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Article:

The proposed Anthropocene Epoch/Series is underpinned by an extensive array of mid-20th century stratigraphic event signals

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ABSTRACT: The extensive array of mid-20th century stratigraphic event signals associated with the 'Great Acceleration' enables precise and unambiguous recognition of the Anthropocene as an epoch/series within the Geological Time Scale. A mid-20th century inception is consistent with Earth System science analysis in which the Anthropocene term and concept arose, and would reflect the reality that our planet has sharply exited the range of natural variability characterizing the Holocene Epoch/Series, which the Anthropocene would therefore terminate. An alternative, recently proposed 'geological event' approach to the Anthropocene is primarily an interdisciplinary concept, encompassing historical and socio-cultural processes and their global environmental impacts over a diachronous timeframe that extends back at least many millennia. Resembling more closely a geological *episode* than an *event*, it would decouple the Anthropocene from its chronostratigraphic delineation and association with an abrupt planetary perturbation; but separately defined and differently named it might be usefully complementary. We recommend a clear separation of *epochs*, *events*, and *episodes*. An *epoch* is a formal subdivision of the geological time scale, and its correlation may be assisted by one or more *events*; an *event* is usually, and particularly in the Quaternary, a brief incident or perturbation with a sedimentary expression; whereas an *episode* is a longer, internally complex time interval that may include several events and even extend across several epochs.

KEYWORDS: Earth System science; Quaternary; epoch; episode; event; chronostratigraphy

Introduction

Gibbard *et al*. (2022) in the *Journal of Quaternary Science* (*JQS*) recently proposed that the Anthropocene be considered a prolonged, diachronous 'geological event' encompassing all *transformative* impacts of humans upon Earth, rather than a formally defined chronostratigraphic unit. The proposal restated arguments published by the same authors in the journal *Episodes* (Gibbard *et al*., 2021), a repetition justified on the grounds that '*Episodes* might not be widely read by Quaternary scientists'. We have submitted a response to the earlier article (Head *et al.*, *in press*) and have prepared a wider analysis of the event concept for publication elsewhere (Waters *et al.*, *submitted*). Here, in like manner, we briefly reiterate for the *JQS* readership our response to their arguments.

The late Paul Crutzen, working within the Earth System science community, conceptualized the Anthropocene as a geological time interval during which human impacts propelled our planet far beyond the natural variability of the Holocene Epoch. Crutzen suggested that its beginning might be placed at the late 18th century onset of the Industrial Revolution in Europe (Crutzen and Stoermer, 2000; Crutzen, 2002) but noted (pers. comm. to M. Meybeck, 2003) that a proposed mid-20th century beginning (Meybeck, 2001) might work equally well. Since 2009, the Anthropocene Working Group (AWG) of the Subcommission on Quaternary Stratigraphy (SQS) has been formally testing this concept chronostratigraphically. They recognised the key geological significance of a major mid-20th century upturn in the rate and magnitude of numerous global socio-economic indicators and Earth System trends that had been identified by the Earth System science community, and termed the Great Acceleration (Steffen *et al*., 2004, 2007, 2015; Head *et al*., 2021a). Many of the Great Acceleration drivers have already produced clear signatures in geological records of the mid-20th century on a global scale.

The plentiful and growing evidence that Great Acceleration geological signals support the formal definition of an Anthropocene epoch/series has been extensively documented (Waters *et al.*, 2016; Zalasiewicz *et al.*, 2017, 2019, 2020; Syvitski *et al.*, 2020; Head *et al.*, 2021a). On the basis of this evidence, a non-binding vote of the AWG in 2016 supported a chronostratigraphically defined Anthropocene at the rank of series/epoch (Zalasiewicz *et al.*, 2017). A supermajority binding vote in 2019 reaffirmed that the Anthropocene should become a formal chronostratigraphic/geochronologic unit within the international Geological Time Scale (GTS), its base aligned with stratigraphic signals dating to the mid-20th century (AWG, 2019; Fig. 1). This process now continues with the analysis of 12 reference sections from which one will be proposed as the Global boundary Stratotype Section and Point (GSSP) (Waters *et al.*, 2018; Head *et al.*, 2021a). Such chronostratigraphic characterization of the Anthropocene would align with the working Earth System science definition of the term (Steffen *et al.*, 2016). The Anthropocene as such effectively represents a *planetary response* to human driving forces. Its accompanying geological signals are essentially simultaneous and worldwide, and would be just as significant if caused by an agency other than humans. The stratigraphic signals cluster closely around the mid-20th century, are supported by observational and instrumental records, and allow practical chronostratigraphic precision to within a decade or less.

Despite the wealth of data favouring a chronostratigraphic Anthropocene, Gibbard *et al*. (2021, 2022) proposed an alternative interpretation: that the Anthropocene be considered a geological 'event' and not a formally defined unit of the GTS. They conceptualized this 'Anthropocene event' as a highly time-transgressive and flexibly interpreted unit incorporating *transformative* human cultural practices, extending as far back as the Late Pleistocene megafaunal extinctions, and yet facilitating '*robust stratigraphic characterization*' (Gibbard *et al.*, 2021, p. 1). Their proposal prompts a novel appraisal of the Anthropocene concept, and anthropogenic impacts generally, through the lens of geological event stratigraphy, and has stimulated discussion of how events are recognised and used in stratigraphy (Waters *et al*., *submitted*). Here we focus on: the characterization of the Anthropocene by Gibbard *et al*. (2021, 2022); the question of whether a chronostratigraphic Anthropocene should be at age/stage or series/epoch level; the *event* interpretation by

Gibbard *et al*. (2021, 2022) *vis-à-vis* the usual meaning of events in geology and particularly within the Quaternary; whether an 'Anthropocene event' may be geologically robust; and how this suggested conceptualization might relate to an Anthropocene epoch.

The Anthropocene as a geological epoch

Gibbard *et al*. (2021, 2022) stated that because significant anthropogenic influence on the stratigraphic record extends over millennia (perhaps over fifty millennia; their fig. 1), such influence should be reflected in the definition of the Anthropocene. This contrasts starkly with the Anthropocene as conceived 'for the current geological epoch' by Paul Crutzen (Crutzen and Stoermer, 2000, p. 17; contra Gibbard *et al*., 2022, p. 3), its use by the Earth System science community, and its subsequent analysis by the AWG. A clear distinction is here made between the protracted, diachronous early record of anthropogenic impacts through the Late Pleistocene and Holocene, which had a relatively small impact on Earth System function, and the much more recent, profound, and abrupt planetary changes to landscape, biosphere and climate that underpin the Anthropocene of chronostratigraphy and Earth System science.

These striking and often irreversible planetary changes, most clearly associated with the 'Great Acceleration', are obscured in figure 1 of Gibbard *et al*. (both 2021 and 2022) and in their text. Our Figure 2 quantifies specific trends in order to show the true magnitudes and rates of change. A large body of observational evidence (Syvitski *et al*., 2020, 2022) shows that human actions from the mid-20th century onwards have driven the Earth System beyond the Holocene envelope of variability and into a new planetary state, the full extent of which will be determined by a combination of ongoing human pressures and planetary feedbacks (Steffen *et al*., 2018). Human- and especially technology-driven changes are already profound as regards their rates (IPBES, 2019; IPCC, 2021) and magnitudes (Waters *et al*., 2016; Head *et al.*, 2021a), producing major impacts on five great Earth spheres – the biosphere, atmosphere, hydrosphere, cryosphere, and the surface of the lithosphere. Direct human perturbation of the biosphere combined with global warming are driving rapid changes in ecosystem function and biological communities (Williams *et al*., 2016, *in press*), with increasing rates of species extinctions since the beginning of the 20th century (Ceballos *et al.*, 2015), severe declines in vertebrate populations from the 20th century onwards (Ceballos *et al*., 2017, 2020; WWF, 2020), unprecedented and irreversible homogenization of once distinct biographic assemblages (Williams *et al*., *in press*), a dramatic increase in a wide range of anthropogenically-derived contaminants, and rapidly increasing global atmospheric surface temperature since 1970 (Sippel *et al*., 2021). The late 20th and early 21st centuries also saw changes in atmospheric circulation and precipitation patterns; warming of the upper ocean, rising sea level and coastal erosion; acidification of the oceans and the spread of oxygen-deficient 'dead zones'; increasingly severe extreme weather events such as heatwaves (terrestrial and marine), tropical cyclones, wildfires, and intense rainfall and flooding; a trajectory towards increasing megadroughts; and wholesale retreat of the cryosphere.

Earth System science analysis clearly indicates a marked change in planetary state from the mid-20th century, and increasing perturbation of oceanic and atmospheric circulation is driving changes in global geochemical, nutrient, sediment and hydrological cycles. The Earth's climate trajectory has very likely escaped from its pacing by Milankovitch (orbital) cycles with consequences that will persist for at least many millennia (Ganopolski *et al*., 2016), while changes to biodiversity and biogeographic assemblages will be even more long-lasting (Williams *et al*., 2015, 2016). The primary drivers of these fundamental changes to the Earth System stem from human impacts, and mostly from their steep post-mid-20th century increase (Syvitski *et al*., 2020, 2022). These observations are all consistent with the Anthropocene as a new epoch in Earth history (Steffen *et al.*, 2016).

Mirroring these observed changes is an extensive array of geological signals in strata from the mid-20th century onwards that provides a stratigraphically robust basis for recognizing the base of the Anthropocene – and hence to support a chronostratigraphic boundary, not replace it (see below). This evidence is abundant, confined to a short time interval, often novel in composition, and global in distribution (Waters *et al*., 2016; Zalasiewicz *et al.*, 2019; Syvitski *et al.*, 2020; Head *et al.*, 2021a).

The suggestion by Gibbard *et al*. (2022) that a formal chronostratigraphically defined Anthropocene would be impractical because it fails to include all significant human impacts is incorrect given that all GSSPs, when viewed at the finest scale, cut indiscriminately through Earth history, as already illustrated for the Meghalayan Stage GSSP (Head *et al.*, 2022). Even so, on practical grounds the base of a formal Anthropocene defined by a close array of mid-20th century stratigraphic signals would be far easier to recognise than a diachronous lower boundary characterised by diffuse anthropogenic signals each requiring interpretation as to its significance in planetary transformation. However, we agree that an *episode* shaped by interdisciplinary characteristics and encompassing these earlier human impacts (Gibbard *et al.*, 2021) could, if appropriately named, be complementary to a formally defined Anthropocene epoch. For instance, archaeological periods, including the Mesolithic, Neolithic, and Bronze Age, are useful because their time-transgressive boundaries accommodate the varying onsets of particular technological developments around the world, as Gibbard *et al*. (2022) note. But this diachroneity is revealed only when a time scale is added. The onset of the Neolithic dates to the latest Pleistocene in the Near East (Ibáñez *et al*., 2018), the Early Holocene in North Africa (Mulazzani *et al*., 2017), and the Middle

Holocene in northern Europe (Nordqvist and Mökkönen, 2017) – these two schemes, one archaeological and the other chronostratigraphic, clearly complement one another.

Any formal chronostratigraphic boundary requires a primary stratigraphic guide that will enable correlation from its GSSP on a global scale. The AWG decided by supermajority vote in 2019 upon the tight array of mid-20th century stratigraphic signals as the primary guide to the proposed Anthropocene epoch (AWG, 2019). Presently favoured (Zalasiewicz *et al*., 2017) is the radiogenic signal generated from fallout produced by above-ground thermonuclear weapons testing, which shows a marked upturn in sedimentary records globally in the early 1950s (Waters *et al*., 2015, 2019). Functionally, this would be analogous to the impact fallout used as the primary guide to the Cretaceous–Paleogene boundary (Molina *et al*., 2006), as both signals are near-isochronous and global in extent. However, Gibbard *et al*. (2022) question whether such a guide would be welcomed by the international geological community given its association with weapons of mass destruction. Here it must be emphasized that the AWG has adopted a scientific approach, not a sociopolitical one, where stratigraphic utility determines the selection of the primary guide. We note that few, if any, of the signals associated with potential definition of a chronostratigraphic Anthropocene have positive connotations.

The Anthropocene as potential stage of the Holocene

The speed and scale of those more recent changes noted above, a large number of which are geologically long-lasting, already irreversible, and rising sharply from the mid-20th century onwards, demonstrate beyond reasonable doubt that conditions characterizing the Holocene Epoch have already ended. To match this, a substantial and highly distinctive stratigraphic record has already accumulated as a material consequence. These changes are far greater than those associated with the temporary climate oscillations used for the tripartite subdivision of the Holocene (Walker *et al*., 2018, 2019), and overall rival or exceed in scale those associated with the Pleistocene–Holocene transition (Waters *et al*., 2016; Syvitski *et al*., 2020; Head *et al*., 2021a). There is therefore an overwhelming case for an Anthropocene epoch and series to succeed the Holocene. Indeed, *not* to recognise the Anthropocene formally in this way would result in the GTS, which inherently reflects major phases of Earth's evolution, in this case departing from observed geological reality. In accordance with required practice, the proposed GSSP for an Anthropocene series/epoch would also define the base of its associated stage/age, which will take the name of the GSSP locality (Salvador, 1994). It would not be subdivided into subseries/subepochs owing to its brief duration to date (Fig. 1).

Event stratigraphy and the Anthropocene

An *event* in geology is informal, and hence cannot comprise one of the hierarchical ranks of units within the International Chronostratigraphic Chart, the basis of the GTS. It refers to a distinct *happening* in time (Salvador, 1994, p. 73), but does not have a counterpart in chronostratigraphic terminology and so has come to refer to both the event itself and its geological expression. *Event stratigraphy* typically refers to the stratigraphic traces of events, whether depositional, erosional or geochemical (Rawson *et al*., 2002). These are not significantly diachronous, and Ager (1973), who introduced the term, specifically valued events for their ability to trace time planes across diachronous boundaries (fig. 7.1 in Ager, 1973; fig. 1 in Head *et al*., 2022). For Ager (1973), and also Salvador (1994, p. 117), the most stratigraphically useful geological events are brief, and essentially instantaneous such as meteorite impacts, tsunami floods, storms that generate tempestites, and volcanic ashfalls, (e.g., Walliser, 1996).

It therefore misleads to suggest (Gibbard *et al*., 2021, 2022) that geological events are time-transgressive by nature, for they have been used as a crucial tool for the event-based recognition of chronostratigraphic boundaries (Salvador, 1994, p. 79). Examples include the 8.2 and 4.2 ka climatic events that serve as primary stratigraphic guides in formally subdividing the Holocene (Walker *et al.*, 2018, 2019). It is the Quaternary application of the event concept that is most relevant to the Anthropocene. An event stratigraphy approach is used to identify and correlate stadial–interstadial oscillations in Greenland ice cores for the Late Pleistocene and Early Holocene (Rasmussen *et al*., 2014). Even those events of relatively long duration, such as Greenland Stadial 1 (GS–1 which is broadly equivalent to the Younger Dryas stadial or 'event'), have abrupt onsets and/or terminations that constitute precise, isochronous reference points for the event stratigraphy (Rasmussen *et al*., 2014, p. 15). In these and other examples (see discussion in Head *et al*., 2022), the conceptualization of geological events for the Quaternary in general is therefore markedly different from the concept employed by Gibbard *et al*. (2021, 2022).

However, the term *event* has over time also been liberally applied to longer-duration and variably diachronous phenomena. The specific examples quoted by Gibbard *et al*. (2021) – the Great Oxidation Event (GOE), the Great Ordovician Biodiversification Event (GOBE), and the Middle–Late Devonian forestation of continents – lasted for tens of millions of years and lie at the extreme end of this spectrum (and indeed, the last of these has to our knowledge not previously been designated as an 'event'). For these phenomena, the term 'episode' (NASC, 2005) not 'event' (Salvador, 1994) is appropriate. The GOE and GOBE are protracted, internally complex and variously diachronous stratigraphic intervals whose status as events has been contested, the former being explicitly categorized as an episode (Shields *et al*., 2022, Poulton *et al*., 2021; see also Servais and Harper, 2018 and Servais *et al*., 2021 regarding the GOBE).

Each such episode typically includes numerous more conventionally understood events – some of which may define or support chronostratigraphic boundaries, as in isotopic events associated with oxygenation now being considered for use in developing a GSSP-based pre-Cryogenian chronostratigraphy (Shields *et al*., 2022). More widely, event stratigraphy is now being increasingly used in defining chronostratigraphic boundaries, as with the carbon isotope anomaly used as the primary marker for the Paleocene–Eocene boundary (Aubry *et al*., 2007), the palaeomagnetic reversal events that are the primary markers for the Neogene–Quaternary (Head, 2019) and Early–Middle Pleistocene boundaries (Suganuma *et al*., 2021), and most famously the bolide event that defines the Cretaceous–Paleogene boundary (Molina *et al*., 2006).

Similarly, the anthropogenic 'event' of Gibbard *et al*. (2021, 2022) is much better conceptualized as a protracted, diachronous *episode* that incorporates the effects of human predation on megafauna, development of agricultural cultivation and deforestation, transfer of species through introduction of colonial trade, and the impacts of the Industrial Revolution. These can be clearly separated from the stratigraphically significant global array of events at or around the mid-20th century level that may be used to support a Holocene–Anthropocene chronostratigraphic boundary (Fig. 1). They include the appearance of novel components such as radionuclides in fallout from atmospheric nuclear testing, pesticides and plastics, marked upturns in concentrations of CO_2, CH_4, heavy metals including Pb, fly ash particulates, black carbon, non-sea-salt-sulfur, accelerated species extinctions and rapid inter-biogeographical translocations of non-native species, and the effects of temperature and sea-level rises, shifts in $\delta^{13}C$ and $\delta^{15}N$ and reduced fluvial sediment flux (e.g., Waters *et al*., 2016; Syvitski *et al*., 2020; Head *et al*., 2021a; Williams *et al*., *in press*). Geological events are thus not an alternative to chronostratigraphy, but rather they offer crucial contextualization and commonly assist in definition.

This more tightly constrained interval – in reality characterized by a unique cluster of distinct lithological, chemical and biological event markers (Fig. 2) that enable extremely high-resolution correlation – is consistent with event stratigraphy as originally proposed by Ager (1973) and with how the event concept is widely used in the Quaternary. Its value here lies in its practical application to chronostratigraphy. The earlier impacts of humans are certainly critical to understanding how the Earth System came to be changed, and in tracing the history of human impacts in leading to these changes. But they are neither globally synchronous nor as clearly marked, tightly clustered, and as varied as the geological signals occurring in the mid-20th century.

Many stratigraphically significant mid-20th century signals comprising the Great Acceleration event array are not mentioned by Gibbard *et al*. (2021, 2022). These include the influx into sedimentary successions worldwide of plastics and many other novel entities, fly ash and black carbon (soot), persistent organic pollutants and artificial radionuclides; global carbon and nitrogen isotope anomalies as a result of hydrocarbon burning and nitrogen production respectively; and a wide range of correlatable bio-events mostly linked to the introduction of non-native species. They have been exhaustively detailed (e.g., Waters *et al*., 2016; Zalasiewicz *et al*., 2019; Head *et al*., 2021a; Syvitski *et al*., 2020, 2022; Williams *et al*., *in press*) and can act to characterize and define a synchronous, globally traceable Holocene–Anthropocene boundary, in exactly the same way that a carbon isotope event defines the Paleocene–Eocene boundary, and a bolide event defines the Cretaceous–Paleogene boundary.

Conclusions

Some geological phenomena that have been termed 'events' are actually time-transgressive, multi-temporal and spatially variable (Gibbard *et al*., 2021, 2022), but others more consistent with the conventional understanding of the term are near-isochronous and may have global extent. Events are used extensively for chronostratigraphic applications in the Quaternary, most notably the 8.2 and 4.2 ka climatic events used to subdivide the Holocene Epoch into its respective formal subepochs (Fig. 1). The chronostratigraphic Anthropocene as an epoch/series with a base coincident with a rich array of stratigraphic event signals dating to the mid-20th century is the evidence-based definition used by the AWG, and offers a robust chronostratigraphic datum of global extent that is not provided by the interdisciplinary anthropogenic 'event' concept proposed by Gibbard *et al*. (2021, 2022). Furthermore, in focusing on the Great Acceleration, *a planetary perturbation caused by human activities rather than the activities themselves*, it aligns with the definition used by the Earth System science community from which the term Anthropocene originated. This community routinely uses the stratigraphic record to identify past changes in the state of the Earth System. The Anthropocene as an epoch would be identified through comparable rigorous processes of definition as, and named in agreement with, other epochs in the Cenozoic Era. The 'Anthropocene event' of Gibbard *et al*. (2021) by contrast, is neither a stratigraphic nor chronostratigraphic concept, but rather encompasses an interdisciplinary and broadly defined range of phenomena with variable physical expression unified only by being anthropogenic (Head *et al*., *in press*). It operates at mostly local to regional scales on land, with little application to the oceanic realm. Embracing wide variation in interpretation and scope, its application may depend on distinguishing *transformative* human-induced changes from other such changes, and indeed from those caused by non-human drivers. Resembling more closely an episode than an event, this is a very different concept to the chronostratigraphic Anthropocene, but separately defined and differently named might usefully complement it.

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Abbreviations.

AWG, Anthropocene Working Group; b2k, before the year 2000 CE; GA, Great Acceleration; GOBE, Great Ordovician Biodiversity Event; GOE, Great Oxidation Event; GSSP, Global boundary Stratotype Section and Point; GTS, International Geological Time Scale; ICS, International Commission on Stratigraphy; IGBP, International Geosphere-Biosphere Programme; IUGS, International Union of Geological Sciences; *JQS*, *Journal of Quaternary Science*; PAGES, Past Global Changes; SQS, Subcommission on Quaternary Stratigraphy.

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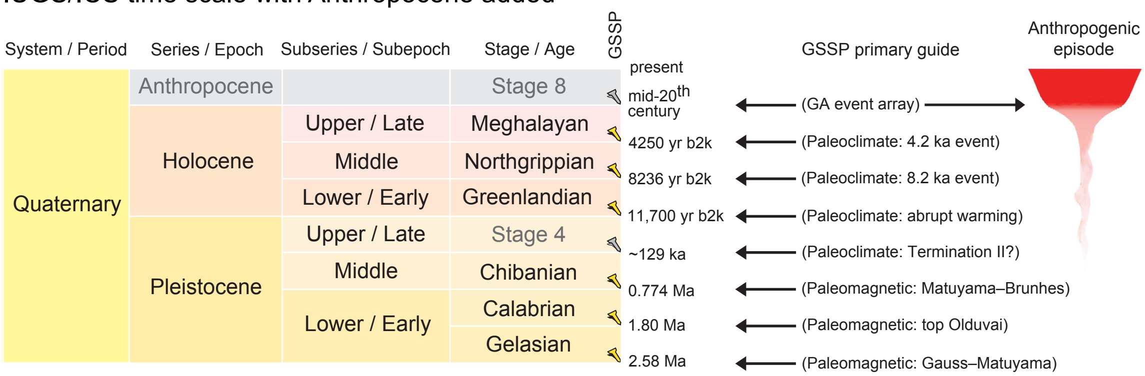
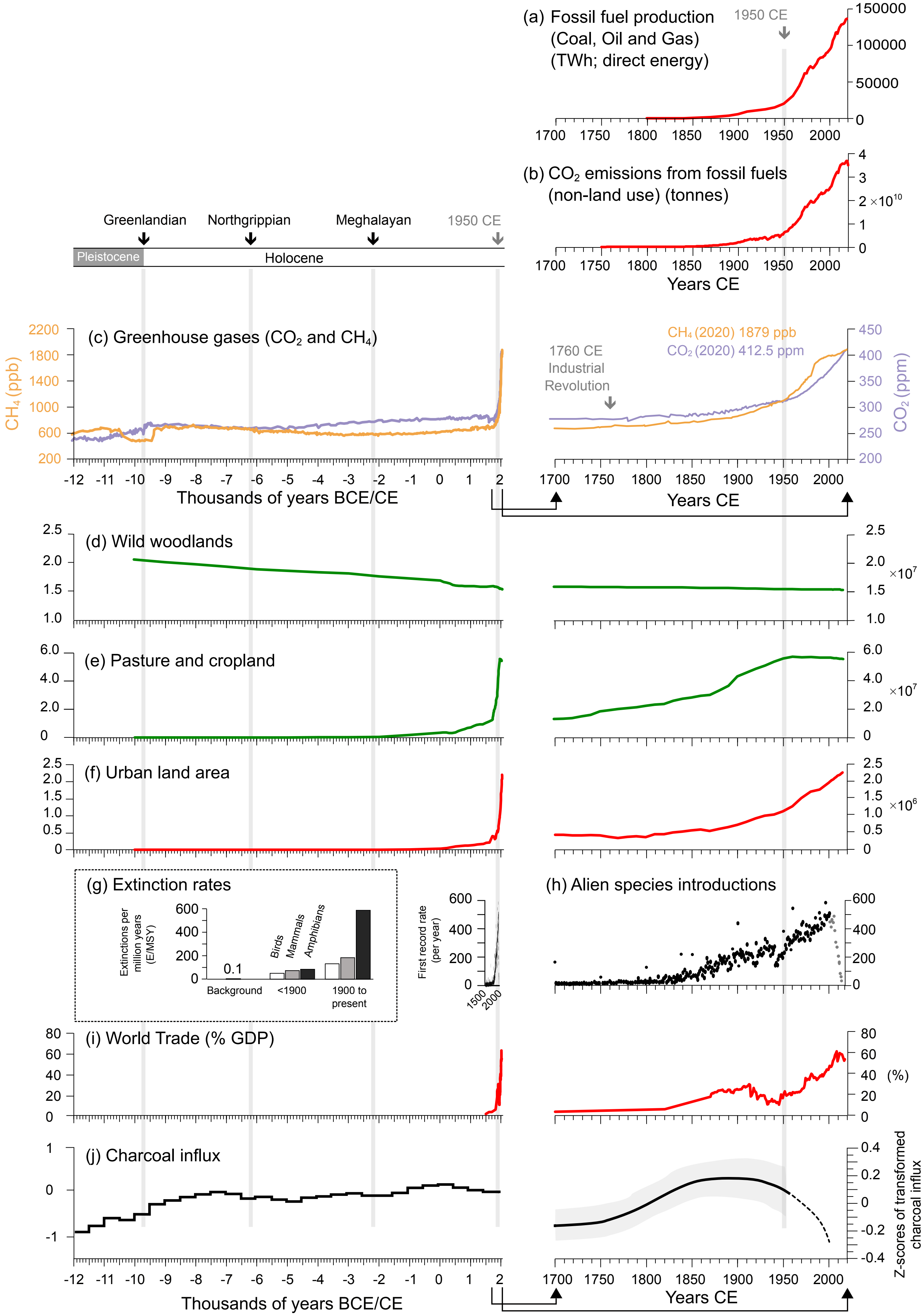
Figure 1. Geological time scale for the Quaternary, as sanctioned by the International Union of Geological Sciences / International Commission on Stratigraphy (from Head *et al*., 2021b), but with the Anthropocene added as a proposed new series/epoch, as conceived by the AWG. Ratified boundaries are identified by a golden spike symbol (indicating a Global boundary Stratotype Section and Point; GSSP) whereas pending and proposed boundaries are marked by a grey spike symbol. The primary guide used for global correlation to each GSSP is given, where GA event array = Great Acceleration event array. Each of these primary guides is chronostratigraphic in nature and could be considered an 'event', and two are explicitly so labelled. The informal and diachronous 'anthropogenic episode' here shown schematically, corresponds with the informal, diachronous and interdisciplinary 'Anthropocene event' of Gibbard *et al*. (2021, 2022).

Figure 2. Geological and historical timelines using empirical data to show the true scale and timing of social and environmental changes shown in figure 1 of Gibbard *et al*. (2021). a) fossil fuel consumption (https://ourworldindata.org/fossil-fuels); b) CO_2 emissions from fossil fuels (https://ourworldindata.org/co2-emissions#global-co2-emissions-from-fossil-fuels-global-co2-emissions-from-fossil-fuels); c) CO_2 and CH_4 data from Antarctic ice cores and direct atmospheric measurements (https://ourworldindata.org/atmospheric-concentrations and https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases respectively); d), e) and f) anthropogenic biomes (https://ourworldindata.org that uses data from Ellis *et al*., 2020 from 10,000 BCE to 2015 CE); g) extinction rates (Pimm *et al*., 2014), where E/MSY is the number of extinctions per million species years; h) first record rate (per year) of all neobiotic species reported by Seebens *et al*. (2017), although data after 2000 CE (grey dots) are incomplete owing to the delay between sampling and publication; i) global trade data is from

https://ourworldindata.org on exports as % GDP 1500 CE to present; and j) global charcoal influx (biomass combustion): data from (left panel) Power *et al*. (2008) and (right panel) Marlon *et al*. (2008).

IUGS/ICS time scale with Anthropocene added




(a) Fossil fuel production
(Coal, Oil and Gas)
(TWh; direct energy)
1950 CE
150000
100000
50000
0
1700 1750 1800 1850 1900 1950 2000
(b) CO2 emissions from fossil fuels
(non-land use) (tonnes)
4
3
2 ×10^10
1
0
1700 1750 1800 1850 1900 1950 2000
Years CE
Greenlandian
Northgrippian
Meghalayan
1950 CE
Pleistocene
Holocene
(c) Greenhouse gases (CO2 and CH4)
CH4 (ppb)
2200
1800
1400
1000
600
200
-12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2
Thousands of years BCE/CE
1760 CE
Industrial
Revolution
CH4 (2020) 1879 ppb
CO2 (2020) 412.5 ppm
CO2 (ppm)
450
400
350
300
250
200
1700 1750 1800 1850 1900 1950 2000
Years CE
(d) Wild woodlands
2.5
2.0
1.5
1.0
×10^7
(e) Pasture and cropland
6.0
4.0
2.0
0
×10^7
(f) Urban land area
2.5
2.0
1.5
1.0
0.5
0
×10^6
(g) Extinction rates
Extinctions per million years (E/MSY)
600
400
200
0
0.1
Birds
Mammals
Amphibians
Background
<1900
1900 to present
First record rate (per year)
600
400
200
0
1500
2000
(h) Alien species introductions
600
400
200
0
(i) World Trade (% GDP)
80
60
40
20
0
(%)
(j) Charcoal influx
1
0
-1
-12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2
Thousands of years BCE/CE
0.4
0.2
0
-0.2
-0.4
Z-scores of transformed charcoal influx
1700 1750 1800 1850 1900 1950 2000
Years CE