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Jan Zalasiewicz, Colin Waters, Martin Head, Clément Poirier, Colin Summerhayes, et al.. A formal Anthropocene is compatible with but distinct from its diachronous anthropogenic counterparts: a response to W.F. Ruddiman's 'three flaws in defining a formal Anthropocene'. *Progress in Physical Geography*, 2019, 43 (3), pp.319-333. <10.1177/0309133319832607>. <hal-02194153>

HAL Id: hal-02194153

<https://normandie-univ.hal.science/hal-02194153v1>

Submitted on 29 Sep 2025

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A formal Anthropocene is compatible with but distinct from its diachronous anthropogenic counterparts: A response to W.F. Ruddiman's 'three flaws in defining a formal Anthropocene'

Progress in Physical Geography
2019, Vol. 43(3) 319–333
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DOI: 10.1177/0309133319832607
journals.sagepub.com/home/ppg



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Abstract

We analyse the ‘three flaws’ to potentially defining a formal Anthropocene geological time unit as advanced by Ruddiman (2018). (1) We recognize a long record of pre-industrial human impacts, but note that these increased in relative magnitude slowly and were strongly time-transgressive by comparison with the extraordinarily rapid, novel and near-globally synchronous changes of post-industrial time. (2) The rules of stratigraphic nomenclature do not ‘reject’ pre-industrial anthropogenic signals – these have long been a key characteristic and distinguishing feature of the Holocene. (3) In contrast to the contention that classical chronostratigraphy is now widely ignored by scientists, it remains vital and widely used in unambiguously defining geological time units and is an indispensable part of the Earth sciences. A mounting body of evidence indicates that the Anthropocene, considered as a precisely defined geological time unit that begins in the mid-20th century, is sharply distinct from the Holocene.

Keywords

Anthropocene, Holocene, chronostratigraphy, geological time scale, Earth sciences

I Introduction

Ruddiman (2018) raises important questions, summarized as ‘three flaws’ in the definition of a formal Anthropocene. His analyses and discussion of the Anthropocene concept, especially as it touches on its interpretation in a chronostratigraphic context, is an important component of the scientific process required to understand whether the Anthropocene should be added to the International Chronostratigraphic Chart and hence the Geological Time Scale. His arguments follow on from notable and ground-breaking studies of how human impacts may interact with land use and climate (Ruddiman, 2003), and specifically on how these interactions may relate to the Anthropocene concept (Ruddiman, 2013; Ruddiman et al., 2015, 2016).

We emphasize here that the task of the Anthropocene Working Group (AWG) is not to provide another prism through which to reinterpret human history and environmental impact, but rather to identify a practical stratigraphic and time marker as point of reference in the formal classification of geological time. In this context, we offer the following responses to the points raised in Ruddiman’s thoughtful analysis.

II Anthropogenic impacts long preceded the mid-20th century, the potential boundary level currently most closely studied by the AWG

Such impacts have never been in doubt, nor questioned by the work of the AWG (e.g. Edgeworth et al., 2015; Zalasiewicz et al., 2017, 2019). Pre-industrial anthropogenic impacts range from the megafaunal extinctions, starting ~50 ka in the Late Pleistocene (Koch and Barnosky, 2006), to the progressive and eventually widespread deforestation associated with agricultural development from near the beginning of the Holocene, the ever-greater spread and population growth of humans, and associated fauna (e.g. rats, pigs) and flora (rice, wheat, maize, etc.) around the world, and, locally, the development and spread of technology and urban centres (Zalasiewicz et al., 2019). Indeed, anthropogenically reduced vertebrate diversity, a rich archaeological record, and a progressively profound anthropogenic impact on terrestrial vegetation have long been key features that distinguish the Holocene from the many preceding interglacial phases of the Quaternary Period.

Consideration of the scale of early human impact focuses on the land surface, its associated biota, and the environment in which we live. But $\sim 70.8\%$ of the Earth's surface is oceans, and human impact there has in comparison been minimal and/or local until the 19th and 20th centuries, except on lowland coastal areas where human population centres were established early because of abundant and accessible food sources. Even on land, by 1700 CE about half of the global ice-free land surface was still wildlands, while 'used' anthromes (anthropogenic biomes) covered only $\sim 11\%$ of the planet's surface close to the dawn of the Industrial Revolution (Ellis et al., 2010). During gradual development of agriculture in the Early and Middle Holocene, the area of influence would be yet less. Ruddiman indicates that per-capita land use was greater millennia ago than at 1700 CE. Nevertheless, estimates of annual human population of about 4 million at the start of the Holocene indicate population increase at $\sim 0.04\%/yr$ throughout most of the Holocene to about 1 billion by 1800 CE (Figure 1). Subsequently, population grew to 3 billion people by 1960 CE and ~ 7.6 billion now, with peak annual growth rate of 2.1% in 1971 CE. The vastly greater and more rapid increases in human population of the last century, together with greatly increased per capita energy expenditure from fossil fuel burning, had commensurately greater impact on landscape modification and cultivation than in earlier times. Even if it is accepted that the pre-1950 changes itemized by Ruddiman 'have been the largest transformations of Earth's surface in all of human history', a point that is arguable given, for example, the growth of the global road network (Alamgir et al., 2017), damming most of the world's major rivers (Syvitski and Kettner, 2011) and $>60\%$ loss of the world's wildlife (Grooten and Almond, 2018) that have taken place since the mid-20th century, compared with recent changes those historic transformations were relatively slow to develop and mainly

affected those parts of the Earth's surface occupied by agriculture. Hence, the physical, biological and geochemical signals evident in geological successions are subdued by contrast with those associated with the accelerated rates of transformation from the mid-20th century onwards (e.g. Waters et al., 2016) (Figure 1).

Ruddiman (2003, 2013) and Ruddiman et al. (2016) argue that deforestation accompanying the increase of farming was a key factor (i) in halting the slow decline of atmospheric CO_2 levels at ~ 8 ka BP, when they had reached ~ 255 ppm (declining from ~ 260 ppm at 11 ka BP at the beginning of the Holocene), and (ii) in slowly raising them to ~ 280 ppm for the millennium prior to 1800 CE (Figure 2), thus postponing the onset of renewed glaciation. While this scenario is plausible and elegant, it may well represent an oversimplification of the origin of this slow CO_2 rise. For instance, Ciais et al. (2013; their Figure 6.5) concluded that the oceans may have contributed most or all of this CO_2 , as they did in the preceding glacial-to-interglacial transition (e.g. Skinner et al., 2010). Along the same lines, Studer et al. (2018) noted that nitrogen isotope evidence from the Southern Ocean was consistent with a weakening of the oceanic biological pump that stores CO_2 in deep water, hence possibly accounting for much of the Holocene rise in atmospheric CO_2 . Observing that the carbonate ion concentration of deep water had declined over the past 8000 years, Broecker et al. (1999) had already pointed out that this fall was consistent with the rise in atmospheric CO_2 seen in ice cores, hence attributing the rise in CO_2 to oceanic rather than terrestrial mechanisms. Broecker and Stocker (2006) subsequently noted that carbon isotopes appeared to rule out the possibility of there having been a large release of terrestrial carbon of the kind required by Ruddiman's hypothesis. By analogy with what happened in the interglacial of Marine Isotope Stage (MIS) 11, Broecker and Stocker concluded that the cause for the

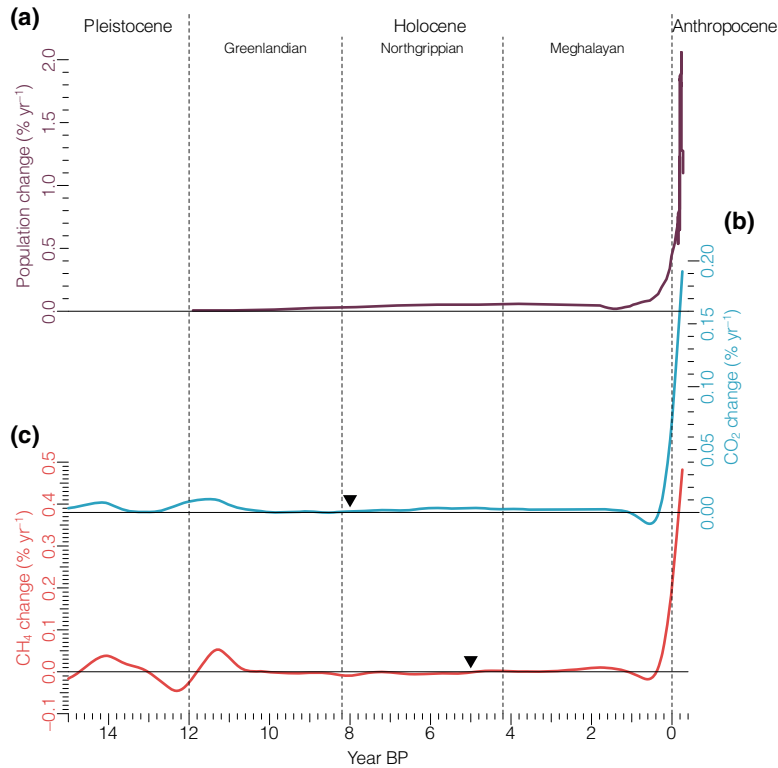


Figure 1. Average values of relative change to (a) global human population, (b) atmospheric CO₂ concentration and (c) CH₄ concentration since the last 20,000 years. World population data is sourced from <https://ourworldindata.org/world-population-growth> (based on Goldewijk et al., 2010). CO₂ and CH₄ data showing the % change per year are stacked from the low-resolution, long Epica Dome C ice record (Monnin et al., 2004; Loulergue et al., 2008), the high-resolution, short Law Dome record (MacFarling Meure et al., 2006) and recent air samples (Dlugokencky et al., 2018a, 2018b). The three stacks were resampled at a 50 year interval and the original data were smoothed with a cubic spline before being converted to % change. Age is in thousands of years before 1950 CE.

CO₂ rise during the last 8000 years was ‘natural’, not anthropogenic.

Ruddiman et al. (2016) agreed that 17 of the 20 ppm rise in atmospheric CO₂ in the Holocene originated from the ocean, arguing that this ocean carbon output was the result of feedbacks triggered by initial carbon emissions from land-use change. An alternative and more direct explanation, though, is that the 17 ppm CO₂ from the ocean was simply the result of ocean carbonate processes. The PAGES (Past Global Changes) 2016 synthesis of interglacials of the past 800,000 years (Past

Interglacial Working Group of PAGES, 2016), including the Holocene, emphasizes the variability in detail of interglacials, and that MIS 1 (the Holocene Series) is not the only interglacial that shows a rising trend of CO₂ after the Early Holocene-like decline. Both MIS 11c and MIS 15e show similar CO₂ trends to those of MIS 1 (see also Ciais et al., 2013). The PAGES synthesis notes that ‘...the relationship between astronomical parameters and CO₂ trends is expected to be indirect and complex’, and likewise suggested that there had probably been an important non-anthropogenic

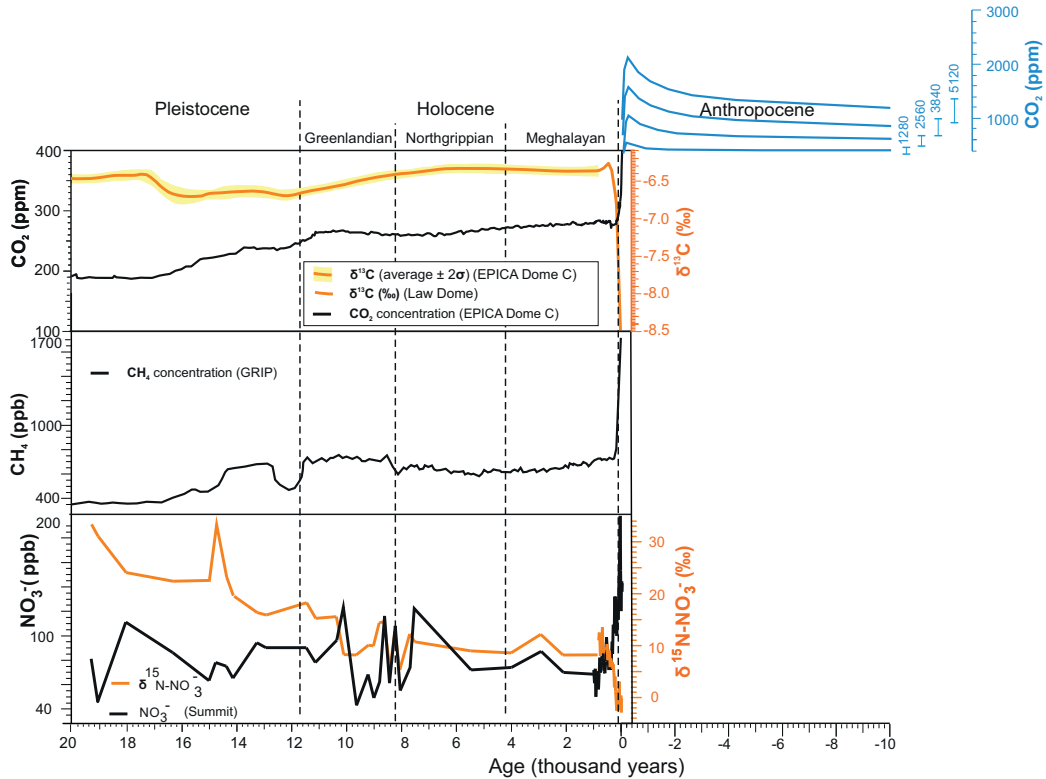


Figure 2. Comparison of key trends in the Holocene and Anthropocene, adapted from Figure 1 in Zalasiewicz et al. (2018), with projected atmospheric CO₂ concentrations from Clark et al. (2016).

component in the slow Middle to Late Holocene rise of atmospheric CO₂.

There is a similar debate as to the cause of the slow increase in atmospheric CH₄ concentrations from ~550 ppb starting ~5 ka ago through to ~675 ppb immediately prior to the onset of the ‘Industrial Revolution’ (Figure 2), which is anomalous compared to previous interglacials. There is certainly good archaeological evidence for the initiation of rice cultivation early in the Middle Holocene, though much of this was conducted in wetlands that were already emitting CH₄. There is no evidence for large-scale creation of artificial wetlands for rice cultivation resulting in extensive terraforming of landscapes across south and southeast Asia until after ~6.5 ka ago (Fuller et al., 2011). An anthropogenic link to changing CH₄

emissions is thus attractive, but not certain. Alternative mechanisms, including increased emissions from natural wetlands in tropical (e.g. Singarayer et al., 2011) and boreal (e.g. Schmidt et al., 2004) settings, have been proposed. Besides that, the much sharper and larger rise in the rate of change in CH₄ in the 20th century indicates a major departure from Holocene trends, as in the case of CO₂ (Figure 1).

As regards modification to the carbon cycle, we consider the striking speed and scale of the post-industrial change (Figure 1), clearly evident in geological successions, to be key. By whatever combination of anthropogenic and non-anthropogenic mechanisms, Middle to Late Holocene stabilization of greenhouse gases may have prevented the Earth from entering a new glacial phase prior to the

Industrial Revolution, as modelling has suggested (Ganopolski et al., 2016). Nevertheless, whether the continuation of Holocene patterns of climate has been anthropogenically influenced or not (see also Pongratz et al., 2011), it is still, from the perspective of the Earth, the Holocene Epoch, when generally stable interglacial conditions persisted for some eleven millennia. Figure 1 indicates that there has subsequently been a profound departure from those relatively stable conditions.

A mounting body of evidence now indicates that the Anthropocene as originally proposed by Crutzen and Stoermer (2000), adopted and developed by the Earth System science (ESS) community (e.g. Steffen et al., 2004, 2007) and more recently analysed in stratigraphic terms by the AWG (e.g. Waters et al., 2016) is clearly distinct from the preceding Holocene. It represents the marked *intensification* (Crutzen, 2002) of anthropogenic change, taking the Earth System beyond the envelope of Holocene conditions. The Earth System parameters show *inter alia* a sharp and ongoing rise in atmospheric CO₂ following the ‘thermo-industrial revolution’ of the mid-19th century (see Wootton, 2015) to now exceed 410 ppm, rising at ~0.25%/year. That compares with a rate rise of about 0.005%/year between ~8 ka BP and 1750 CE (Figure 1). An even sharper rise in atmospheric methane is recorded (see Ghosh et al., 2015), now exceeding 1700 ppb and rising at 0.5%/year over the past century, compared with a rate of <0.001%/yr between ~5 ka BP and 1750 CE. (Figures 1 and 2). At the same time there has been an approximate doubling in NO_x levels and of the surface nitrogen and phosphorus cycles, a greater than order-of-magnitude increase in erosion and sediment transport (Cooper et al., 2018), a marked increase in species extinctions and bio-invasions, and an array of other changes, some novel to the Earth System (Waters et al., 2016). We emphasize here the difference between any measurable human impact and a *decisive*

impact, a distinction ignored or minimized by Ruddiman in his commentary.

The geological interpretation of the Anthropocene complements the ESS interpretation (Steffen et al., 2016). The stratigraphic signals, summarized in Waters et al. (2016) (and see Figure 2 herein), allow a post-mid-20th century chronostratigraphic unit to be identified near-globally, by such means as a carbon isotope anomaly now exceeding 2 permil, globally distributed fly ash particles, abundant and globally distributed novel ‘minerals’ and ‘mineraloids’ including aluminium and plastics, novel rock types such as concrete (~500 billion metric tons produced since the mid-20th century), a range of global chemostratigraphic indicators including metals, persistent organic pollutants and artificial radionuclides such as plutonium and ‘bomb spike’ radiocarbon, and a diversity of biostratigraphic signals arising from extinctions, local extirpations, bio-invasions and agriculturally modified organisms.

These signals are also, and in this case unambiguously, anthropogenic – but they have produced a distinctly different (and still diverging) Earth System from that of the Holocene, and this is reflected in a distinct preserved global stratal archive separable from that of the Holocene. These signals, and their significance, are given little weight in Ruddiman’s analysis, and not illustrated in his Figure 1 (which suggests, for instance, that the rate of growth of atmospheric CO₂ has stabilized since the Iron Age, completely omitting its explosive growth from the mid-20th century, see above). Instead, Ruddiman offers comparisons of carbon emissions from deforestation before and after 1950 CE as evidence for the scale of earlier human modification to the planet. His figures simply compare the ~400 GtC emissions from deforestation over 8000 years (average 0.05 GtC/yr) with ~75 GtC from 1950 to 2005 CE (average 1.36 GtC/yr). This masks the great increase in rate of emissions from deforestation since 1950 CE, and completely ignores the even more

significant contribution of carbon emissions from combustion of fossil fuels of ~ 300 GtC since 1860 CE (Houghton, 2007).

Ruddiman asks the question: how can the significant pre-industrial anthropogenic signals from deforestation, mammal extinctions and so on be excluded from the Anthropocene, to the extent that locally the terms are conflated, as in the ‘Anthropocene Working Group’ (p.1) and ‘pre-Anthropogenic time’ (p. 9)? The answer is ‘very easily’, as Anthropocene as defined stratigraphically should *not* be equated with ‘anthropogenic’. The Anthropocene, we stress, is not synonymous with anthropogenic activity. Ruddiman’s conflation of ‘Anthropocene’ with ‘anthropogenic era’ does not recognize this important point, nor does it recognize the developing understanding of the Anthropocene is as a potential epoch, a more modest unit than an era (Waters et al., 2016). Had Paul Crutzen used a different term in 2000, not including an ‘anthropos’, then both the Earth System meaning and justification, and the stratigraphic integrity, of the term would have remained exactly the same, but the conflation of meaning may not have arisen. Equally, had the post-mid-20th century changes we associate with the Anthropocene been produced not by human actions but by, say, volcanoes or a meteorite strike, then the justification and meaning of the Anthropocene both in ESS terms and stratigraphically would also have remained similarly valid. The Anthropocene as an ESS and a chronostratigraphic unit recognizes dramatic changes to the Earth System, using the same criteria that delineates any other previous epoch – it just so happens that the cause is humans this time, rather than some other forcing factor.

The pattern of increasing CO₂ with time over the past 8000 years has small fluctuations superimposed upon it, some of which have also been suggested to be due to human activity, though such attributions are becoming increasingly questioned. A small dip in the Little Ice Age

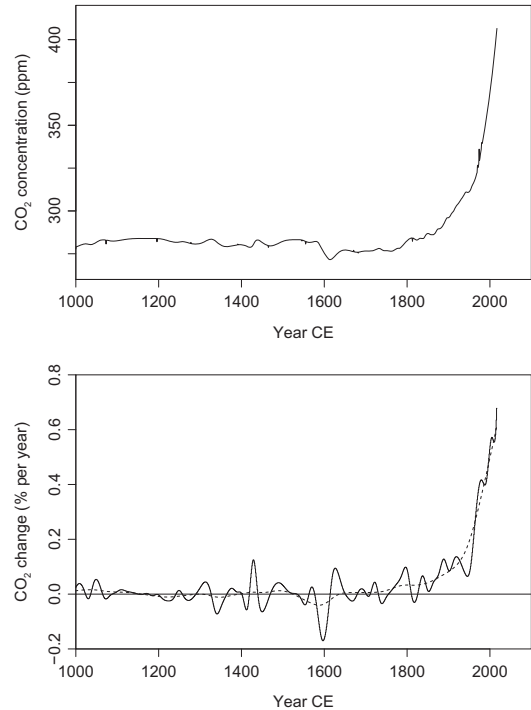


Figure 3. Atmospheric carbon dioxide concentrations and rate of change of the past 1000 years; for data sources see Figure 1.

(1450–1850 CE) (Figure 2), translates to a significant dip in the rate of change (% change/year) in CO₂ (Figure 1). In Figure 3 we focus on that dip in CO₂ in the Little Ice Age, by displaying the rate of change in CO₂ for the past 1000 years. The CO₂ dip (Figure 2) resolves as a succession of alternating low and ‘normal’ CO₂ values (Figure 3). It had been suggested that one of these low values (around 1620 CE, termed the ‘Orbis’ event) – a drop of about 10 ppm – was due to the recovery of forests following depopulation of the North American interior (Lewis and Maslin, 2015). However, examining the various low CO₂ levels during the Little Ice Age, Rubino et al. (2016) found them to be associated with elevated levels of carbonyl sulphide, and thus more likely to be associated with a decrease rather than an increase in primary production. The cause of the decreased

production was most likely the extra cooling associated with minimal solar activity during the Little Ice Age (Rubino et al., 2016). Extremes of cooling during this period were associated with both large sunspot minima (Steinhilber et al., 2012) and large volcanic eruptions (Sigl et al., 2015; see also discussion in Zalasiewicz et al., 2015).

III The formal chronostratigraphic rules reject the pre-industrial anthropogenic signals

The rules do not at all exclude or reject pre-industrial anthropogenic signals, though the current AWG analysis places these signals in the Holocene for the reasons given above. We see no reason why this in any way diminishes or downgrades their considerable inherent importance as precursors or a prelude to later changes we adduce to the Anthropocene, or regarding their significance to the Earth System. In terms of intrinsic value or significance, they are not worse placed in the Holocene than they would be in the Anthropocene. The Holocene/Anthropocene boundary would, if eventually formalized, simply be a rung within a geological time framework, as for every other geological time unit. And, that framework has only been designed to allow Earth's complex history to be placed within a widely understood, precise and stable temporal context.

Indeed, stratigraphic practice and rules encourage recognition of local or regional signals as formal stratigraphic units, such as the Land-Mammal Ages, that are extremely important and useful at sub-global scales and can also be valuable at global scales when adequate correlations are established (Woodburne, 2004, 2006). For example, the North American Land Mammal Ages (NALMAs) and the South American Land Mammal Ages were defined solely by recognizing biostratigraphic changes confined to the respective continents, but are also extremely valuable in recognizing temporal

equivalence of strata that occur on the two continents. Also, defining regional stratigraphic units is an effective way of recognizing the step-wise changes that, when looked at over much longer time perspectives, appear to be gradual transformations within and even across epochs. In this respect, the two most recent land-mammal ages defined for North America highlight the successively more intensive human impacts that were associated with first entry into the Americas (the Santarosean NALMA), then the entry and spread of European immigrants (Saintagustinean NALMA) (Barnosky et al., 2014). Importantly, such subdivisions do not contradict definitions of epochs – the Santarosean in fact begins in the Pleistocene and ends in the Holocene – but rather they recognize a finer level of detail than is appropriate for defining epochs. And of course such independent subdivisions of time need not be geologically or stratigraphically based—from anthropology, examples also abound, such as Palaeolithic, Mesolithic and Neolithic.

The key factor for recognizing an Anthropocene Epoch is that chronostratigraphical boundaries by definition must be based upon signals that are as near globally synchronous as possible (so that most phenomena, which are diachronous to various degrees, can be more easily ordered and analysed with reference to them), and that the stratigraphically stacked units below and above a series boundary be reasonably distinguishable from each other, by virtue of some characteristic combination of physical, chemical and biological traces. Usually this means that that the respective units represent some kind of distinct dynasty within Earth history. Such a boundary allows rates and processes to be systematically compared between the intervals of time that we assign to the Holocene and the Anthropocene, but – as with all other geological boundaries – in no way puts a barrier between the two intervals of time so defined, any more than there is a 'barrier' between the Pleistocene and Holocene, or between the 19th and the 20th centuries.

Abundant stratigraphic evidence now supports our contention that an Anthropocene beginning ~1950 CE would define a unit as clear and distinct as any in the geological record. At the same time, we emphasize, this marker does not in any sense ‘reject’ or minimize the importance of prior signals. In the Geological Time Scale, whether a particular phenomenon lies above or below a chronostratigraphic boundary has no significance to its inherent or perceived worth or significance. For instance, the Silurian is a period/system separate from the Ordovician because of a brief but intense glaciation and its collapse, a concomitant steep fall and rise in sea level, the inception of marine anoxia, and two associated closely-spaced bursts of mass extinction. The chronostratigraphic Ordovician–Silurian boundary reflects none of these large events, but rather a later trivial event *but* one that is widely traceable and thought to be near-synchronous – the appearance and spread of a distinctive species of plankton (Zalasiewicz and Williams, 2014). This pragmatic boundary-defining decision in no way ‘rejected’ any of the period-changing events; in fact the stratigraphic marker gives temporal meaning to other events.

Chronostratigraphic boundaries therefore do not ‘accept’ or ‘reject’ any given phenomenon: rather they provide a framework that allow all geologically significant phenomena to be placed within a context of space and time – and therefore for these phenomena to be better understood.

IV Classical chronostratigraphic terminology is little used in scientific study of geologically recent phenomena, and therefore an informal and flexible ‘anthropocene’ is preferable to a precisely defined and formal Anthropocene

Classical chronostratigraphic terminology, used to construct the Geological Time Scale, is

primarily used by and constructed for geologists, but is of course available to all who wish to use it. Equally, there is no compulsion for anyone (not even geologists) to use it in any instance where it is not considered necessary. Nevertheless, it is widely used (essentially universally by geologists) as it affords an effective means of arranging and communicating a wide range of phenomena within time and space on Earth.

Key to its importance is the precise and unambiguous definition of its component units, so that (say) the Jurassic System used by one scientist is the same as the Jurassic System used by another. And, as these are time units, their boundaries must be defined as precisely as possible. Otherwise, using them would cause ambiguity and confusion.

It is true that palaeoceanographers and paleoclimate scientists working on the younger part of the geological record may have little need for units of the Geological Time Scale when comparing deep ocean records around the world. Their time scale is provided by MISs, which for the Quaternary are numbered from MIS 103 to MIS 1 (Lisiecki and Raymo, 2005), with subdivisions being available for the last 28 of these (Railsback et al., 2015). But constructing these isotopic records is both time-consuming and expensive, and not all deep ocean sediments are amenable to high-precision astrochronology, of which marine isotope stratigraphy is one kind. The reality is that many deposits around the world are not suitable for high-precision dating, and this is true of most sediments deposited on the continental shelves and on land, at least those extending beyond the ~50 ka reach of radiocarbon dating. The scientists studying these more chronologically challenging deposits, and their contained fossils and climate indicators, have no choice but to use the more accommodating units of the Geological Time Scale, and so too must the deep ocean paleoclimate community if it wishes to communicate with these other scientists. The International

Ocean Discovery Program (IODP), and its predecessors including the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP), continues to supply the deep ocean community with sediment cores from around the world's oceans for its climate research. Yet the IODP continues a long tradition of using the Geological Time Scale for its cored sediment, and a cursory glance through any IODP/ODP/DSDP publication will attest to its complete reliance upon this 'classical stratigraphic approach'.

When the base of the Pleistocene Series was lowered in 2009 to align with that of the newly defined Quaternary System, dated at 2.58 Ma (Gibbard and Head, 2010; Gibbard et al., 2010), it was the culmination of a long and at times fraught process in which the Quaternary had to fight for its very existence (Head and Gibbard, 2015). It is hard to accept that practising scientists were 'not paying much attention' when the scientific press was reporting extensively on developments (e.g. Kerr, 2008). Moreover, a review of the literature shows that, in a matter of years, the Pleistocene was being used with its new definition almost without exception.

It is true that Quaternary stage names have not been used frequently in the literature (although the Calabrian Stage has been cited 1307 times in the Web of Science), but that is because the tradition in the Quaternary is to use subseries names, such as Middle Pleistocene, for which there are 4742 citations in the Web of Science. This compares with just 478 citations for the Aalenian Stage of the Jurassic for example (figures as of 6 August 2018). It might be added that the 'Ionian' and 'Tarantian' are not formal stage names, contrary to Ruddiman's claims, so would not be expected to be cited much. In general, citation metrics give a clear picture of the utilization of formal time units in the recent geological past, and robustly contradict the claim that subdivisions of the Geological Time Scale are 'largely disregarded today

among scientists working in the younger geologic record'.

In recent geological time – the Quaternary and especially the Holocene – stratigraphy is arguably more, and not less, widely used by scientists other than geologists. The journal *The Holocene*, for instance, ranges across ecology, geomorphology, archaeology, climatology, oceanography and many other disciplines as well as geology. And the Holocene Epoch itself, with its recent formally ratified subdivision, is an example of 'classical' stratigraphy following long-time mainstream scientific practice, and rendering it more useful.

Since the 1970s, an informal tripartite subdivision of the Holocene into 'early', 'mid' or 'middle' and 'late' parts has been widespread in the literature, though inconsistently applied, with the early/mid boundary ranging from 9 to 6 ka BP, and the mid/late boundary ranging from 5 to 2.5 ka BP in different studies (Walker et al., 2012). This imprecision hindered communication, and therefore Walker et al. (2012) proposed that the tripartite classification be formalized, with boundaries set at short-lived but globally correlatable events dated at 8.2 ka and 4.2 ka, and defined within Greenland ice and a speleothem in India respectively.

A formal proposal based on Walker et al. (2012) has recently been approved by both the Subcommittee on Quaternary Stratigraphy (SQS) and International Commission on Stratigraphy (ICS), and ratified by the Executive Committee of the International Union of Geological Sciences (IUGS) (Figure 4; Walker et al., 2018). It formalizes and gives precise unambiguous meaning to the widely used Early, Middle and Late subepochs (with their chronostratigraphic counterparts the Lower, Middle and Upper subseries), by providing definitions of their lower boundaries. These subdivisions equate with the new Greenlandian, Northgripian and Meghalayan ages/stages (representing the necessary baseline hierarchical level in geological time nomenclature). Regardless of

Eonothem & Eon	Erathem & Era	System & Period	Series & Epoch	Subseries & Subepoch	Stage & Age	GSSP
Phanerozoic (pars)	Cenozoic (pars)	Quaternary	Anthropocene		Unnamed	present
			Holocene	Upper & Late	Meghalayan	mid-20th century
				Middle	Northgrippian	4250 years b2k
				Lower & Early	Greenlandian	8236 years b2k
			Pleistocene	Upper & Late	Unnamed	11,700 years b2k
				Middle	Unnamed	~126 ka
				Lower & Early	Calabrian	~0.773 Ma
					Gelasian	1.80 Ma
						2.58 Ma

Figure 4. The Quaternary time scale as currently preferred by the Anthropocene Working Group, with the Anthropocene shown at the rank of series/epoch. Black type indicates names officially approved and ratified by the International Commission on Stratigraphy (ICS)/Executive Committee of the International Union of Geological Sciences (IUGS EC). Names in grey type have yet to be sanctioned officially by ICS/IUGS EC. Note that if the Anthropocene is proposed as depicted here, then one or more stages/ages corresponding to the Anthropocene should also be proposed for approval. Golden spikes = approved/ratified GSSPs; grey spikes = GSSPs awaiting submission or approval.

whether these will be used following subepoch/subseries or age/stage nomenclature, they now unambiguously represent specific time intervals, based upon brief, significant climate perturbations of global reach. We note that these newly formalized subdivisions are not based on any of the anthropogenic changes which slowly unfolded through Holocene time (as outlined in Ruddiman, 2018, Figure 1) – but, they do now allow those anthropogenic changes, and also other Holocene trends (e.g. Waters et al., 2016, Figures 1 and 3–6) to be placed and discussed within a precise and durable time framework. Moreover, formalization of the Meghalayan Stage does not contradict or exclude establishment of an Anthropocene with a mid-20th century start, but would preclude an ‘early Anthropocene’ option for a chronostratigraphic unit commencing before 4.2 ka.

Finally, we emphasize that the subdivision of the Holocene arose from the practicing community. It was not imposed by bureaucratic fiat, but

formalized merely to make the terminology more useful. The wide currency of these terms, even before formalization in July 2018, is again reflected by the Web of Science citation metrics: 5982 and 8648 citations for the terms ‘Early Holocene’ and ‘Late Holocene’ respectively, compared for example with 7478 citations for the term ‘Silurian’ (figures as of 6 August 2018).

The Anthropocene is currently studied by the AWG with regards to making a practical proposal to the same bodies (SQS/ICS and IUGS) following the same requisite regulations for its formalization as that for the Holocene, and is being considered with the same logic in mind. The boundary level now pursued as regards a potential GSSP and auxiliary stratotypes lies in the mid-20th century (Zalasiewicz et al., 2017; Waters et al., 2018), and so does not crosscut or negate the just-ratified Holocene subdivision (as an ‘early Anthropocene’ chronostratigraphical boundary would), but would, if accepted,

complement this subdivision. The resulting Anthropocene geological time unit, being so sharply and clearly distinct from the preceding Holocene (Figures 1 and 2), would reflect a real and critically important phenomenon of both Earth System process and chronostratigraphic composition. Furthermore, many of the component changes of the chronostratigraphic Anthropocene reflect a shift in the Earth System that may well be effectively irreversible for many millennia to come, during which, for instance, the rapid rise in CO₂ alone – even with the lowest projections of its trajectory – will influence climate and sea level, and so the character of stratal successions, for many millennia (Clark et al., 2016; see Figure 2 herein).

Thus, precise definition and characterization of a chronostratigraphic Anthropocene would, in reflecting a real and distinct phenomenon and facilitating clear and unambiguous communication, be of use to both science and the rest of society.

V Conclusion

A precisely defined and formalized chronostratigraphic Anthropocene, if ultimately agreed and ratified, need not exclude use of a more informal ‘anthropocene’ in the meaning of Ruddiman, which conveys a quite different concept: that of the time when human impact became significant, the definition of which can vary from author to author and the recognition of which can vary from place to place to reflect both individual interpretation of significance and the diachronous spread of human influence (see Edgeworth et al., 2015). We suggest that, to avoid needless confusion, it would make sense not to use the same term ‘Anthropocene’ (or ‘anthropocene’) for these very different concepts.

Ruddiman’s concept is an important and valid one, but *does not* exclude or displace a chronostratigraphic Anthropocene, particularly given that a chronostratigraphic Anthropocene

was exactly the meaning intended by Crutzen and Stoermer (2000) and Crutzen (2002) when they proposed the term – and thus can claim to have priority. Crutzen’s concept has survived testing in the stratal record and in accordance with the rules of formal stratigraphic nomenclature (Waters et al., 2016). It possesses thus geological as well as Earth System reality and distinctiveness and – regardless of whether or not it is formalized in the near future – this warrants retention of the term Anthropocene for this specific concept.

Ruddiman’s concept has parallels with both established archaeological time nomenclature (e.g. Neolithic, Bronze Age, Iron Age) which are inherently diachronous time units, and specifically with the more recent concept of the archaeosphere (Edgeworth, 2013), denoting anthropogenically modified ground to contrast with the underlying ‘natural’ ground. The archaeosphere, indeed, is directly translatable into geological stratigraphy – but as a material-based litho- or biostratigraphic unit, which may have diachronous boundaries, rather than as a chronostratigraphic one. The Palaeoanthropocene (Foley et al., 2013) has also been suggested as a time interval to encompass the long and important interval of gathering pre-industrial human impact.

Yet other time terms have been suggested to highlight specific aspects of human impact, including the Capitalocene (Haraway, 2015) to indicate a dominant political/economic driver, the Homogenocene (Samways, 1999) to reflect the enormous impact of human-driven species invasions, or the Myxocene (Pauly, 2010) to represent changes to the ocean state. There is no shortage of available time terms, encompassing specific and variably overlapping concepts relating to anthropogenic modification of the Earth. Hence, there seems little risk of the scale and long duration of human impact on the environment being overlooked or minimized.

We thus suggest that in proposing his ‘three flaws’, Ruddiman is defending a concept that is

perfectly valid, and for which terms have already been proposed. However, this concept is *not* the same as that of the Anthropocene as a potential unit of the Geological Time Scale, which is defined according to chronostratigraphic criteria and reflects profound and ongoing Earth System change.

In making this distinction, our response provides a re-articulation of the critical importance, as regards the definition of a formal geological time unit, of emphasizing the differences between chronostratigraphy and lithostratigraphy, between records of global and of local processes, between consequence and cause, between identification and explanation, between pragmatic and ideal solutions, and between the technical task of the AWG and a common desire to elaborate narratives of planetary phenomena. Confusion between these complementary ‘alternatives’, which our response tries to clarify, seems to be the source of much of the disagreement, among both scientists and the interested public, over what formalizing a usable Anthropocene geological time unit necessarily entails, and what that formalization would mean to a diversity of studies of the present and geologically recent past. When the conflation of widely varying concepts over how the word ‘anthropocene’ should be used is stripped away, the chronostratigraphic Anthropocene retains its distinctiveness, validity and importance.


Declaration of conflicting interests


The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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References

- Alamgir M, Campbell MJ, Sloan S, et al. (1999) Economic, socio-political and environmental risks of road development in the tropics. *Current Biology* 27(20): R1130–R1140.
- Barnosky AD, Holmes M, Kirchholtes R, et al. (2014) Prelude to the Anthropocene: two new North American Land Mammal Ages (NALMAs). *The Anthropocene Review* 1(3): 225–242.
- Broecker WS and Stocker TE (2006) The Holocene CO₂ rise: anthropogenic or natural? *Eos, Transactions American Geophysical Union* 87(3): 26–27.
- Broecker WS, Clark E, McCorkle DC, et al. (1999) Evidence for a reduction in the carbonate ion content of the deep sea during the course of the Holocene. *Paleoceanography* 14(6): 744–752.
- Ciais P, Sabine C, Bala G, et al. (2013) Carbon and other biogeochemical cycles. In Stocker TF, Qin D, Plattner G-K, et al. (eds) *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 465–570.
- Clark PU, Shakun JD, Marcott SA, et al. (2016) Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change* 6(4): 360–369.
- Cooper AH, Brown TJ, Price SJ, et al. (2018) Humans are the most significant global geomorphological driving force of the 21st century. *The Anthropocene Review* 5(3): 222–229.
- Crutzen PJ (2002) Geology of mankind. *Nature* 415(6867): 23.
- Crutzen PJ and Stoermer EF (2000) The Anthropocene. *Global Change Newsletters* 41: 17–18.
- Dlugokencky EJ, Lang PM, Crotwell AM, et al. (2018a) Atmospheric methane dry air mole fractions from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network, 1983–2017, Version: 2018-08-01.
- Dlugokencky EJ, Lang PM, Mund JW, et al. (2018b) Atmospheric carbon dioxide dry air mole fractions from the NOAA ESRL Carbon Cycle Cooperative

- Global Air Sampling Network, 1968–2017, Version: 2018-07-31.
- Edgeworth M (2013) Scale. In: Graves-Brown P, Harrison R and Piccini A (eds) *The Oxford Handbook of the Archaeology of the Contemporary World*. Oxford: Oxford University Press, Chapter 27.
- Edgeworth M, deB Richter D, Waters C, et al. (2015) Diachronous beginnings of the Anthropocene: the lower bounding surface of anthropogenic deposits. *The Anthropocene Review* 2(1): 33–58.
- Ellis EC, Klein Goldewijk K, Siebert S, et al. (2010) Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography* 19(5): 589–606.
- Foley SF, Gronenborn D, Andreae MO, et al. (2013). The Palaeoanthropocene: the beginnings of anthropogenic environmental change. *Anthropocene* 3: 83–88.
- Fuller DQ, van Etten J, Manning K., et al. (2011) The contribution of rice agriculture and livestock pastoralism to prehistoric methane levels: an archaeological assessment. *The Holocene* 21(5): 743–759.
- Ganopolski A, Winkelmann R and Schellnhuber HJ (2016) Critical insolation–CO₂ relation for diagnosing past and future glacial inception. *Nature* 529(7585): 200–203.
- Ghosh A, Patra PK, Ishijima K, et al. (2015) Variations in global methane sources and sinks during 1910–2010. *Atmospheric Chemistry and Physics* 15: 2595–2612.
- Gibbard PL and Head MJ (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 PL, Head MJ, Walker MJC, et al. (2010) Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *Journal of Quaternary Science* 25(2): 96–102.
- Goldewijk KK, Beusen A and Janssen P (2010) Long-term dynamic modelling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene* 20(4): 565–573.
- Grooten M and Almond REA (2018) *Living Planet Report 2018: Aiming Higher*. Gland, Switzerland: WWF.
- Haraway D (2015) Anthropocene, Capitalocene, Plantationocene, Chthulucene: making kin. *Environmental Humanities* 6(1): 159–165.
- Head MJ and Gibbard PL (2015) Formal subdivision of the Quaternary system/period: past, present, and future. *Quaternary International* 383: 4–35.
- Houghton RA (2007) Balancing the global carbon budget. *Annual Review of Earth and Planetary Sciences* 35: 313–347.
- Kerr RA (2008) A time war over the period we live in. *Science* 318(5862): 402–403.
- Koch PL and Barnosky AD (2006). Late Quaternary extinctions: state of the debate. *Annual Review of Ecology, Evolution, and Systematics* 37: 215–250.
- Lewis SL and Maslin MA (2015) Defining the anthropocene. *Nature* 519(7542): 171–180.
- Lisiecki LE and Raymo ME (2005) A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography* 20(1): 522–533.
- Loulergue L, Schilt A, Spahni R, et al. (2008) Orbital and millennial-scale features of atmospheric CH₄ over the past 800,000 years. *Nature* 453: 383–386.
- MacFarling Meure C, Etheridge D, Trudinger C, et al. (2006) The Law Dome CO₂, CH₄ and N₂O ice core records extended to 2000 years BP. *Geophysical Research Letters* 33(14): L14810.
- Monnin E, Steig EJ, Siegenthaler U, et al. (2004) Evidence for substantial accumulation rate variability in Antarctica during the Holocene, through synchronization of CO₂ in the Taylor Dome, Dome C and DML ice cores. *Earth and Planetary Science Letters* 224(1–2): 45–54.
- Past Interglacial Working Group of PAGES (2016) Interglacials of the last 800,000 years. *Reviews of Geophysics* 54(1): 162–219.
- Pauly D (2010) *5 Easy Pieces: The Impact of Fisheries on Marine Systems*. Washington, DC: Island Press.
- Pongratz J, Caldeira K, Reick CH, et al. (2011) Coupled climate–carbon simulations indicate minor global effects on wars and epidemics on atmospheric CO₂ between AD 800 and 1850. *The Holocene* 21(5): 843–851.
- Railsback LB, Gibbard PL, Head MJ, et al. (2015) An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. *Quaternary Science Reviews* 111: 94–106.
- Rubino M, Etheridge DM, Trudinger CM, et al. (2016) Low atmospheric CO₂ levels during the Little Ice Age due to cooling-induced terrestrial uptake. *Nature Geoscience* 9(9): 691–694.
- Ruddiman WF (2003) The atmospheric greenhouse era began thousands of years ago. *Climatic Change* 61(3): 261–293.

- Ruddiman WF (2013) The Anthropocene. *Annual Review of Earth and Planetary Sciences* 41: 45–68.
- Ruddiman WF (2018) Three flaws in defining a formal ‘Anthropocene’. *Progress in Physical Geography: Earth and Environment* 42(4): 451–461.
- Ruddiman WF, Ellis EC, Kaplan JO, et al. (2015) Defining the epoch we live in: Is a formally designated “Anthropocene” a good idea? *Science* 348(6230): 38–39.
- Ruddiman WF, Fuller DQ, Kutzbach JE, et al. (2016) Late Holocene climate: natural or anthropogenic? *Reviews of Geophysics* 54(1): 93–118.
- Samways M (1999) Translocating fauna to foreign lands: here comes the Homogenocene. *Journal of Insect Conservation* 3(2): 65–66.
- Schmidt GA, Shindell DT and Harder SL (2004) A note on the relationship between ice core methane concentrations and insolation. *Geophysical Research Letters* 31(23): L23206.
- Sigl M, Winstrup M, McConnell JR, et al. (2015) Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature* 523(7562): 543–549.
- Singarayer JS, Valdes PJ, Friedlingstein P, et al. (2011) Late Holocene methane rise caused by orbitally controlled increase in tropical sources. *Nature* 470(7332): 82–85.
- Skinner LC, Fallon S, Waelbroeck C, et al. (2010) Ventilation of the deep Southern Ocean and deglacial CO₂ rise. *Science* 328(5982): 1147–1151.
- Steffen W, Crutzen PJ and McNeill JR (2007) The Anthropocene: are humans now overwhelming the great forces of Nature? *Ambio* 36(8): 614–621.
- Steffen W, Leinfelder R, Zalasiewicz J, et al. (2016) Stratigraphic and Earth System approaches in defining the Anthropocene. *Earth’s Future* 4(8): 324–345.
- Steffen W, Sanderson A, Tyson PD, et al. (2004) *Global Change and the Earth System: A Planet under Pressure*. The IGBP Book Series. Berlin: Springer-Verlag.
- Steinhilber F, Abreu JA, Beer J, et al. (2012) 9,400 years of cosmic radiation and solar activity from ice cores and tree rings. *Proceedings of the National Academy of Science* 109(16): 5967–5971.
- Studer AS, Sigman DM, Martinez-Garcia A, et al. (2018) Increased nutrient supply to the Southern Ocean during the Holocene and its implications for the pre-industrial atmospheric CO₂ rise. *Nature Geoscience* 11(10): 756.
- Syvitski JPM and Kettner A (2011) Sediment flux and the Anthropocene. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 369(1938): 957–975.
- Walker MJC, Berkelhammer M, Björck S, et al. (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(7): 649–659.
- Walker M, Head MJ, Berkelhammer M, et al. (2018) Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries. *Episodes* 41(4): 213–223.
- Waters CN, Zalasiewicz J, Summerhayes C, et al. (2016) The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* 351(6269): 137.
- Waters CN, Zalasiewicz J, Summerhayes C, et al. (2018) Global Boundary Stratotype Section and Point (GSSP) for the Anthropocene series: where and how to look for potential candidates. *Earth-Science Reviews* 178: 379–429.
- Woodburne MO (2004) *Late Cretaceous and Cenozoic Mammals of North America*. New York: Columbia University Press.
- Woodburne MO (2006) Mammal ages. *Stratigraphy* 3: 229–261.
- Wootton D (2015) *The Invention of Science: A New History of the Scientific Revolution*. New York: HarperCollins.
- Zalasiewicz J and Williams M (2014) The Anthropocene: a comparison with the Ordovician-Silurian boundary. *Rendiconti Lincei – Scienze Fisiche e Naturali* 25(1): 5–12.
- Zalasiewicz J, Waters CN, Barnosky A, et al. (2015) Colonization of the Americas, ‘Little Ice Age’ climate, and bomb-produced carbon: Their role in defining the Anthropocene. *The Anthropocene Review* 2(2): 117–127.
- Zalasiewicz J, Waters CN, Head MJ, et al. (2018) The geological and Earth System reality of the Anthropocene: reply to Bauer AM and Ellis EC The Anthropocene Divide: Obscuring understanding of social-environmental change. *Current Anthropology* 59(2): 220–223.
- Zalasiewicz J, Waters CN, Williams M, et al. (2019) *The Anthropocene as a Geological Time Unit*. Cambridge: Cambridge University Press.
- Zalasiewicz J, Waters CN, Wolfe AP, et al. (2017) Making the case for a formal Anthropocene: an analysis of ongoing critiques. *Newsletters on Stratigraphy* 50(2): 205–226.