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The Anthropocene within the Geological Time Scale: a response to fundamental questions

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The Anthropocene as a prospective new, ongoing series/epoch must be defensible against all relevant concerns. We address the seven, still-relevant challenges posed to the Anthropocene Working Group by the Chair, International Commission on Stratigraphy (ICS), in 2014. (1) Concept or reality? The Anthropocene possesses a substantial, sharply distinctive stratigraphic record recognisable through many proxy signals from the mid-20th century onwards; (2) GSSP or GSSA? The Anthropocene can be defined by a GSSP and correlated globally; (3) Past or future? The Anthropocene unquestionably represents geological time, its transformations having already moved the Earth System beyond Holocene norms towards an irreversible future trajectory; (4) Utility? The Anthropocene's distinctive material content allows useful delineation on geological sections/maps; (5) Indelibility? Many of the Anthropocene's transformative effects cannot be subsequently effaced or overprinted; (6) Fit within the Geological Time Scale (GTS)? The Anthropocene represents a unique, youngest, interval in Earth history and strata of profound significance; (7) What is its value? The chronostratigraphic Anthropocene has conceptual usefulness even informally, but would then lack the clarity, stability and recognition that formalization provides. Without its formalization, the GTS would no longer accurately reflect Earth history, diminishing the relevance of geological science for analysis of ongoing planetary change.

Introduction

The Anthropocene was proposed as a new geological time interval by Paul Crutzen (Crutzen and Stoermer, 2000; Crutzen, 2002) to denote transformative, human-driven planetary changes that ended the relative stability of Holocene conditions; it was rapidly adopted by the Earth System science (ESS) community (e.g., Meybeck, 2001; Steffen et al., 2004, 2007; Hibbard et al., 2007). In 2009, the Anthropocene Working Group (AWG) was established by the Subcommission on Quaternary Stratigraphy (SQS) of the International Commission on Stratigraphy (ICS) to analyse the Anthropocene as a potential addition to the ICS-administered International Chronostratigraphic Chart (ICC) (Cohen et al., 2013), which forms the basis of the Geological Time Scale (GTS). The AWG was appointed to investigate whether this term and concept had geological validity; and, if it did, then to propose a formal definition consistent with how other units of the ICC have been defined. Crutzen originally suggested that the Anthropocene inception could be placed at the Industrial Revolution's beginning in the late 18th century (Crutzen and Stoermer, 2000; Crutzen, 2002). Subsequently, the AWG produced overwhelming evidence that the major mid-20th century planetary transition recognised in Earth System science (ESS; Steffen et al., 2004, 2007) also caused profound change to the litho-, chemo- and biostratigraphic character of strata, and formed the optimum level to mark the Anthropocene onset (Waters et al., 2016; Zalasiewicz et al., 2019). Key mid-20th century changes include: steep rises in atmospheric CO_2 and CH_4, now 50% and 260% higher than pre-industrial levels, respectively, that drive ongoing global warming; approximate doubling of phosphorus and reactive nitrogen levels at the Earth's surface; accelerated production and wide dispersal of many anthropogenically produced materials (many of them entirely novel) including concrete, plastics and persistent organic pollutants; sharply increased species extinctions, and unprecedented levels of species domestications and translocations (e.g., Syvitski et al., 2020; Williams et al., 2022). This growing evidence base led the AWG to conclude that an Anthropocene chronostratigraphic unit congruent with its meaning and use in the ESS community (e.g., Steffen et al., 2015) could also adhere to ICC/GTS principles and usefully complement the Holocene (Zalasiewicz et al., 2016a). Work then began to select and analyse Global boundary Stratotype Section and Point (GSSP) candidate and other reference sections for the Anthropocene and its associated stage (Waters et al., 2018, 2023a).

Nevertheless, the case for the Anthropocene as a unit of the ICC and GTS with globally isochronous onset continues to be questioned by a range of scholars (e.g., Bauer and Ellis, 2018; Ruddiman, 2018) including stratigraphers (Finney and Edwards, 2016; Gibbard et al., 2022a, 2022b; Edwards et al., 2022). Successive critiques have been addressed in detail by Zalasiewicz and Waters (2016), Zalasiewicz et al. (2016a, 2017a, b, 95 2018, 2019b), Head et al. (2022a, b, 2023a, b) and Waters et al. (2022, 2023a, b).

A key early step in the AWG's assessment was the special publication: "*A Stratigraphical Basis for the Anthropocene*" (Waters et al., 2014). The volume included an important contribution by Finney (2014), then Chair of the ICS, the body responsible for overseeing internationally recognized geological standards and the development of the ICC. In addition to noting that defining the Anthropocene would truncate the Holocene Series/Epoch, Finney (2014) outlined seven issues that would need to be addressed by the AWG. As the AWG approaches the completion of its primary task, selection of a candidate GSSP that would define the base of the Anthropocene as an epoch/series (Waters et al., 2023a), it is both timely and necessary to revisit and address these fundamental issues. We discuss Finney's seven questions below in their original order.

Concept or Reality? Is the Anthropocene a Concept in Search of a Distinct Stratigraphic Record? (Finney, 2014, p. 24)

Here, Finney (2014) noted that any chronostratigraphic unit of the GTS requires *content* as well as a basal stratigraphic marker, leading to a related question: *Is there a well-documented and significant stratigraphic record for the Anthropocene*? We address both questions. First, the Anthropocene originated within a context of stratigraphic data, including lacustrine and ice-core records, and modification of the GTS was explicitly stated. Paul Crutzen's first, improvised use of the term 'Anthropocene' in 2000 was made during an exposition of PAGES (i.e., essentially stratigraphic) data, where he said the Holocene no longer effectively described an Earth System now abruptly and heavily modified by the impacts of industrialized human society (Grinevald et al., 2019). Crutzen was crystallizing a wider awareness that had been growing over the previous decade. Indeed, an 'Anthrocene' had been proposed to denote an Earth dominated by human activity (Revkin, 1992), and independently the 'Homogenocene', to reflect a biosphere massively and irrevocably changed by global species transfers (Samways, 1999). These were also 'concept' proposals, though each is based on forms of recent planetary change that may be clearly recorded in strata via proxy signals. It was Crutzen's term, however, that was almost immediately adopted as a key framing concept by the ESS community in which he was a central figure.

The Anthropocene is not unique, though, in having been conceptualized prior to the search for its chronostratigraphic definition. The Quaternary became associated in the 19th century with the Ice Age, and this conceptualization as a climatostratigraphic unit led to questioning of its chronostratigraphic validity (Head and Gibbard, 2015a). It was subsequently studied in the context of climate change well before its formal definition in 2009 to coincide with intensified Northern Hemisphere glaciation at ~2.7–2.5 Ma (Gibbard and Head, 2010). The Holocene similarly has a conceptual underpinning. Its precursor, the "Recent" of Charles Lyell, received special status for having been "tenanted by man" (Lyell, 1833, p. 52). The Holocene, eventually formalized in 2008 by a GSSP in a Greenland ice core, represents rapid warming at the start of our present interglacial (Walker et al., 2009), but the concept was defined much earlier.

New stratigraphic evidence emerged of highly correlatable proxy signals such as globally distributed sedimentary microplastics (Ivar do Sul and Costa, 2014), fly ash (Rose, 2015; Swindles et al., 2015), artificial radionuclides (Waters et al., 2015), stable isotopic patterns (Dean et al., 2014), and biotic signals (Wilkinson et al., 2014; Barnosky, 2014). This growing range of geological signals, some without precedent in the stratigraphic record, complemented evidence gathered by the ESS community (e.g., Steffen et al., 2007). Together, they built a strong case for formalizing the Anthropocene (Table 1; Waters et al., 2016; Zalasiewicz et al., 2019b). A material Anthropocene unit predicated on a mid-20th century base (see discussion below) could indeed be recognised worldwide, in both marine and terrestrial deposits (Zalasiewicz et al., 2014). Evidence has continued to grow and includes global assessments (e.g., Syvitski et al., 2020), the adaptation of classical techniques such as biostratigraphy (Williams et al., 2022) and appraisals of the stratigraphic content of the Anthropocene in diverse

Table 1. Selected key proxy signals for the Anthropocene and studies discussing the relevance of these proxies to the Anthropocene

Type	Key proxy signals	References
Exogenic particles	Concrete	Waters and Zalasiewicz (2017)
	Microplastics	Ivar do Sul and Costa (2014); Zalasiewicz et al. (2016b)
	Fly ash (SCP/SAP)	Rose (2015); Swindles et al. (2015); Fiałkiewicz-Kozieł et al. (2016)
	Black carbon/microcharcoal	Han et al. (2017, 2023)
	Glass microspheres	Gałuszka and Migaszewski (2018a)
	CO_2	MacFarling Meure et al. (2006)
	CH_4	MacFarling Meure et al. (2006)
	S, SO_4^{2-}	Mayewski et al. (1990); Fairchild (2019)
	C stable isotopes	Rubino et al. (2013)
Geochemical (organic & inorganic)	N_2O/nitrates	Wolff (2013)
	N stable isotopes	Hastings et al. (2009); Holtgrieve et al. (2011)
	Hg	Hylander and Meili (2002)
	Heavy metals (e.g., Pb)	Gałuszka and Wagreich (2019)
	Pb isotopes	Dean et al. (2014)
	Polycyclic aromatic hydrocarbons (PAH)	Bigus et al. (2014); Kuwae et al. (2023)
	Polychlorinated biphenyls (PCBs)	Gałuszka et al. (2020); Kuwae et al. (2023)
	Pesticides (e.g., DDT)	Gałuszka and Rose (2019)
Radiogenic isotopes	^{241}Am, ^{137}Cs	Appleby (2008); Foucher et al. (2021)
	Pu isotopes	Hancock et al. (2014)
	U isotopes	Takahashi et al. (2023)
	^{14}C	Hua et al. (2021); DeLong et al. (2023)
	^{129}I	Bautista et al. (2016); Han et al. (2023)
Climate/pH	Oxygen isotopes	Masson-Delmotte et al. (2015)
	Element ratios (Sr/Ca)	Tierney et al. (2015)
	Boron isotopes	Waters et al. (2019)
Biotic turnover	Molluscs	Hausdorf (2018); Himson et al. (2020)
	Diatoms	Wilkinson et al. (2014); McCarthy et al. (2023)
	Foraminifera	Wilkinson et al. (2014); Jonkers et al. (2019); Himson et al. (2023)
	Ostracods	Wilkinson et al. (2014); Himson et al. (2023)
	Pollen	Tokarska-Guzik et al. (2011); Wilkinson et al. (2014); McCarthy et al. (2023)
	Zooplankton	Wilkinson et al. (2014); Jonkers et al. (2019)
	Testate amoebae	Fiałkiewicz-Kozieł et al. (2023)
	Pigments/biomarkers	Oleksy et al. (2020); Kuwae et al. (2023)

environments (Waters et al., 2018). In the last three years, analyses of 12 GSSP candidate sites and other reference sections have been undertaken and published: Waters and Turner, 2022; Waters et al., 2023a). Building on the earlier work, the quality and depth of information obtained in analysing these 12 sections represents a step-change in precise, multi-proxy stratigraphic resolution.

Anthropocene strata now occur widely as Earth's topmost layer, being commonly substantial and distinctive in both terrestrial (e.g., Terrington et al., 2018; Wagreich et al., 2023) and marine (e.g., Pierdomenico et al., 2019) settings. The deposits comprise a rich and diverse stratal archive that is correlatable around the world via a wealth of proxy data (e.g., Waters et al., 2023a and table 3 and fig. 2 therein) that can commonly be precisely tied to historical records.

The Anthropocene stratigraphic record is therefore distinct, has objective reality and substantial content, and represents an abrupt and major Earth System change consistent with the establishment of a new chronostratigraphic unit. That it arose as a concept formulated by an atmospheric chemist within a broad scientific community with only modest professional stratigraphic representation exemplifies the effective functioning of cross-disciplinary dialogue and the scientific process, in a context where stratigraphic data can be analysed in parallel with historical records and monitoring data. Crutzen's hypothesis has been amply supported by subsequent critical examination (e.g., Zalasiewicz et al., 2019b; Waters et al., 2016, 2023b).

GSSP or GSSA? Should the Base of the 'Anthropocene' be Defined on a Stratigraphic Signal or Instead should its beginning be Defined on a Date in Human History? (Finney, 2014, p. 25)

The Anthropocene, with its extraordinarily well resolved stratigraphic record tied to a historical and instrumental record, might be defined by a Global Standard Stratigraphic Age (GSSA), i.e., an absolute age in years before present, as mooted by Finney (2014). Subsequently Zalasiewicz et al. (2015) suggested a GSSA founded on the timing of the first atom bomb test detonation in 1945. This was not meant to symbolize the beginning of the nuclear age within humanity's development, but to define a point encompassing all anthropogenic radioactive fallout products within strata: an unambiguous marker for a chronostratigraphic Anthropocene that could be further characterised by many other stratigraphic markers (plastics, fly ash and so forth: see Table 1). This suggested GSSA signalled a distinct stratigraphic interval that could be effectively identified and traced by numerical or relative dating methods or both (see also Cohen and Gibbard, 2019, p. 22).

Nevertheless, this option was not pursued because initial feedback from the stratigraphic community was that a GSSP approach would more likely be favourably considered, given that GGSPs are otherwise universally used for the Phanerozoic timescale. The choice for a GSSP, moreover, would emphasize that the Anthropocene, despite its current brevity, has tangible geological expression and content. Even so, a chronostratigraphic Anthropocene, to be used across academic disciplines, would require its defining GSSP to be extraordinarily precisely dated compared with GSSPs of the Holocene and earlier units. Because the Anthropocene exists within the overlap of geological, instrumental and historical timescales, all three should ideally converge precisely at the GSSP, which should therefore be resolvable at annual, potentially sub-annual, scale and if linked to a specific event could have qualities of a GSSA as well. Head (2019) proposed that such a GSSP could be agreed by convention to represent a point in time, precise to the day, hour and minute if that were desirable, as a means of uniting geochronological and historical timescales at the GSSP. This would compare with the approach used for the K/Pg boundary, its age agreed to coincide with the moment of impact of the K/Pg bolide (Molina et al., 2006) which will have predated, by days or months, the age of the GSSP itself; and with the position of the Meghalayan Stage/Upper Holocene Subseries GSSP which was finely adjusted to coincide with the point where a numerical age of 4200 years BP had been calculated (Walker et al., 2018), allowing this date to represent the routine correlatory level. A GSSP representing such an agreed and rounded day and time would be convenient where the Anthropocene is considered in wider, for example legal, contexts (Vidas et al., 2019).

The consequent quest for a GSSP launched by the AWG led to the identification and exploration of 12 reference sites including nine potential candidate GSSPs (Waters and Turner, 2022; Waters et al., 2023a). This increased understanding of the Anthropocene's stratigraphic detail in diverse environments worldwide—and confirmed that the Anthropocene has distinctive stratigraphic content and may be precisely identified and correlated globally across both terrestrial and marine realms. Nearly all 12 sites show uninterrupted sedimentation, many with annual or sub-annual resolution. While resolution remains coarser than that of months and days, effective integration of overlapping geological and human historical records may be obtained by specifying the beginning of the calendar year of the precisely dated GSSP level ultimately chosen, as noted above.

Past or Future? Is the 'Anthropocene' a Unit of Earth History or Human History, or is it More a Projection into the Future? (Finney, 2014, p. 25)

This question is part-paraphrased later by Finney (2014, p. 26) as *Should not the 'Anthropocene', however it is defined, really be considered instead as a unit of an archaeological timescale or of recorded human history?* Geological time extends to the present day, and therefore incorporates human history including archaeological, written and instrumental records: this overlap ranges back into Holocene and even into Pleistocene times. Paul Crutzen, in 2000, framed the Anthropocene in explicitly geological terms as a unit of Earth history, and the remit of the AWG, and its subsequent analysis (after an initial scoping phase), has centred on a classically stratigraphic approach, involving litho-, chemo- and biostratigraphic patterns already preserved in strata (Waters et al., 2022). The Anthropocene is a distinct unit of Earth history because the clear and unique patterns recognised convincingly demonstrate a distinctive stratigraphic succession, of global reach, that reflects an abrupt and largely irreversible departure of the Earth System and its fundamental components (climate, biosphere, etc.) away from the conditions that characterised the Holocene, into a new and still-evolving state.

Alternative concepts have been suggested for the term Anthropocene, such as a time-transgressive archaeology-based and essentially lithostratigraphic unit (Edgeworth et al., 2015) and an interdisciplinary 'Anthropocene event' approach that encompasses all significant human impacts extending back ~50 millennia (Gibbard et al., 2022a, b). These represent very different concepts that might well *complement* a formally defined and much briefer chronostratigraphic Anthropocene by capturing its antecedents. But it is unclear why these alternative diachronous concepts should be labelled as the Anthropocene, which is a term rooted by its etymology in chronostratigraphy, as confusion would inevitably result (Head et al., 2022b, 2023a; Waters et al., 2022, 2023b). Formalization on the ICC would give the Anthropocene the level of precision and stability commonly accorded to equivalent scientific terms.

Finney (2014) also questioned the need to study geological archives in assessing global human impacts, given that continuous historical and instrumental records exist. The Anthropocene could then be characterised by historical records alone and have little relevance for geology and the GTS. However, detailed long-term environmental monitoring stations are sparsely distributed around our planet, whereas geological archives of the Anthropocene have a dense and global distribution. Many Anthropocene signals are not routinely measured in monitoring stations, such as biotic remains, stable isotopes and black carbon, or have incompletely monitored records of deposition or fallout. Such records are in fact commonly reconstructed using geological and other archive records, including Hg (Cooke et al., 2020) and U and Pu isotopes (Warneke et al., 2002). Many new and emergent contaminants (for example microplastics) do not yet have long-term monitoring programmes or standardised methodologies to do this. Geological traces are more durable, and allow direct comparison with older deposits far beyond the temporal range of instrumental measurements, so helping assess degrees of environmental impact. Where historical records are available, they assist in calibrating geological time scales and constraining interpretations. The way geological and instrumental evidence complement each other strengthens the case for chronostratigraphic recognition.

Stratigraphic signals of the Anthropocene are increasingly widely studied (see Table 1) and help fill important gaps in knowledge, such as tracking rapidly proliferating novel materials in different depositional environments. Such signals in Anthropocene strata do not simply duplicate data from environmental monitoring stations. Delays in deposition of the signal (Dong et al., 2021), and variation in its characteristics (e.g., solubility, biodegradability, hydrophobicity) and depositional environment (e.g., redox conditions, pH, mineral composition), affect the expression of Anthropocene signals in geoarchives just as they have affected signals in the deep time record.

Concerning the statement that "*Implicit in proposals for formal recognition of the* '*Anthropocene*' *is its projection into the future*" (Finney, 2014, p. 26), we emphasise that the definition and characterization of the Anthropocene are based purely on records present in strata today. Recognition that the Earth System trajectory has rapidly exceeded Holocene norms, and in some respects Quaternary norms, with evidence for this preserved in geological deposits worldwide, is central to the justification of the Anthropocene as a new epoch (Waters et al., 2016), not future projections.

However, assessment of the future is important for two separate reasons. Firstly, stratigraphic signals to be used by geologists to recognise the Anthropocene must be evaluated for their durability over geological timescales. For instance, plutonium-239, released into the atmosphere through nuclear weapons testing from 1945 onwards, represents the preferred primary guide for the base of the Anthropocene owing to its long half-life of 24,110 years, allowing detection for over ~100,000 years, and then beyond as the decay product uranium-235 with a much longer half-life of about 700 million years (Hancock et al., 2014; Waters et al., 2015). Secondly, forward modelling of the Earth System trajectory shows that the Earth cannot return to its previous Holocene state in the geologically near future. Thus, the Anthropocene cannot be regarded as a temporary 'blip' within the Quaternary record; its preserved global event array layer (Waters et al., 2022) is linked to geologically long-term consequences.

The planetary changes justifying the Anthropocene as a new epoch will clearly continue into the geological future. Most obviously, the biosphere, now deeply perturbed, can never return to the state of its Holocene predecessor, and may not return even to the overall functionality of the Holocene biosphere (e.g., Pimiento et al., 2020). Anthropogenic climate change, critical to planetary (including biospheric) evolution, will also have long-term consequences over hundreds of millennia (Talento and Ganopolski, 2021). The Anthropocene's climate impact is driving geologically long-lasting alterations of stratigraphic patterns quite separate from that of the Holocene, and in several respects distinct from that of the Quaternary as a whole. In the Anthropocene, the present is increasingly less the key to the past.

Projected future states are well expressed through two kinds of climate model. The first includes general circulation models (GCMs) which lie at the core of global climate projections contained in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021) and are based on interlinked atmosphere–ocean dynamics interpreted from a combination of fundamental physical principles and empirical observations (Forster et al., 2021). They are nonetheless constrained by such parameters as equilibrium climate sensitivity in part determined from geological records. Models have been run under different future CO_2 emissions scenarios, with climate projections typically made up to the year 2300 CE (Fig. 1).

In the highest CO_2 emissions scenario (Fig. 1B), the global climate (Fig. 1C) potentially exceeds Early Eocene values by 2300 CE (Fig. 1A; Arias et al., 2021). Even under the lowest emissions scenario, where CO_2 levels return to just below 400 ppm by 2150 CE, the projected climate for 2100 CE (Fig. 1C) approaches conditions last seen during the middle of the Piacenzian Stage of the Pliocene at ~3.1 Ma. Intermediate emissions scenarios could achieve climates last seen during the Miocene Climatic Optimum at ~16.9–14.7 Ma, an interval now increasingly seen as a deep-time analogue for the near-future (Steinthorsdottir et al., 2020; Fig. 1). Realistic long-term projections of global temperature in IPCC (2021) may lie within the higher range of possible outcomes (Hansen et al., 2023). For the next three centuries at least, no scenario considered avoids further global surface warming. Warming is projected to continue over the 21st century regardless of CO_2 emissions scenario (Arias et al., 2021; Cheng et al., 2022).

Other analyses combine forward-modelled climate projections with reconstructed deep-time climate trends (e.g., Burke et al., 2018; Clark et al., 2016; Stokes et al., 2022). Regardless of which carbon emissions scenario is followed, all projections depart markedly from the Holocene pattern, a consequence of the extra ~140 ppm (and rising) CO_2 rapidly loaded into the ocean–atmosphere system. The authors of these projections all use the term Anthropocene to denote this emerging new state of Earth history.

The second kind of climate modelling involves Earth System models of intermediate complexity that extend the forward modelling of GCMs by thousands of years. Such explorative scenario forecasts devised by Talento and Ganopolski (2021; Fig. 2) suggest that the *already accumulated* emissions of ~470 Gt C (Ritchie et al., 2020; of which >400 Gt C have been emitted since 1950) will affect climate for up to half a million years into the future, with the Holocene–Anthropocene interglacial lasting ~120 kyr, some five-fold the duration of a typical Quaternary interglacial (Fig. 2).

Whatever the future of emissions and their potential mitigations, and minimal progress has been made so far in countering climate change (Ripple et al., 2023), the extra ~140 ppm CO_2 in the atmosphere, together with other greenhouse gas increases, is affecting climate *now* (IPCC, 2021). Effects to date include: substantial ongoing loss of the world's glaciers (Rounce et al., 2023) with a corresponding rise in the snow/tree lines and release of stored contaminants (Schmid et al., 2011); increased erosion (Rose et al., 2011; Syvitski et al., 2022) and fluvial sediment flux (Li et al., 2021; Syvitski et al., 2022); and sea-level rise accelerating to 4.4 mm/yr during 2012–2022 (WMO, 2022; cf. the extreme Late Holocene stability described by Onac et al., 2022) and now thought certain to exceed 2 m in coming centuries (Vernimmen and Hoojier, 2023). The opportunity to preserve the West Antarctic Ice Sheet from collapse, for instance, has probably already passed (Naughten et al., 2023). Effects of this kind will remain as long as will the Earth's energy imbalance, and are almost certain to persist in this perturbed Anthropocene state far longer than the approximately ten thousand years of Holocene stability.

Pronounced multiple proxy event signatures existing within already-substantial sediment accumulations demonstrate that Anthropocene signals even now are sharply distinct from those of the Holocene and therefore consistent with series/epoch rank. Moreover, these signals

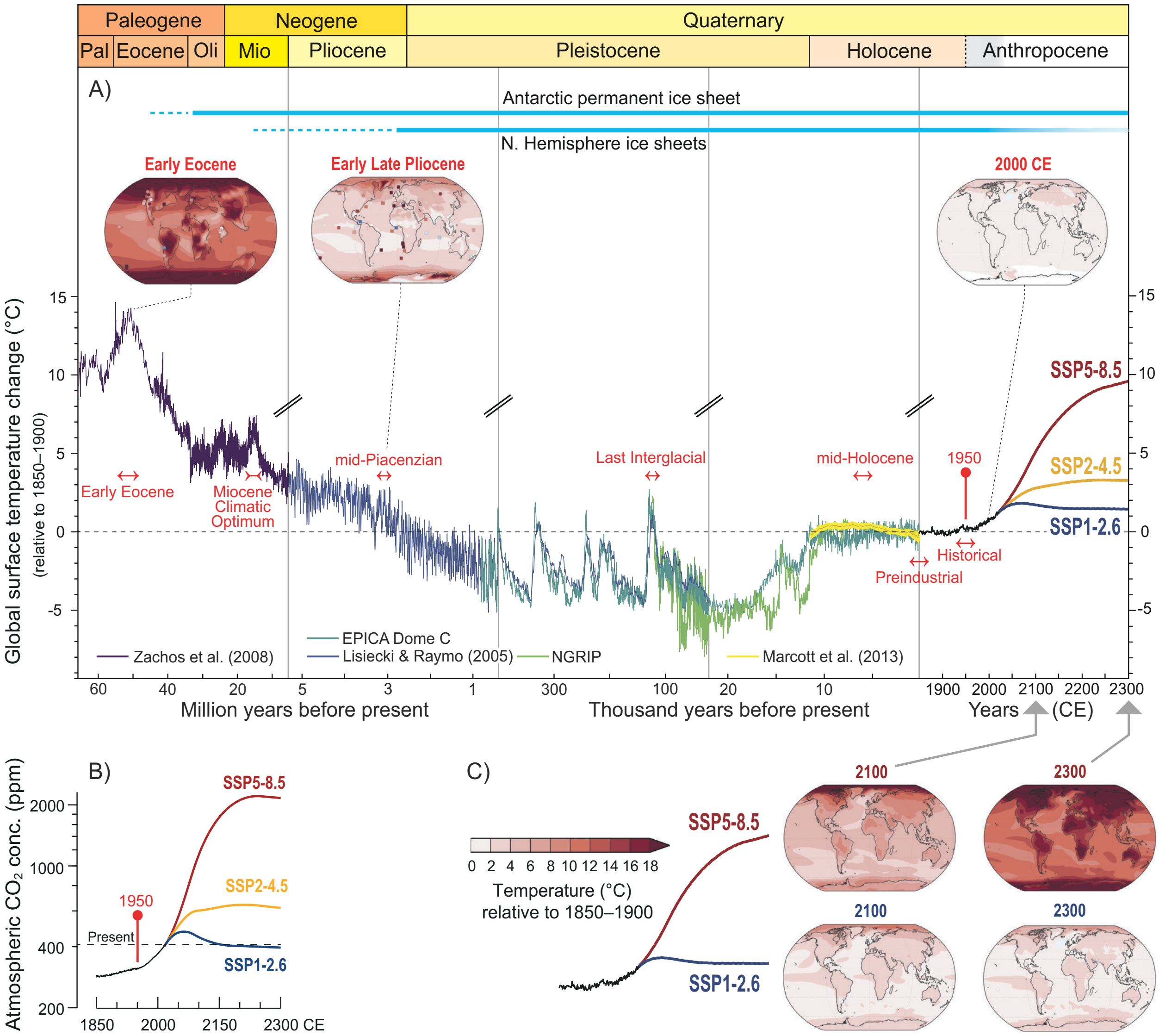

Figure 1. Global surface temperature change, relative to 1850–1900, from 65 million years ago to the year 2300 CE, and comparisons of projected future climate scenarios with reconstructed climates from the geological record with a particular focus on the Early Eocene and mid-Piacenzian. (A) Reconstructed temperatures are from Zachos et al. (2008), Lisiecki and Raymo (2005), EPICA Dome C (EPICA Community Members, 2006), NGRIP (Andersen et al., 2004, 2006), and Marcott et al. (2013), with post-1850 reconstructions from Arias et al. (2021). Note the breaks in scale. The three future climate projections to the year 2300 CE, the 'Shared Socioeconomic Pathways' (SSPs) SSP5-8.5, SSP2-4.5 and SSP1-2.6, are based on the three CO_2 emissions scenarios shown in (B); these are respectively a 'high fossil-fuel development world' with a nominal 8.5 W m^{-2} radiative forcing level by 2100 CE, a 'middle of the road' scenario with 4.5 W m^{-2} radiative forcing level by 2100 CE and 'sustainability' scenario with 2.6 W m^{-2} radiative forcing level by 2100 CE (Arias et al., 2021). In (C), the highest and lowest CO_2 emissions scenarios, SSP5-8.5 and SSP1-2.6 respectively, are modelled as global temperature maps for the years 2100 and 2300 CE, allowing comparison with global maps reconstructed for the Early Eocene and mid-Piacenzian and presented for the year 2000 CE (A). Pal = Paleocene; Mio = Miocene; Oli = Oligocene. Modified from fig. 1 in Burke et al. (2018) and fig. TS.1 in Arias et al. (2021).

and their resultant patterns (Section 5) cannot fail to persist far into the geological future, particularly where deposited in accumulative sedimentary settings.

Utility? What is the Usefulness of the 'Anthropocene' as a Material Unit to be Represented on Geological Maps? (Finney, 2014, p. 26)

The standard units depicted on most geological maps and sections are lithostratigraphic, whereas the Anthropocene as a series is a chronostratigraphic unit. Lithostratigraphy comprises *local* units of rock/sediment that are then placed into a *global* chronostratigraphic framework, the boundaries of which commonly do not coincide with the lithostratigraphic ones: indeed, one of the prime uses of chronostratigraphy is to constrain diachronous facies changes, and so build up palaeogeographic histories that are realistically complex in time and space. This is true of sedimentary strata of any age.

Nevertheless, it can sometimes be useful to show maps and sections of chronostratigraphic units, though these are usually highly simpli-

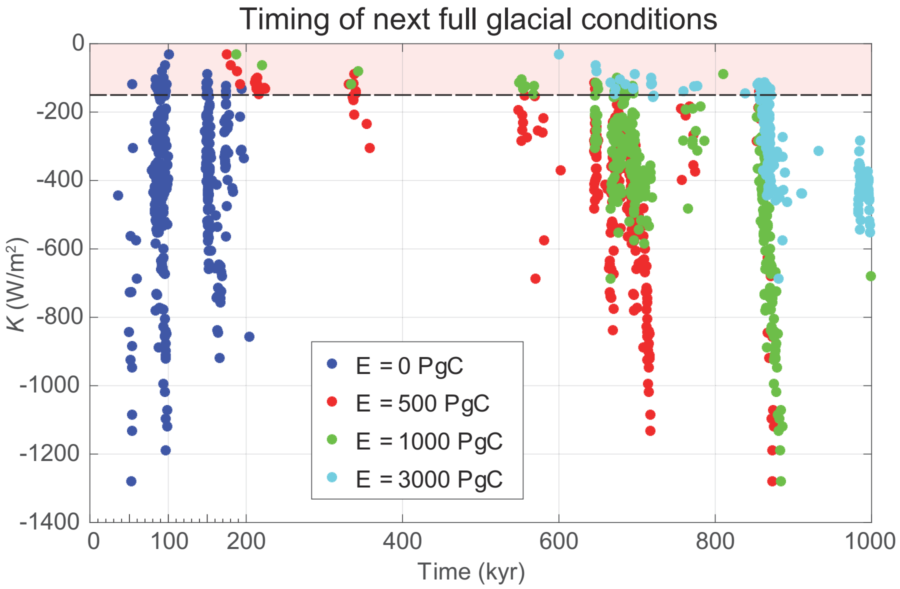

Figure 2. Timing of the next full glacial conditions (v = 0.5 where v = ice volume, 0 = present conditions and 1 = those during the Last Glacial Maximum at 21 ka) under the different cumulative CO_2 emissions (E) scenarios (PgC = petagram= gigatonne [Gt] of carbon) considered by Talento and Ganopolski (2021). The coefficient K is a measure of the sensitivity of the critical orbital forcing to the atmospheric CO_2 concentration. The pink shaded area indicates the solutions in the accepted set of these authors. The horizontal axis measures future time in thousands of years from the present. For the natural scenario (E = 0 Gt), glacial inception would most likely occur ~50 kyr from the present, with full glacial conditions ~90 kyr from the present, whereas with currently achieved cumulative anthropogenic CO_2 emissions (E = 500 Gt C) full glacial conditions would not occur until 200 kyr from now. From fig. 3 of Talento and Ganopolski (2021).

fied, often with interpolated boundaries, as in summary national or global geological maps. Unlike for instance the Pliocene–Pleistocene boundary, the Holocene lends itself well to such simplifications, because it is largely a near-surface unit representing the latest of many Quaternary marine transgressions, and so typically includes the modern deltas, coastal plains and river floodplains, which are generally easily delineated by geomorphological mapping. Mapping the subdivisions of the Holocene, especially the (mostly subsurface) Greenlandian and Northgrippian stages, will be much more challenging, though of course these can be shown on vertical cross-sections where the lithostratigraphic mapping framework has resolution to allow correlation/alignment, as in the typical Northgrippian onset of modern deltas (Hori and Saito, 2007). This potential difficulty of separately mapping the three stages (and their respective subseries) of the Holocene, or indeed any other subdivision of the Quaternary, was not raised as a concern in formalising these units.

Mapping Anthropocene deposits has rarely been attempted, though that mostly reflects the novelty of this concept as a geological entity: it has been less than a decade since the chronostratigraphic Anthropocene concept crystallized around a mid-20th century base. Nevertheless, there is good reason to think that Anthropocene deposits will be widely distinguishable, and mappable, in many settings, and that there will be real value, both practical and academic, in systematically delineating them from earlier, Holocene and pre-Holocene deposits. Finney (2014, p. 26) asked "*Following procedures used in geological mapping, would 'Anthropocene' be used for both human-induced features on the surface as well as the soil that surrounds them, in which case both would be included in the same unit basically covering the entire map?*" In geological mapping, soils are not routinely mapped (these appear on soil survey, not geological survey, maps). Anthropogenic deposits are, though, increasingly mapped, as on maps (1:25,000 and 1:50,000) of the Austrian Geological Survey where they form the youngest mappable units. Such anthropogenic deposits might be subdivided into units from the Holocene (e.g., waste tips from pre-mid-20th-century mining) and those of the Anthropocene (e.g., landfills younger than 1950 CE). As with any chronostratigraphic unit, the detail resolved will depend on the scale of the map and the age information available.

The inherent mappability of Anthropocene strata stems from the many (and growing) lines of evidence that can be used to recognise post-mid-20th century deposits (Table 1); some require laboratory analysis, but others can be used in the field (macroplastics, technofossils, characteristic fossils of introduced species and so on) (Fig. 3). Both in terrestrial and marine deposits, this affords a wide range of means of stratigraphic identification. Such information has already been used to attempt to delineate Anthropocene from pre-Anthropocene deposits in geometrically complex urban settings, as in Swansea (fig. 14 in Ford et al., 2014), London (Terrington et al., 2018), Berlin (the "Teufelsberg Formation": Scheffold, 2014; fig. 2 in Zalasiewicz et al., 2017b) and Vienna (Wagreich et al., 2023).

Anthropocene deposits extend beyond purely anthropogenic ones, to encompass lacustrine, fluvial, marine and other typical sedimentary facies, where they may be recognised using a wide range of stratigraphic proxies (e.g., Williams et al., 2022), for instance in fluvial settings (Russell et al., 2021).

Anthropocene deposits as mapped, measured, monitored and budgeted mark a pronounced increase in global sedimentation and erosion rates beginning in the mid-20th century, driven by human activities that are in turn largely powered by hydrocarbon combustion. Global sediment mobilization and transport has increased more than 4-fold since 1950 and is now overwhelmingly (~95%) anthropogenic (Fig. 5 in

Figure 3. Anthropocene sedimentary archives can be very accessible and show the abundant and distinctive geological record accumulated since the mid-20th century. A) Teufelsberg war debris mound (Germany) represents a distinct, mappable, lens-like lithostratigraphic unit up to 80 m thick, piled up between 1950 and 1972, that correlates with other war debris mounds of the Berlin area; B) Karlsplatz (city of Vienna, Austria) artificial soil and urban rubble layers. The coarse lower part of this Anthropocene reference section includes war rubble of 1945, overlain by a 1959 fine-grained layer marked by fallout-derived plutonium in an urban park; C) Rautenweg Landfill (Vienna, Austria), up to 187 m of anthropogenic material accumulated since 1960; D: Rautenweg Landfill composed of waste combustion residue mixed with some other residual waste. Examples of natural beachrock deposits made of iron slags originally dumped into the open sea with abundant techno-fossils from northern Spain: E) Tunelboca beachrock unconformable over Middle Eocene deposits started in the 1940s close to the city of Bilbao (Basque Region, Geosite 96); F) Furnace bricks from the Tunelboca beachrock; G) Portazuelos beachrock initiated in the 1960s over Devonian carbonates close to the city of Avilés (Asturias); H) Plastic bottles and expanded polystyrene from the Portazuelos beachrock.

Syvitski et al., 2022). Globally, mainly in urban and quarried/mined/dredged areas, anthropogenic deposits are accumulating at rates (in 2015 CE) of 316 Gt/yr or 150 km^3/yr, ~30-fold greater than in 1950 (Cooper et al., 2018) and ~25 times greater than the sediment transported each year by the world's major rivers to the oceans. The total sediment mass produced during the Anthropocene is already disproportionately large and continues to grow rapidly. As just one example, more than 95% of the world's dammed reservoir capacity has been emplaced since 1950 (Syvitski et al., 2022), and these dams have subsequently trapped 3200 Gt of sediment, 'equivalent to a 5 m-thick deposit covering all of California or Spain' (Syvitski et al., 2020). Many cities and the urban deposits they rest upon have rapidly expanded laterally during the Anthropocene, such as Shanghai (Fig. 2 in Zalasiewicz et al., 2014). Even in the centre of 2000 year-old London, analysis of borehole data indicates that the 'artificial ground' formed since 1950 represents ~40% of the total mass of urban deposits in two central London boroughs (Terrington et al., 2018).

Anthropocene deposits, too, have individual characteristics that make them useful to recognise and delineate (Vidas et al., 2019). These include growing and compositionally evolving masses of landfill material (Tame et al., 2013) and earthquake-liquified reclaimed land, as formed off Tohoku in Japan in 2011 (Yasuda et al., 2012). Buried plastic debris, in adding a novel barrier to water, oxygen and biological action, has affected the permeability, redox characteristics and biological habitability of sediments. Many novel toxins are concentrated in, or are more or less restricted to, Anthropocene deposits (e.g., Gałuszka and Migaszewski, 2018b), including artificial radionuclides, and many persistent organic pollutants and trace metal pollutants. Much Anthropocene-age 'artificial ground' has a high concrete debris content, affecting its engineering geology properties (Waters, 2018). More distally, an Anthropocene unit may also be distinctive in many lake successions, where deposits formed since the mid-20th century show relative thickness increase because of human-driven increased erosion/sedimentation rates (Cendrero et al., 2022) and are commonly darker, their higher organic content reflecting eutrophication from agriculture-related nitrogen/phosphorus runoff (Rose et al., 2011; Jenny et al., 2016).

Clearly, especially in urban settings, the geometric relationships of Anthropocene deposits *vis-à-vis* older deposits will commonly be complex, as with tunnel-fills (Williams et al., 2019), and may not follow simple superposition. But many natural geological deposits have complex geometries too, for instance in karst, desert, glacial and volcanic settings; that has not prevented geologists from delineating their different units and placing them in a chronostratigraphic framework.

Indelibility. Has the Change to a Human-Dominated Earth System Overwhelmed the Natural Earth System, or Might Geological Processes both Internal and External still Overwhelm the Human Influence? (Finney, 2014, p. 26)

Human influence on the Earth System might have initiated thousands of years ago, for it has been proposed that early agriculture caused atmospheric CO_2 and CH_4 levels to rise slowly from 7 ka and 5 ka, respectively (e.g., Ruddiman, 2003, 2007; Ruddiman and Thomson, 2001; Ruddiman et al., 2016; Fig. 4C, D). This is an attractive hypothesis, though isotopic data (Elsig et al., 2009; Schmitt et al., 2012) indicate instead that oceanic outgassing led to the gradual rise in CO_2 (Studer et al., 2018; Brovkin et al., 2019), while isotopic and modelling studies suggest that natural rather than anthropogenic emissions account for the rise in CH_4 (Beck et al., 2018; Singarayer et al., 2011). These explanations have been challenged (Ruddiman et al., 2020) but the causes for these early rises in CO_2 and CH_4 remain uncertain (Chen et al., 2021; see also Hansen et al., 2023). In any event, this slow greenhouse gas rise (whatever its cause) may have prolonged the stable warmth of the Holocene (Ganopolski et al., 2016) during a long decline in June insolation at 65°N (Fig. 4B).

In contrast to the fundamentally stable Earth System throughout the Holocene, the transition to a state dominated by intensifying human impacts, including sharp greenhouse gas rises (Fig. 4C, D, E) and radical modification of the biosphere, was largely accomplished in several decades during the mid-20th century. The unique modification during the Anthropocene of global biogeographic patterns that have been in existence for millions of years, via many species domestications and translocations (Duarte et al., 2017; Seebens et al., 2018; Williams et al., 2022) together with already substantial species extinctions (Ceballos et al., 2015, 2020; Pimm et al., 2014; McCauley et al., 2015; Cowie et al., 2022), comprise irreversible phenomena already recorded in our planet's strata (Goodfriend et al., 1994; Burney et al., 2001; Himson et al., 2020, 2023; Williams et al., 2022). The geological (fossil) record of a transformed biosphere will persist into the indefinite future. Already profound, this may well be the largest signal of the Anthropocene from the perspective of millions of years hence, just as clearly recognizable biotic change marks the difference between earlier epochs, periods and eras of the GTS.

Global erosion and sedimentation patterns, pervasively transformed via processes such as surface and subsurface mining, river regulation and damming, industrial agriculture, deforestation, and urbanization (Syvitski et al., 2022), will not soon re-achieve natural equilibria. Even then, continued exhumation of plastics, persistent organic pollutants and other novel materials, via the progressive erosion of landfill sites and other artificial ground, will continue to rework these materials progressively into future sedimentary pathways and deposits (e.g., Rose et al., 2012).

Possible future events that might affect stratigraphic records of the Anthropocene include catastrophic meteorite impacts and extraordinary flood basalt eruptions. Meteorite impacts of K-Pg boundary event scale happen rarely; there has only been one of such consequence through the entire Phanerozoic, so this is a remote possibility. Even so, an impact at the scale of the K-Pg event would not obliterate most Anthropocene deposits; it would simply, like the K-Pg event itself, form an identifiable layer above them. Smaller meteorites such as one that formed the Nördlinger Ries impact of Germany at 14.8 Ma (Buchner et al., 2022) have caused substantial regional damage but not global Earth System reorganization. A similar impact today would perturb the Earth System, especially given the fragmented biosphere, diminished biodiversity and anthropogenically disturbed climate. But it would only modify, not wholly overprint, the emerging patterns of the Anthropocene Earth System.

Flood basalt outpourings of the kind that led to Earth System shifts now marked by chronostratigraphic boundaries are also relatively rare. Flood basalt provinces, too, develop over long timescales: ~0.8 myr for the Deccan Traps (Schoene et al., 2020) and ~ 2 myr for the Sibe-

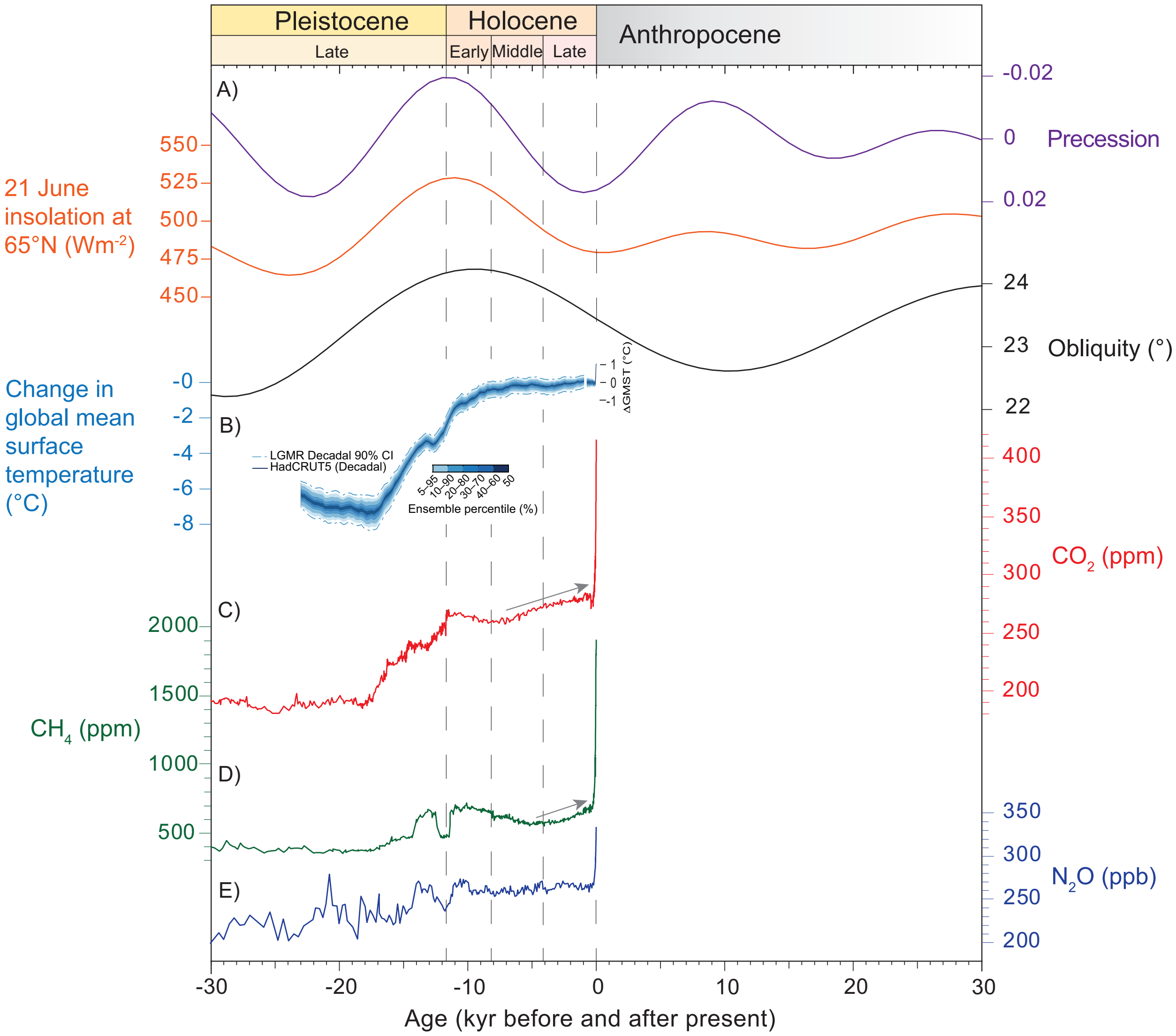

Figure 4. Earth's orbital forcing parameters during 30 kyr before and after present, and global atmospheric concentrations of greenhouse gases (carbon dioxide, methane and nitrous oxide) and temperature over the past 30 kyr. A) Precessional amplitude, showing low mid-latitude insolation over the next 30 kyr. B) Mean surface temperature change over the past 24 kyr (relative to the interval 1000–1850 CE; from Osman et al., 2021). C) Carbon dioxide based on Antarctic ice cores, and direct measurements at Mauna Loa from 1959 with the last measurement in 2021 (fig. 1 of the United States Environmental Protection Agency, 2022). D) Methane based on EPICA Dome C and Law Dome ice cores, Antarctica, and direct measurements at Mauna Loa from 1984 with the last measurement in 2020 (fig. 2 of the United States Environmental Protection Agency, 2022). E) Nitrous oxide based on Antarctic ice cores, and direct measurements at Cape Grim, Tasmania from 1979 with the last measurement in 2021 (fig. 3 of the United States Environmental Protection Agency, 2022).

rian Traps (Burgess et al., 2017), so much more gradually than the greatly accentuated evolution (within 0.0001 myr) of the Earth System today. In the unlikely event of another flood basalt province emerging on Earth in the near future, its effects (including elevated CO_2 emissions) would undoubtedly interact with, though not efface, those generated by humans.

These are long-term possibilities, unlikely in the near (centuries to millennia) future when the current phase of human impacts will – at least initially – play out. A more likely and imminent possibility is that of a global nuclear conflagration and its effects, another scenario researched by Paul Crutzen (Crutzen and Birks, 1982). This has been an ever-present danger since 1949, when rival states developed these weapons, and one likely to continue for the foreseeable future (Spencer, 2022). Even for the most catastrophic outcomes, however, the conflagration layer would overlie the currently existing Anthropocene stratigraphic record, and likely be categorized with it. In other words, Anthropocene markers are sufficiently robust to outlast the tenure of the human species on Earth, as will be their long-term geological consequences.

Fits with ICC/GTS? What is, after all, the Conceptual Basis of the ICC/GTS? (Finney, 2014, p. 26)

The ICC/GTS provides the primary framework for dividing the 4.54 billion years of Earth time into a manageable number of units. For the

Precambrian, many of these units are essentially conveniently rounded divisions of numerical time. But, where sufficient evidence exists, the stratigraphic record is divided into units which essentially reflect distinct dynasties of Earth history, recognisable through specific patterns of stratigraphic content. Variations on this theme, reflections of the Earth's changing system state, may be seen throughout the ICC/GTS. For the Quaternary System, its onset and subdivisions all reflect shifts in Earth System functioning. In particular, the beginning of the Quaternary at 2.58 Ma recognises the intensification of Northern Hemisphere glaciation (Head et al., 2008) and that of the Middle Pleistocene at 774 ka reflects an important transition to ~100 kyr climate cyclicity (Head and Gibbard, 2015b).

As discussed earlier (Section 1, above), the youngest geological time unit will always include the present where it now occurs in parallel with, and can be supported by, historical and instrumental data. The proposed Anthropocene, though less than a century into its span, clearly represents a major new chapter in Earth history. Its stratigraphic content is durable, highly distinctive, and can be correlated worldwide through terrestrial and marine realms (e.g., Waters et al., 2018; Zalasiewicz et al., 2019a). The case, therefore, for inclusion of the Anthropocene within the ICC/GTS is extremely strong.

Value? Will the 'Anthropocene' have Value Even if it is Not Ratified as a Formal Chronostratigraphic/ Geochronological Unit? (Finney, 2014, p. 27)

Finney (2014, p. 27) argued that "*A number of very significant, long-term geological events recorded by extensive rock records and reflecting major upheavals in the Earth system are not represented by units in the ICS International Chronostratigraphic Chart/Geologic Time Scale*".

In contrast to the long-term changes alluded to in this seventh question, the Anthropocene as characterized by the AWG represents the stratigraphic record of an abrupt and unprecedented planetary transformation clearly registered in the stratigraphic column as an array of geosignals generated during and since the mid-20th century. This transformation contrasts markedly with Holocene stability. The principal value to the geological community of a chronostratigraphic Anthropocene defined and characterized according to ICS requirements is that it fixes the stratigraphic meaning of "Anthropocene" to reflect the reality of ongoing major Earth System change.

In informal usage the term's meaning has varied widely (e.g., the greatly extended, diachronous and interdisciplinary "Anthropocene event" of Gibbard et al., 2022a,b), not least as the Anthropocene has been extensively used in various senses in social sciences, humanities and the arts (Zalasiewicz et al., 2021; Simon & Thomas, 2022). Nevertheless, within a given scientific field, definitions of units have value only if they are clear, precise, consistent and stable, and if they are widely accepted within the profession. The AWG has provided in its publications on the Anthropocene the required clarity, precision and consistency, but stability will only be guaranteed, and widespread acceptance and usage will only develop, upon approval and ratification of the formal AWG proposal by SQS, ICS and IUGS. Ratification of the Anthropocene as an epoch and its associated stage would confer the same confidence in its stratigraphic standing as for any other measure of time and its corresponding rock record. Official recognition would also acknowledge the rate and magnitude of transformation at the onset of the Anthropocene, recognise the value of associated stratigraphic signals, and accept that the Earth System has already shifted to a long-term trajectory different from that of the Holocene planetary state. Indeed, formalization of the Anthropocene would also increase the utility of the Holocene, limiting it to an epoch of relative climatic stability (Zalasiewicz et al., 2017; Head et al., 2023b).

Failure to ratify would be a missed opportunity by the stratigraphic community to reflect Earth history in a consistent manner within the GTS and to stabilize the meaning of the Anthropocene. An unofficial chronostratigraphic Anthropocene would continue to be used alongside a plethora of other "anthropocenes" but its precise properties would be unclear. The material reality of the concept would remain, and indeed will likely become increasingly pronounced, but, lacking a fixed, consistent and effective label, it will be more difficult to appreciate and harder to communicate.

Most importantly, if the chronostratigraphic Anthropocene were to remain formally undefined, the meaning of the Geological Time Scale itself would suffer, as it would no longer describe contemporary stratigraphic and Earth System conditions. The Holocene component of the GTS will increasingly fail to reflect emerging geological reality and so will lose descriptive value if its characterization is stretched to cover both the broadly stable conditions of its first 11.7 kyr and the fundamentally different conditions developing from ~1950 CE. In the absence of formalization, stratigraphy would have diminished relevance in assessment of contemporary planetary conditions, and this loss would affect the usefulness of stratigraphy and more broadly geology, within the wider scientific enterprise.

Conclusions

To many geologists who have spent careers working on deep time geology, analysing multi-million-year Earth histories marked by great planetary changes, the concept of an epoch that spans (so far) a single human lifetime may well seem surreal. Even for Quaternary geologists, who work within a timespan of ~2.6 Ma, the Anthropocene timescale is a sliver of the duration of an interglacial phase, of which the Quaternary holds more than 50. Moreover, the marked oscillations of climate and sea level paced by Milankovitch forcing, and the scale of some of the associated phenomena such as meltwater pulses, also provide a context that can make any human action seem negligible. Extraordinary claims, thus, demand extraordinary evidence, and the range of critiques that have been made on the Anthropocene concept are due reflection of this. The AWG has responded to all of these (see above). Finney's (2014) list of seven issues for the AWG to address remain relevant today in representing questions the ICS must ask, and it is now timely to respond to directly, given that the AWG has gathered the evidence base (AWG, 2019; Waters et al., 2023) for its forthcoming formal proposal.

As with the other published critiques, from both stratigraphers and non-geoscientists, these questions can be comprehensively answered. Thus: (1) the Anthropocene did arise as a concept—but so too have other chronostratigraphic units, and abundant material stratigraphic evidence exists to justify the Anthropocene concept; (2) the Anthropocene may be effectively defined by GSSA or GSSP, with analysis currently advanced for a GSSP, consistent with the most familiar way of defining Phanerozoic units; (3) the Anthropocene is unquestionably a meaningful division of geological time, reflecting major and largely irreversible change to the trajectory of the Earth System; (4) Anthropocene deposits, already substantial and distinctive, have been shown to be geologically mappable; (5) it is highly unlikely that future natural events will overwhelm the stratigraphic patterns of the Anthropocene; rather, these may be intensified by future anthropogenic forcing; (6) the Anthropocene clearly fits the conceptual framework of the ICC/GTS, with ever more relevance (Stewart et al., 2023); (7) failing to formalize the Anthropocene would mean the ICC/GTS no longer reflects Earth history accurately, and will hinder and destabilize scientific communication by leaving a major planetary phenomenon without settled name or status, an omission that may work to the detriment of stratigraphy itself.

Despite the brevity of the Anthropocene to date, its reality as a sudden, major perturbation of Earth history is no longer in doubt, nor is the wealth of stratigraphic signals that may be used to track, precisely, the resulting major change in strata worldwide. All the challenges posed to a chronostratigraphic Anthropocene have been answered fully: there is a clear and objective basis to this emergent new planetary and chronostratigraphic entity.

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