Gibbard and Head, 2010) to more closely reflect the inception of northern hemisphere glaciation, and of all the related changes in surface geological processes, such as the beginning of widespread loess deposition in continental China. Both the original and modified boundaries coincide with reversals of Earth's magnetic field, optimizing correlation.

2. Evaluating options to define the Anthropocene as a geological time unit

2.1. Three potential durations for the Anthropocene

(1) There is increasing awareness of early human impacts on the landscape, in terms of habitat modification (Kaplan et al. 2011; Ellis et al. 2013), terrestrial biotic change (e.g. Barnosky, 2008; Ellis et al., 2012), marine microbiotic change as a consequence of land use changes as early as 3700 BP (Wilkinson et al., 2014) and, partly related to this, a hypothesis that early agriculture altered carbon dioxide levels sufficiently (raising them from 260 to 280 ppm over several thousand years: Ruddiman, 2003, 2013) to maintain stable Holocene warmth and prevent or delay the transition into the next glacial phase. This has led to support for an 'early Anthropocene' concept; the positioning of a boundary has been suggested as, for instance, the base of a widespread European soil layer formed about 2000 years BP (Certini and Scalenghe, 2011). Reaching yet farther back in time, the Late Pleistocene extinctions of large mammals represent a significant biotic perturbation, with potential wider consequences to vegetation and to the global carbon cycle (Doughty et al., 2010). However, as with the spread of agriculture, the extinctions are diachronous between continents, spanning some fifty millennia of the Late Pleistocene–Holocene interval (Koch and Barnosky, 2006).

(2) The first proposals of the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002) clearly linked the start of the Anthropocene with the Industrial Revolution, around the beginning of the 19th century, following the invention of James Watt's steam engine. This marks the change from a long period of slow, if uneven, human population growth, expanding agricultural modification of the landscape and energy use primarily from a combination of wood-burning and muscle-power, to an interval of rapid population growth, urban growth and industrialization powered by increasing use of fossil fuels. This event had deep roots – Fischer-Kowalski et al. (2014) identify a key historical threshold in the energy metabolism of humans (from biomass to fossil fuels) starting at ca 1500 CE – and a complex trajectory (e.g. Davis, 2011). Once humans began adding fossil fuels into the global ecosystem, they increased its carrying capacity for large-bodied animals (notably humanity) by an order of magnitude (Barnosky, 2008).

(3) Examination of more recent environmental history has identified a phase of enhanced population growth, global economic growth and associated environmental change starting in the mid-twentieth century, following the end of WWII. This has been termed the 'Great Acceleration' (Steffen et al., 2007). It includes, for instance, the bulk of the rise in carbon dioxide levels since pre-industrial times, the rise of the private automobile, a very large intensification in agriculture, made possible by the enhanced energy use and by the greatly increased use of fertilizers, and the phenomenon we term 'globalization'. It represents a pronounced, relatively sharp threshold in human modification of the global environment, and the wide extent of discernable effects in areas far distant from urban centres has already led to the suggestion that a Holocene/Anthropocene boundary may be placed around this level (Wolfe et al., 2013). Since 1945 the proportion of people living in cities climbed from ~27% to ~53% today; in absolute numbers from ~730 million to ~3.7 billion. In 1945 there were only 2 megacities (>10 m population) and now there are ~25 megacities. Since ancient cities show up well in archeological excavations, this spate of urbanization will be evident stratigraphically in the distant future. It is estimated that the global deliberate annual transport of materials by human activity is 57 000 million tonnes and exceeds that of transport by rivers to the oceans by almost a factor of three (Douglas and Lawson, 2001). Anthropocene biotic changes on the scale of those that differentiate the previous Cenozoic epochs, and which will leave a similarly lasting palaeontological signature, have also become evident worldwide, and most of these date from the mid-twentieth century (Barnosky, 2014).

There has also been the suggestion (Wolff, 2014) that the greatest changes arising from anthropogenic perturbation still lie ahead of us – and that we need a much longer perspective in order to assess this: i.e. we should simply wait until the entire phenomenon is considerably more advanced before attempting to make formal judgment. We agree that greater changes likely lie ahead and that the stratigraphic character of the Anthropocene will probably appear different from a far future perspective. However, the scale of these projected changes in the geological near future argue for perturbations of such as the biosphere (Barnosky et al., 2012) and ocean/atmosphere system (Tyrrell, 2011) that are commensurate with period/era level changes. The Anthropocene already has a robust geological basis, is in widespread use and indeed is becoming a central, integrating concept in the consideration of global change (e.g. Nature, 2011; Stockholm Memorandum 2011). We therefore consider that an interim definition of duration for it as a unit, regardless of formal status, would be useful, not least for clarity of communication. Hence, we discuss the three main candidate levels below.

3. Discussion

3.1. Exploring precise timing of the levels

All three suggested levels mark significant turning points in Earth history. The 'early Anthropocene' hypothesis marks the beginning of significant modification of the landscape (Ellis, 2011), and the progressive conversion of humanity from largely hunting/gathering communities to settled agricultural and cattle-raising life, from which sprang the first urban centres. These human communities locally left an abundant archaeological record (e.g. Edgeworth, 2014) that marks this interglacial phase as different from previous interglacial phases. Hence the view, particularly held within archaeological communities that widespread to locally pervasive human influence since the mid-Holocene suggests that 'the Anthropocene began a long time ago' (Ellis et al., 2013; Smith and Zeder, 2013).

Regarding the stratigraphic definition and correlation concepts, an early Anthropocene boundary level based on human-made stratigraphic signals would be difficult to trace and correlate in practice. This is because the signals of anthropogenic change (artefacts, anthropogenically modified vegetal and animal biotas) reflect the expansion and shifting nature of the human domain (e.g. Brown et al., 2013), and significant marker levels such as soil horizons (Gale and Hoare, 2012) are local to regional rather than continent-wide or global signals – and are largely restricted to the terrestrial and coastal realms (for the latter see e.g. Cohen and Lobo, 2013), with the oceans (and hence the accumulation of marine strata) remaining unaffected. An early Anthropocene level risks confusion with the tripartite division of the Holocene, with Early, Mid- and Late Holocene age/stage-level units proposed to be defined making use of the 8.2 ka BP and 4.2 ka BP climate events (Walker et al., 2012), and the broad overlap with Pleistocene and/or Holocene would make the Anthropocene redundant as a unit of geologic time.

Furthermore, focus on an 'early Anthropocene' level places emphasis on the interpretation of this time interval as one denoting human influence on geological process. We note the suggestion of the term 'Palaeoanthropocene' by Foley et al. (2013) to encompass this concept – it is clearly indicated to be a diachronous unit, and akin to the 'archaeosphere' of Edgeworth (2014). However, the archaeosphere, unlike the Palaeoanthropocene, is still in the process of formation, and is likely to continue forming and being transformed in the future. We suggest that these useful terms represent precursors to the Anthropocene sensu stricto. We also note that the Anthropocene and 'Palaeoanthropocene' can practically be subdivided into shorter, temporally discrete units appropriate to different scientific disciplines (such as archaeology, palaeontology, soil science, etc.) to even further emphasize that the build-up of human impacts proceeded in a stepwise fashion (for example, Barnosky et al., 2014). The defining criteria for such subdivisions are typically recognizable locally up to the continent scale, but globally may be diachronous on timescales that range from millennia to tens of millennia, thus rendering them less useful for defining a potential epoch-level boundary. An example would be the first record of *Homo sapiens* on various continents and islands.

The significance of the Anthropocene lies not so much in seeing within it the "first traces of our species" (i.e. an anthropocentric perspective upon geology), but in the scale, significance and longevity of change (that happens to be currently human-driven) to the Earth system. Hence, the clear step-change in Earth system evolution seen since the Industrial Revolution represents a more considerable perturbation than that achieved in pre-industrial times. The question here is, if the boundary is somehow to be associated with these larger-scale changes – where can a stratigraphically effective boundary be placed?

A boundary associated with the beginning of the Industrial Revolution is more clearly representative of major change to the Earth system than one placed some millennia ago. However, in terms of correlating a boundary within recent strata, it reprises, albeit to a lesser degree, the problems associated with an early Anthropocene boundary. Thus, the Industrial Revolution (and the stratigraphic signals directly associated with it) spread from England to mainland Europe to North America over a time span of a century (Waters et al., 2014b), and in some respects the current industrialization of China, India and other countries represents its continuation. The direct stratigraphic signals associated with industrialization and related urbanization will hence also be diachronous and affected by small-scale discontinuities, though mineral magnetic signals associated with coal burning have been suggested as a marker (Snowball et al., 2014). Meanwhile, global signals, such as the rise in atmospheric carbon dioxide levels and related increase in the amount of atmospherically light carbon in surface carbon reservoirs, are gradual over decades and of limited help in tracing any putative boundary precisely, though these signals show a significant increase beginning around 1950. One might select a strong natural signal at around this level, such as the Tambora eruption at 1815 CE (Smith, 2014), regionally recorded via its widespread ash deposits and more widely seen in ice cores and tree rings (Wolff, 2014), or link it with a climate signal, such as the end of the Little Ice Age (Fairchild and Frisia, 2014). This might well be effective regionally, but we consider that it would not be as widely traceable as a boundary placed at the youngest of the three main candidate levels, that we discuss below. Besides, the Little Ice Age itself is not identifiable globally – it is most prominent in the Northern Hemisphere, and absent from the Antarctic Peninsula (Mulvaney et al., 2012).

The 'Great Acceleration' originally identified by Steffen et al. (2007) as a step change in human activity on Earth appears, on current evidence, to be reflected too in practically useable stratigraphic markers, as shown by a number of the studies in Waters et al. (2014a) together with others (e.g. Holtgrieve et al., 2011; Wolfe et al., 2013).

These include:

- the global spread of artificial radionuclides from surface A-bomb explosions (Fairchild and Frisia, 2014; Hancock et al., 2014; Wolff, 2014);
- doubling of the surface reactive nitrogen reservoir (a result of fertilizer manufacture via the Haber–Bosch process), reflected in nitrogen isotope changes in far-field lacustrine deposits (Holtgrieve et al., 2011; Wolfe et al., 2013);
- the creation and wide (global) dispersal of new human-made materials (Ford et al., 2014; Zalasiewicz et al., 2014c) and artefacts that may be regarded as technofossils (Zalasiewicz et al., 2014b) in the environment – almost all the discarded plastic and aluminium waste in surface sediments date from the mid-twentieth century, for instance;
- rapid expansion in the distribution of artificial deposits on land, associated with urbanization (Ford et al., 2014), and of reworked sediment on continental shelves and slopes, associated with deep-sea trawling (see references in Zalasiewicz et al., 2014a);

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- global dispersal of pollutants associated with expansion of industrial activities, including novel organic contaminants that include persistent organic pollutants (POPs) (Muir and Rose, 2007) and increased concentrations of heavy metals that are relatively rare in nature (Leorri et al., 2014; Gałuszka et al., 2014);
- a significant 'step' in the rate of increase of anthropogenic biotic change (Wolfe et al., 2013; Barnosky, 2014; Wilkinson et al., 2014), including accelerated species invasions on land and in the sea that alter species compositions in a wide spectrum of terrestrial and marine communities, in ways that will leave a clear palaeontological signal as we go into the future;
- a significant signal in polar ice marked by such indicators as lead from gasoline (Wolff, 2014) of different isotopic characteristics than Roman lead from smelting that forms an earlier signal;
- acceleration in the burning of hydrocarbons that has produced much of the ~120 ppm increase in atmospheric carbon dioxide levels since the mid-twentieth century, and hence much of the associated carbon isotope signal (Al-Rousan et al., 2004);
- the majority of human-created trace fossils derived from sediment and rock drilling. The drilling for petroleum is often particularly deep. The 2.6 million petroleum wells drilled in the U.S. domain reach a cumulative length of more than 5 million km. Canada's 400 000 petroleum wells are even deeper on average and exceed more than 2 million km. Petroleum drilling has occurred world-wide. In addition academic drilling using petroleum drilling technology has covered the deep ocean since the launch of the Deep Sea Drilling Project in 1968, and its successors the Ocean Drilling Program, Integrated Ocean Drilling Program, and most recently the International Ocean Discovery Program. These international efforts have penetrated the sediment and rock in all major oceans and seas, including in water depths exceeding 7 km. These anthropogenic trace fossils will last for tens of millions of years (Zalasiewicz et al., 2014d);
- A massive increase in marine oil-tanker traffic that has led to numerous accidental oil spills on coasts globally (especially along tanker routes);
- Increasing numbers of large dams (e.g. Aswan) that have radically reduced runoff and sand and silt supply to coastal seas globally, leading to the retreat of major deltas.

Some of these signals (e.g. the radionuclides) are in effect globally synchronous, while others are of relatively low diachroneity, given that the latter half of the twentieth century saw the phenomenon of globalization, or, the emplacement of a strongly globally interlinked technosphere (Haff, 2014); because of this, many of the industrially or agriculturally-related signals (e.g. of technofossils such as ball-point pens, CDs or mobile phones) spread rapidly around the world from the time of their first use. Hence, there are multiple practical stratigraphic criteria that can be used to identify deposits that post-date the mid-twentieth century, and this, on current evidence, we consider to be the optimal position for an Anthropocene boundary, even though it locally may lie unambiguously *within* deposits that are clearly of anthropogenic origin (Edgeworth, 2014).

3.2. GSSP versus GSSA, and precise placement of boundary

All of the units of the Phanerozoic Eon within the International Chronostratigraphic Chart are now defined, or are intended to be defined, by Global Boundary Stratigraphic Sections and Points (GSSPs = 'golden spikes' in the vernacular). This is because the fossil record, either by itself or (better) with isotopic or palaeomagnetic signals, is considered to give higher resolution than attempts to correlate to selected numerical dates, i.e. to Global Standard Stratigraphic Ages (GSSAs) (although see Smith et al., 2014). The last unit to be defined by a GSSA, the Holocene (previously at 10 000 radiocarbon years before 1950 CE) has recently been replaced by a GSSP dated at 11 703 ice-layer years b2k (before 2000 CE) (and rounded for convenience to 11 700 years b2k). It is placed at 1492.45 m depth within a Greenland ice core (Walker et al., 2009), identified by a clear change in deuterium composition among other proxy changes. Most of the Precambrian, though, continues to be subdivided via GSSAs, largely because of the lack of a precise and effective biostratigraphic record that might act as a framework into which other stratigraphic signals can be integrated.

For the Anthropocene, especially if defined as starting in the mid-twentieth century, it is not clear that a GSSP offers significant practical advantage over a GSSA. Over the interval of time considered, the stratigraphic record combines with the historical and observational record, so that the standard temporal framework — years relative to CE of the Gregorian calendar — can be used effectively, whether in the Earth sciences or in any other discipline of study.

If a GSSA is chosen within the mid-twentieth century, at which point in time should it be placed? The use of the beginning of 1950 would bisect the century, and also be at the traditional reference point for radiocarbon dating and for the BP ('before present') dating notation. Considering the combination of traceable stratigraphical indicators and steps of significance to Earth history, we propose that the beginning of the nuclear age, that led to dispersal of artificial radionuclides worldwide, may be adopted as an effective stratigraphic boundary in Earth history. These radioisotopes appear in ice at both poles and on all continents.

Hence, we suggest that the Anthropocene (formal or informal) be defined to begin historically at the moment of detonation of the Trinity A-bomb at Alamogordo, New Mexico, at 05:29:21 Mountain War Time (± 2 s) July 16, 1945 (= 11:29:21 Co-ordinated Universal Time = Greenwich Mean Time). This would have a parallel with the Cretaceous–Paleogene boundary which, although defined by a GSSP at El Kef, Tunisia, has been expressly placed at the moment of impact of the meteorite on the Yucatan Peninsula (Molina et al., 2006).

Practically speaking, this radiogenic signal became prominent worldwide a few years later than 1945 (e.g. Hancock et al., 2014; Wolff, 2014; Waters et al., 2015), as nuclear testing became more widespread. Nevertheless, placing the benchmark at the first nuclear test provides a clear, objective moment in time.

Since 1945 more than 500 nuclear weapons tests were conducted in the atmosphere until a Test Ban Treaty became mostly

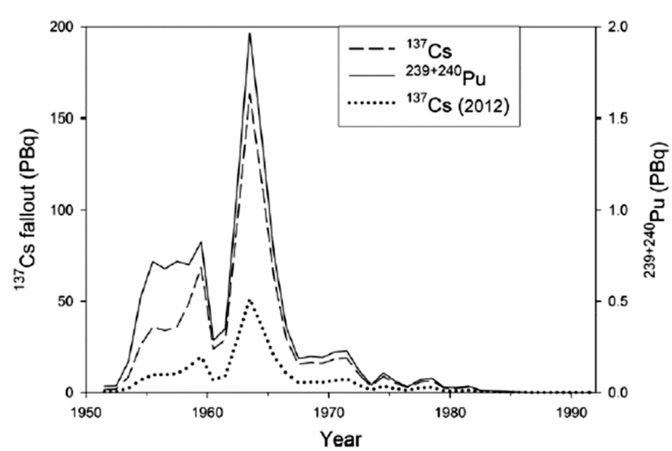

Fig. 1. ^{137}Cs and $^{239+240}$Pu radiogenic fallout from nuclear weapons testing (from Hancock et al., 2014).

effective in 1963 (UNSCEAR, 2000). This testing is the major cause of distribution of human-made radionuclides over the globe. The small particles of radioactive debris from nuclear explosions (global fallout) were injected into the stratosphere where they circulate globally and re-entry from the troposphere to the Earth's surface being deposited worldwide (Ritchie and McHenry, 1990; Aoyama et al., 2006).

The most widely recognised radioactive isotope produced as a result of the nuclear weapons testing programmes that followed WWII has been Caesium-137. There are no natural sources of Cs-137 and it shows the first pronounced atmospheric increase in the northern hemisphere in 1954 CE (Fig. 1) and a well-defined maximum in 1963 CE (in this latter case together with other human-made fallout radionuclides such as Plutonium 239 + 240 or Americium 241). The short-lived radioisotope Cs-137 has been used extensively to date recent sediments (Pennington et al., 1973; Ritchie and McHenry, 1990; Walker, 2005), although in the next few decades it will be replaced by long-lived Pu-239 as the most distinguishable artificial radionuclide on Earth and the best chronological marker of the Anthropocene (Hancock et al., 2014; Waters et al., 2015).

Furthermore, the large, short-lived increase in bomb-produced ^{14}C production has left a marked signal in carbon-bearing matter formed after the onset of extensive nuclear tests after 1950 CE (Dean et al., 2014). This '^{14}C bomb peak' (Fig. 2) is commonly found in most carbon reservoirs around the globe (Reimer et al., 2004; Levin et al., 2008; Hua et al., 2013), it provides a high-resolution chronometer for current scientific use, and owing to a relatively long half-life (5730 a) it will in general be detectable as a 'spike' for ~50 000 years into the future.

Hence, the most pronounced peaks in the radionuclide signal are not precisely coincident with the start of A-bomb tests. Therefore, alternative possibilities for an Anthropocene GSSA are either 1950 CE (as being closer to this date) or 1954 CE to mark the first *widespread* appearance of artificial radioisotopes in the geological record, part of the clear, globally distributed signal from the more extensive above-ground nuclear testing that took place mainly in the 1950s and early 1960s (Gabrieli et al., 2011; Wolff, 2014; Hancock et al., 2014; Waters et al., 2015). Either of these two possibilities might also be considered as more 'neutral' time references than the Trinity test, even though we stress here the functional stratigraphic, rather than societal, implications.

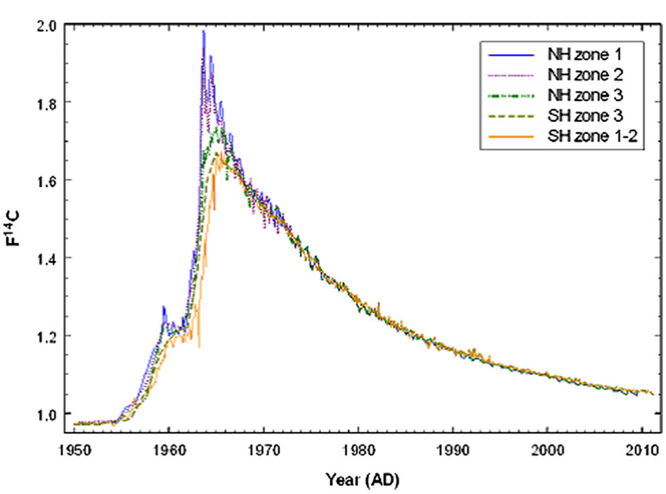

Fig. 2. Atmospheric ^{14}C concentration changes across the Earth (NH1 is Northern Hemisphere zone 1, being most northerly, and SH1-2 Southern Hemisphere Zone 1–2 most southerly) (from Hua et al., 2013).

However, a boundary placed at the time instant of the Alamogordo test would mark a historic turning point of global significance associated with the Great Acceleration, while in practical stratigraphic terms it would include *all* primary stratigraphic signals of bomb-related radionuclides, including those of the geologically simultaneous Hiroshima – August 6, 1945 – and Nagasaki – August 9, 1945 – bombs). Moreover, placing the boundary at an exact point in time, related to the appearance of a chemostratigraphic marker, is consistent with the International and North American Stratigraphic Codes and with the definition of the Pleistocene–Holocene boundary at a deuterium excursion dated at high precision in the NGRIP Ice Core.

Correlation to the precise boundary would in practice be effected using a broad range of stratigraphic criteria, the detailed pattern of which (the effective appearance of, say, plastics and aluminium in the geological record, and the cessation of production of WW2-related debris) correlate well with a 1945 boundary. We propose, for wider discussion, this as on balance an effective and appropriate boundary, currently, for the Anthropocene. While it may be superseded in a more distant future, especially as other stratigraphic signals are produced (e.g. of a marine transgression or mass extinction event), it reflects present geological reality and has practical utility, and may be effectively used by at least the current generation of scientists.

4. Conclusion

Here, we evaluate when the Anthropocene might be considered to have begun, not whether the term is geologically justifiable, whether its formalization is useful or how it might be characterized and defined. In conclusion, the significance of the Anthropocene lies not so much in seeing within it the "first traces of our species", but in the scale, significance and longevity of change to the Earth system. Humans started to develop an increasing, but generally regional and highly diachronous, influence on the Earth System thousands of years ago. With the onset of the Industrial Revolution, humankind became a more pronounced geological factor, but in our present view it was from the mid-20th century that the worldwide impact of the accelerating Industrial Revolution became both global and near-synchronous.

Given that we possess both a precisely dated historical observational record and a stratigraphic record over this interval, we suggest that a GSSA-based boundary is likely to be simpler and more direct than one based on a GSSP. Hence, we propose here a boundary in 1945 based on both a historical turning point (the Alamogordo test explosion) and the source of a chemostratigraphic signal. Such a boundary selection may open possibilities for historical fields other than Earth history (geology) to more easily engage in the emerging interdisciplinary science base of the Anthropocene.

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References

Al-Rousan, S., Pätzold, J., Al-Moghrabi, S., Wefer, G., 2004. Invasion of anthropogenic CO_2 recorded in planktonic foraminifera from the northern Gulf of Aquaba.

International Journal of Earth Sciences 93, 1066–1076. http://dx.doi.org/10.1007/s00531-004-0433-4.
Aoyama, M., Hirose, K., Igarashi, Y., 2006. Re-construction and updating our understanding on the global weapons tests 137Cs fallout. Journal of Environmental Monitoring 8, 431–438.
Babcock, L.E., Peng, S., Zhu, M., Xiao, S., Ahlberg, P., 2014. Proposed reassessment of the Cambrian GSSP. Journal of African Earth Sciences 98, 3–10.
Barnosky, A.D., 2008. Megafauna biomass tradeoff as a driver of quaternary and future extinctions. Proceedings of the National Academy of Sciences Unites States of America 105 (Suppl. 1), 11543–11548.
Barnosky, A.D., 2014. Palaeontological evidence for defining the Anthropocene. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 149–165. http://dx.doi.org/10.1144/SP395.6. First Published Online October 24, 2013.
Barnosky, A.D., Hadly, E.A., Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., Getz, W.M., Harte, J., Hastings, A., Marquet, P.A., Martinez, N.D., Mooers, A., Roopnarine, P., Vermeeij, G., Williams, J.W., Gillespie, R., Kitzes, J., Marshall, C., Matzke, N., Mindell, D.P., Revilla, R., Smith, A.B., 2012. Approaching a state-shift in the biosphere. Nature 486, 52–56.
Barnosky, A.D., Holmes, M., Kirchholtes, R., Lindsey, E., Maguire, K.C., Poust, A.W.,M., Stegner, A., Sunseri, J., Swartz, B., Swift, J., Villavicencio, N.A., Wogan, G.O.U., 2014. Prelude to the anthropocene: two newly-defined North American land-mammal ages. Anthropocene Review. http://dx.doi.org/10.1177/2053019614547433. First Published Online September 9, 2014.
Brown, A., Toms, P., Carey, C., Rhodes, E., 2013. Geomorphology of the Anthropocene: time-transgressive discontinuities of human-induced alluviation. Anthropocene 1, 3–13.
Certini, G., Scalenghe, R., 2011. Anthropogenic soils are the golden spikes for the Anthropocene. The Holocene 21, 1269–1274.
Cohen, K.M., Lobo, F.J., 2013. Continental shelf drowned landscapes: submerged geomorphological and sedimentary record of the youngest cycles. Geomorphology 203, 1–5.
Cohen, K.M., Finney, S.C., Gibbard, P.L., Fan, J.-X., 2013; Updated. The ICS International Chronostratigraphic Chart. Episodes 36, 199–204.
Crutzen, P.J., Stoermer, E.F., 2000. The "Anthropocene". Global Change Newsletter 41, 17–18.
Crutzen, P.J., 2002. Geology of mankind. Nature 415, 23.
Davis, R.V., 2011. Inventing the present: historical roots of the Anthropocene. Earth Science History 30, 63–84.
Dean, J.R., Leng, M.J., Mackay, A.W., 2014. Is there an isotopic signature of the Anthropocene? The Anthropocene Review. http://dx.doi.org/10.1177/2053019614541631.
Doughty, C.E., Wolf, A., Field, C.B., 2010. Biophysical feedbacks between the Pleistocene megafauna extinction and climate: the first human-induced global warming? Geophysical Research Letters 37, L15703. http://dx.doi.org/10.1029/2010GL043985.
Douglas, I., Lawson, N., 2001. The human dimensions of geomorphological work in Britain. Journal of Industrial Ecology 4 (2), 9–33.
Edgeworth, M., 2014. The relationship between archaeological stratigraphy and artificial ground and its significance to the Anthropocene. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 91–108. http://dx.doi.org/10.1144/SP395.3. First Published Online October 25, 2013.
Ellis, E.C., 2011. Anthropogenic transformation of the terrestrial biosphere. Philosophical Transactions of the Royal Society A369, 1010–1035.
Ellis, E.C., Antill, E.C., Kreft, H., 2012. All is not loss: plant biodiversity in the Anthropocene. PLoS ONE 7, e30535. http://dx.doi.org/10.1371/journal.pone.0030535.
Ellis, E.C., Kaplan, J.O., Fuller, D.Q., Vavrus, S., Klein Goldewijk, K., Verburg, P.H., 2013. Used planet: a global history. Proceedings of the National Academy of Sciences 110 (20), 7978–7985.
Fairchild, I.J., Frisia, S., 2014. Definition of the Anthropocene: a view from the underworld. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 239–254. http://dx.doi.org/10.1144/SP395.7. First Published Online October 24, 2013.
Finney, S.C., 2014. The 'Anthropocene' as a ratified unit in the ICS International Chronostratigraphic Chart: fundamental issues that must be addressed by the Task Group. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 23–28. http://dx.doi.org/10.1144/SP395.9. First Published Online October 24, 2013.
Fischer-Kowalski, M., Krausmann, F., Pallua, I., 2014. A sociometabolic reading of the Anthropocene: modes of subsistence, population size and human impact on Earth. Anthropocene Review 1. http://dx.doi.org/10.1177/2053019613518033.
Foley, S.F., Gronenborn, D., Andreae, M.O., Kadereit, J.W., Esper, J., Scholz, D., Pöschl, U., Jacob, D.E., Schöne, B.R., Schreg, R., Vött, A., Jordan, D., Lelieveld, J., Weller, C.G., Alt, K.W., Gaudzinski-Windheuser, S., Bruhn, K.C., Tost, H., Sirocko, F., Crutzen, P.J., 2013. The Palaeoanthropocene – The beginnings of anthropogenic environmental change. Anthropocene 3, 83–88.
Ford, J.R., Price, S.J., Cooper, A.H., Waters, C.N., 2014. An assessment of lithostratigraphy for anthropogenic deposits. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 55–89. http://dx.doi.org/10.1144/SP395.12. First Published Online January 23, 2014, Updated April 8, 2014.
Gabrieli, J., Cozzi, G., et al., 2011. Contamination of Alpine snow and ice at Colle Gnifetti, Swiss/Italian Alps, from nuclear weapons tests. Atmospheric Environment 45, 587–593. http://dx.doi.org/10.1016/j.atmosenv.2010.10.039.
Gale, S.J., Hoare, P.G., 2012. The stratigraphic status of the Anthropocene. The Holocene 22, 1478–1481.
Gałuszka, A., Migaszewski, P., Zalasiewicz, J., 2014. Assessing the Anthropocene with geochemical methods. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 221–238. http://dx.doi.org/10.1144/SP395.5. First Published Online October 24, 2013.
Gibbard, P.L., Head, M.J., 2010. The newly-ratified definition of the quaternary system/period and redefinition of the Pleistocene Series/Epoch, and comparison of proposals advanced prior to formal ratification. Episodes 33, 152–158.
Gibbard, P.L., Walker, M.J.C., 2014. The term 'Anthropocene' in the context of formal geological classification. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 29–37. http://dx.doi.org/10.1144/SP395.1. First Published Online October 25, 2013.
Haff, P.K., 2014. Technology as a geological phenomenon: implications for human well-being. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 301–309. http://dx.doi.org/10.1144/SP395.4. First Published Online October 24, 2013.
Hancock, G.J., Tims, S.G., Fifield, L.K., Webster, I.T., 2014. The release and persistence of radioactive anthropogenic nuclides. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 265–281. http://dx.doi.org/10.1144/SP395.15. First Published Online February 28, 2014.
Hilgen, F.J., Lourens, L.J., Van Dam, J.A., 2012. The Neogene period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), The Geologic Time Scale 2012. Elsevier, pp. 923–978. http://dx.doi.org/10.1016/B978-0-444-59425-9.00001-9.
Holtgrieve, G.W., Schindler, D.E., Hobbs, W.O., Leavitt, P.R., Ward, E.J., Bunting, L., Chen, G., Finney, B.P., Gregory-Eaves, I., Holmgren, S., Lisac, M.J., Lisi, P.J., Nydick, K., Rogers, L.A., Saros, J.E., Selbie, D.T., Shapley, M.D., Walsh, P.B., Wolfe, A.P., 2011. A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the Northern Hemisphere. Science 334, 1545–1548.
Hooke, R.LeB., Martín-Ducque, J.F., Pedraza, J., 2012. Land transformation by humans: a review. GSA Today 22 (12), 4–10.
Hua, Q., Barbetti, M., Rakowski, A.Z., 2013. Atmospheric radiocarbon for the period 1950–2010. Radiocarbon 55, 2059–2072.
Kaplan, J.O., Krumhardt, K., Ellis, E.C., Ruddiman, W.F., Lemmen, C., Goldewijk, K.K., 2011. Holocene carbon emissions as a result of anthropogenic land cover change. The Holocene 21 (5), 775–791.
Keller, G., Stinnesbeck, W., Adatte, T., Stüben, D., 2003. Multiple impacts across the Cretaceous–Tertiary boundary. Earth Science Reviews 62, 327–363.
Koch, P.L., Barnosky, A.D., 2006. Late quaternary extinctions: state of the debate. Annual Review of Ecology, Evolution and Systematics 37, 215–250.
Landing, E., 1994. Precambrian–Cambrian global stratotype ratified and a new perspective of Cambrian time. Geology 22, 179–182.
Leorri, E., Mitra, S., Irabien, M.J., Zimmerman, A.R., Blake, W.H., Cearreta, A., 2014. A 700 year record of combustion-derived pollution in Northern Spain: tools to identify the Holocene/Anthropocene transition in coastal environments. Science of the Total Environment 470–471, 240–247.
Levin, I., Hammer, S., Kromer, B., Meinhardt, F., 2008. Radiocarbon observations in atmospheric CO_2: determining fossil fuel CO_2 over Europe using Jungfraujoch observations as background. Science of the Total Environment 391, 211–216.
Melchin, M.J., Sadler, P.M., Cramer, B.D., 2012. The Silurian period. In: Gradstein, F., Ogg, G., Schmitz, M., Ogg, G. (Eds.), The Geological Time Scale 2012. Elsevier, pp. 526–558, 1144 pp.
Molina, E., Alegret, L., Aremillas, I., Arz, J.A., Gallala, N., Hardenbol, J., von Salis, K., Steuerbaut, E., Vandenberghe, N., Zagbib-Turki, D., 2006. The global boundary stratotype section and point for the base of the Danian stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia – original definition and revision. Episodes 29 (4), 263–273.
Muir, D.C.G., Rose, N.L., 2007. Persistent organig pollutants in the sediments of Lochnagar, pp. 375–402. In: Rose, N.L. (Ed.), Lochnagar: the Natural History of a Mountain Lake, Developments in Palaeoenvironmental Research, vol. 12. Springer, Dordrect, The Netherlands.
Mulvaney, R., Abram, N.J., Hindmarsh, R.C.A., Arrowsmith, C., Fleet, L., Triest, J., Sime, L.C., Alemany, O., Foord, S., 2012. Recent Antarctic Peninsula warming relative to Holocene climate and ice-shelf history. Nature 489, 141–145.
Pennington, W., Tutin, T.G., Cambray, R.S., Fisher, E.M., 1973. Observations on lake sediments using fallout 137Cs as a tracer. Nature 242, 324–326.
Price, S.J., Ford, J.R., Cooper, A.H., Neal, C., 2011. Humans as major geological and geomorphological agents in the Anthropocene: the significance of artificial ground in Great Britain. Philosophical Transactions of the Royal Society A369, 1056–1084.
Reimer, P., Brown, T., Reimer, R., 2004. Discussion: reporting and calibration of post-bomb C-14 data. Radiocarbon 46, 1299–1304.

Ritchie, J.C., McHenry, J.R., 1990. Application of radioactive fallout Cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. Journal of Environmental Quality 19, 215–233.
Ruddiman, W.F., 2003. The Anthropogenic Greenhouse Era began thousands of years ago. Climatic Change 61, 261–293.
Ruddiman, W.F., 2013. Anthropocene. Annual Review of Earth and Planetary Sciences 41, 45–68. http://dx.doi.org/10.1146/annurev-earth-050212-123944.
Schulte, P., Alegret, L., et al., 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. Science 327, 1214–1218.
Sheehan, P.M., 2001. The late Ordovician mass extinction. Annual Review of Earth and Planetary Sciences 29, 331–364.
Smith, A.G., Barry, T., Bown, P., Cope, J., Gale, A., Gibbard, P., Gregory, J., Hounslow, M., Kemp, D., Knox, R., Marshall, J., Oates, M., Rawson, P., Powell, J., Waters, C.N., 2014. GSSPs, global stratigraphy and correlation. In: Smith, D. (Ed.), Strata and Time: Probing the Gaps in Our Understanding, Proceedings of the William Smith Meeting 404. http://dx.doi.org/10.1144/SP404.8.
Smith, B.D., Zeder, M.A., 2013. The onset of the Anthropocene. Anthropocene. http://dx.doi.org/10.1016/j.ancene.2013.05.001.
Smith, V.C., 2014. Defining the onset of the Anthropocene using tephrochronology. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 283–299. http://dx.doi.org/10.1144/SP395.11. First Published Online November 21, 2013.
Snowball, I., Hounslow, M.W., Nilsson, A., 2014. Geomagnetic and mineral magnetic characterization of the Anthropocene. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 119–141. http://dx.doi.org/10.1144/SP395.13. First Published Online December 19, 2013.
Steffen, W., Crutzen, P.J., McNeill, J.R., 2007. The Anthropocene: are humans now overwhelming the great forces of Nature? Ambio 36, 614–621.
Tyrrell, T., 2011. Anthropogenic modification of the oceans. Philosophical Transactions of the Royal Society A369, 887–908.
UNSCEAR-United Nations Scientific Committee on the Effects of Atomic Radiation, 2000. Sources and Effects of Ionizing Radiation, 2000 Report. United Nations, New York.
Vandenberghe, N., Hilgen, F.J., Speijer, R.P., 2012. The Paleogene period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), The Geologic Time Scale 2012. Elsevier, pp. 855–921. http://dx.doi.org/10.1016/B978-0-444-59425-9.00001-9.
Walker, M., Johnsen, S., Olander Rasmussen, S., Popp, T., Steffense, J.-P., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L.C., Hughen, K., Newham, R., Schwander, J., 2009. Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. Journal of Quaternary Science 24, 3–17.
Walker, M.J.C., 2005. Quaternary Dating Methods. John Wiley and Sons, Chichester, 286 pp.
Walker, M.J.C., Berkelhammer, M., Björck, S., Cwynar, L.C., Fisher, D.A., Long, A.J., Lowe, J.J., Newnham, R.M., Rasmussen, S.O., Weiss, H., 2012. Formal subdivision of the Holocene Series/Epoch: a discussion paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). Journal of Quaternary Science 27, 649–659. http://dx.doi.org/10.1002/jqs.2565.
Waters, C.N., Syvitski, J.P.M., Gałuszka, A., Hancock, G.J., Zalasiewicz, J., Cearreta, A., Grinevald, J., Jeandel, C., McNeill, J.R., Summerhayes, C., 2015. Can environmental radiogenic signatures define the beginning of the Anthropocene Epoch? Bulletin of Atomic Scientists (submitted for publication).
Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), 2014a. A Stratigraphical Basis for the Anthropocene. Geological Society, London, Special Publications 395.
Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A., 2014b. A stratigraphical basis for the Anthropocene? In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 1–21. http://dx.doi.org/10.1144/SP395.18. First Published Online March 24, 2014.
Wilkinson, I.P., Poirier, C., Head, M.J., Sayer, C.D., Tibby, J., 2014. Micropalaeontological signatures of the Anthropocene. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 185–219. http://dx.doi.org/10.1144/SP395.14. First Published Online January 31, 2014.
Williams, M., Zalasiewicz, J., Haywood, A., Ellis, M. (Eds.), 2011. The Anthropocene: a New Epoch of Geological Time?. Philosophical Transactions of the Royal Society 369A, pp. 833–1112.
Williams, M., Zalasiewicz, J., Waters, C.N., Landing, E., 2014. Is the fossil record of complex animal behaviour a stratigraphical analogue for the Anthropocene? In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 143–148. http://dx.doi.org/10.1144/SP395.8. First Published Online October 25, 2013.
Wolfe, A.P., Hobbs, W.O., Birks, H.H., Briner, J.P., Holmgren, S.U., Ingólfsson, Ó., Kaushal, S.S., Miller, G.H., Pagani, M., Saros, J.E., Vinebrooke, R.D., 2013. Stratigraphic expressions of the Holocene–Anthropocene transition revealed in sediments from remote lakes. Earth-Science Reviews 116, 17–34.
Wolff, E.W., 2014. Ice sheets and the Anthropocene. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 255–263. http://dx.doi.org/10.1144/SP395.10. First Published Online November 25, 2013.
Zalasiewicz, J., Williams, M., Smith, A., Barry, T.L., Coe, A.L., Bown, P.R., Brenchley, P., Cantrill, D., Gale, A., Gibbard, P., Gregory, F.J., Hounslow, M., Kerr, A.C., Pearson, P., Knox, R., Powell, J., Waters, C., Marshall, J., Oates, M., Rawson, P., Stone, P., 2008. Are we now living in the Anthropocene? Geological Society of America Today 18, 4–8.
Zalasiewicz, J., Cita, M.B., Hilgen, F., Pratt, B.R., Strasser, A., Thierry, J., Weissert, H., 2013. Chronostratigraphy and geochronology: a proposed realignment. GSA Today 23 (3), 4–8.
Zalasiewicz, J., Williams, M., Waters, C.N., 2014a. Can an Anthropocene series be defined and recognised? In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 39–53. http://dx.doi.org/10.1144/SP395.16. First Published Online March 10, 2014.
Zalasiewicz, J., Kryza, R., Williams, M., 2014c. The mineral signature of the Anthropocene. In: Waters, C.N., Zalasiewicz, J., Williams, M., Ellis, M.A., Snelling, A. (Eds.), A Stratigraphical Basis for the Anthropocene, Geological Society, London, Special Publications 395, pp. 109–117. http://dx.doi.org/10.1144/SP395.2. First Published Online December 19, 2013.
Zalasiewicz, J., Williams, M., 2014. The Anthropocene: a comparison with the Ordovician–Silurian boundary. Rendiconti Lincei, Scienze fisische e naturali 25 (1), 5–12. http://dx.doi.org/10.1007/s12210-013-0265-x. First Published Online December 3, 2013.
Zalasiewicz, J., Williams, M., Waters, C.N., Barnosky, A.D., Haff, P., 2014b. The technofossil record of humans. Anthropocene Review 1, 34–43. http://dx.doi.org/10.1177/2053019613514953.
Zalasiewicz, J., Waters, C.N., Williams, M., 2014d. Human bioturbation, and the subterranean landscape of the Anthropocene. Anthropocene. http://dx.doi.org/10.1016/j.ancene.2014.07.002.

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