Part 1: Anthropocene Series/Epoch: stratigraphic context and justification of rank

The Anthropocene Epoch and Crawfordian Age: proposals by the Anthropocene Working Group

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Submission prepared by members of the Anthropocene Working Group:
Colin N. Waters (Chair): University of Leicester, UK
Simon Turner (Secretary): University College London, UK
An Zhisheng: Chinese Academy of Sciences, Xi'an, China
Anthony Barnosky: University of California, Berkeley CA, USA
Alejandro Cearreta: Universidad del País Vasco, Spain
Andrew Cundy: University of Southampton, UK
Ian Fairchild: University of Birmingham, UK
Barbara Fiałkiewicz-Kozieł: Mickiewicz University, Poznań, Poland
Agnieszka Gałuszka: Jan Kochanowski University, Kielce, Poland
Jacques Grinevald: IHEID Genève, Switzerland
Irka Hajdas: ETH Zurich, Switzerland
Han Yongming: Chinese Academy of Sciences, Xi'an, China
Peter Haff: Duke University, Durham NC, USA (deceased)
Martin J. Head: Brock University, St. Catharines, Canada
Juliana Assunção Ivar do Sul: Leibniz Institute for Baltic Sea Research, Germany
Catherine Jeandel: LEGOS Université de Toulouse, France
Reinhold Leinfelder: Freie Universität Berlin, Germany
Francine McCarthy: Brock University, St. Catharines, Canada
John McNeill: Georgetown University, Washington DC, USA
Eric Odada: University of Nairobi, Kenya
Naomi Oreskes: Harvard University, Cambridge, USA
Clément Poirier: Normandie Université, Caen, France
Daniel deB. Richter: Duke University, Durham NC, USA
Neil Rose: University College London, UK
Yoshiki Saito: Shimane University, Matsue, Japan
William Shotyk: University of Alberta, Canada
Colin Summerhayes: University of Cambridge, UK
Jaia Syvitski: University of Colorado, Boulder CO, USA
Davor Vidas: The Fridtjof Nansen Institute, Lysaker, Norway
Michael Wagreich: University of Vienna, Austria
Mark Williams: University of Leicester, UK
Scott Wing: Smithsonian Institution, Washington DC, USA
Jan Zalasiewicz: University of Leicester, UK
Jens Zinke: University of Leicester, UK

Corresponding author: Colin Waters cw398@leicester.ac.uk
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ABSTRACT

The Anthropocene Working Group (AWG) has concluded that the Anthropocene represents geological reality and should be linked with the plethora of stratigraphic proxies that initiate or show marked perturbations at around the 1950s, and should be defined using a Global boundary Stratotype Section and Point (GSSP). We propose formalizing the Anthropocene as series/epoch, terminating the Holocene Series/Epoch with a single Crawfordian stage/age. The GSSP should be located at the level where the primary marker shows a rapid increase in $^{239+240}$Pu concentrations (coinciding with a globally recognisable, isochronous signal of the first above-ground thermonuclear tests).

The stratigraphic signature of the Anthropocene comprises: a) lithostratigraphic signals, including many new proxies, such as synthetic inorganic crystalline mineral-like compounds, microplastics, fly ash and black carbon, in addition to direct modification through human terraforming of landscape and indirect influences on sedimentary facies through drivers such as climate change; b) chemostratigraphic signals including inorganic and organic contaminants and isotopic shifts of carbon and nitrogen; c) fallout from above-ground nuclear weapons testing; d) stratigraphic effects of climate warming, sea-level rise and ocean acidification; and e) biostratigraphic signals, especially range and abundance changes characterised by unprecedented rates and extents of non-native species introductions, increased population and species extinction and extirpation rates. These correlative markers are present in many kinds of geological deposits around the world. This ubiquity of signals verifies that the Anthropocene can be widely delineated as a sharply distinctive chronostratigraphic unit in diverse terrestrial and marine depositional environments, and reflects a major Earth System change that will have geologically lasting consequences.

As background, the Anthropocene was suggested as a new epoch by Paul Crutzen in 2000. The AWG was established in 2009 by the Subcommission on Quaternary Stratigraphy to examine the evidence for the potential inclusion of the Anthropocene in the International Chronostratigraphic Chart (ICC) and, if warranted, to formulate a definition and proposal. Various suggested start dates were considered, and the mid-20th century was found to be the only one associated with an extensive array of effectively globally isochronous geological markers reflecting the 'Great Acceleration' of population, industrialization and globalization. Alternative interpretations of the Anthropocene, including as an informal 'event', were considered in detail by the AWG and found to be inconsistent with the stratigraphic evidence.

1. INTRODUCTION

Anthropocene (meaning 'human new', from the ancient Greek terms for human (*anthropos*) and *cene*, from *kainos*, for 'new' or 'recent' time) is the name formally proposed here for the most recent interval of Earth history, extending from the mid-20th century (specifically 1952: see Part 2) to the present day. It is proposed as the third series/epoch of the Quaternary System/Period, following the Holocene Series/Epoch (Figure 1).

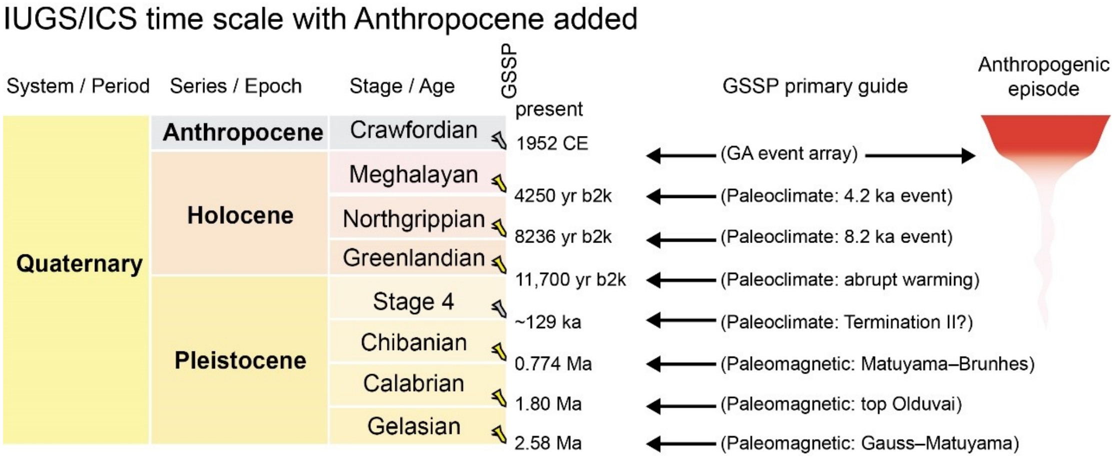

Figure 1. Chronostratigraphic subdivision of the Quaternary System/Period showing the position of the proposed Anthropocene Series/Epoch. Black type and yellow golden-spike symbols indicate ratified names and Global boundary Stratotype Sections and Points (GSSPs); grey type and grey golden spike symbols indicate names not yet approved (Stage 4 is a placeholder) and GSSPs in progress. Abbreviations yr b2k = years before 2000 CE; GA = Great Acceleration (modified from Head et al., 2022a).

With the effective introduction of the Anthropocene term very recently in 2000 (see Section 2), there has not been a long history of practical use, and no tradition among geologists of recognizing and distinguishing a coherent unit of time and strata in what was simply regarded as the latest part of the Holocene Epoch of the Quaternary Period (Zalasiewicz *et al*., 2023).

The Anthropocene Working Group (AWG) was established in 2009 by the International Commission for Stratigraphy's Subcommission on Quaternary Stratigraphy (SQS), to analyse the Anthropocene as a potential addition to the International Chronostratigraphic Chart (ICC), which forms the basis for the Geological Time Scale (GTS). The AWG was appointed to investigate whether this term and concept had geological validity and, if so, to then propose a formal definition consistent with established stratigraphic practice. With this remit, it has analysed, published on, and widely and openly discussed diverse aspects of this new stratigraphic concept, including: the origins and application of the term; the scale and timing of anthropogenic drivers and their subsequent reflection in the lithostratigraphic, chemostratigraphic and biostratigraphic records, including determination of a preferred primary marker; the most appropriate rank; the need for the term and definition to represent geological and Earth System reality; consideration of the relative merits of a Global Standard Stratigraphic Age (GSSA), or a Global boundary Stratigraphic Section and Point (GSSP); assessment of the optimal age of onset of the Anthropocene; the practical recognition of the Holocene–Anthropocene boundary in different kinds of archive; and a detailed proposal of a candidate GSSP and recommended supporting Standard Auxiliary Boundary Stratotypes (SABSs).

This submission (Part 1) represents the formal proposal to SQS, presenting the case for the Anthropocene to be recognised as the youngest series/epoch of the ICC, terminating the Holocene Series/Epoch. Section 2 covers the origin of the term Anthropocene and role of the AWG in researching the merit of the term as a chronostratigraphic unit. Section 3 describes the diverse range of stratigraphical proxies that provide a means to identify the Anthropocene and help delineate the base, and Section 4 discusses the nature of the physical record of the Anthropocene present in a range of sedimentary environments. Section 5 provides the evidence in support of the Anthropocene at series/epoch rank, based upon assessment of the key stratigraphic markers in relation to the Holocene Series/Epoch and component stages/ages. Details of the current AWG membership and the voting results for all decisions by the AWG are supplied in Part 1 Appendix 1 and 2, respectively. Responses to critiques of the Anthropocene as a chronostratigraphic unit are summarised in Appendix 3. Separately, Part 2 of the submission provides an assessment of candidate sites and the formal proposals for a GSSP (at Crawford Lake, Canada) and three SABSs, with recommended reference sections detailed in an appendix to Part 2.

2. ORIGIN OF THE TERM AND BRIEF HISTORY OF RESEARCH AS A STRATIGRAPHIC UNIT

The Anthropocene originated as a geological time term and concept at the 15th Scientific Committee meeting of the International Geosphere-Biosphere Programme (IGBP) from 22–25th February 2000. Paul J. Crutzen (then Vice-Chair of IGBP) improvised the term during an oral exposition of PAGES (Past Global Changes; one of IGBP's initial core projects) data to reflect the growing realisation that anthropogenic changes to the atmosphere, oceans and biosphere had intensified following the Industrial Revolution, to take the Earth System outside of the conditions and variability prevalent during the Holocene. He co-published an article first referring to the 'Anthropocene' in 2000 in an IGBP Newsletter (Crutzen & Stoermer, 2000), and subsequently in 2002 in *Nature* (Crutzen, 2002). Though originating in Earth System science (ESS), the Anthropocene was expressly indicated in these publications as a geological time term, an epoch to follow the Holocene. This differed from earlier notions of humanity as a transformer of nature or Earth processes which have been around for several centuries and which had included the term 'Anthropozoic' and subsequently had become conflated with geologically recent strata and formed part of the characterisation of the Holocene Epoch (see Grinevald et al., 2019). But this association did not form part of the definition of the Holocene and its component stages, which were defined based upon non-anthropogenic climatic variations and with a realisation that human activity was not significantly modifying the Earth System – which is evidently correct at least until the late 18th Century.

The Anthropocene began to be widely used and published among the ESS community (e.g., Meybeck, 2001, 2003; Steffen *et al*., 2004, 2007). Continued research within the IGBP community led to the recognition that the time since ~1950 CE has seen the most rapid transformation of the human relationship with the natural world in the history of humankind (Steffen *et al*., 2004). A sharp upward inflexion of many trends of global significance in the mid-20th century was recognised and termed the 'Great Acceleration' (Hibbard *et al*., 2006) and first used in a journal article in 2007 (Steffen *et al*., 2007), in which it was regarded as a 'second stage' of the Anthropocene.

The emerging visibility of the Anthropocene led to a preliminary analysis by the Stratigraphy Commission of the Geological Society of London (Zalasiewicz *et al*., 2008) in which they suggested that a stratigraphic case might exist for the Anthropocene and that the term should be investigated further as a potential new unit of the International Chronostratigraphic Chart. This study resulted in an invitation by the Chair of the SQS to set up the AWG in 2009. The AWG developed as a considerably more diverse body than is typical of ICS working groups, as the Anthropocene time interval is one where geological processes overlap not only with a range of human forcings but with an increasingly detailed and sophisticated observational record of both human-driven and Earth processes: hence it has included not only stratigraphers but Earth System scientists, oceanographers, historians, archaeologists, geographers and an international lawyer, to include consideration of questions of potential wider societal relevance and application (e.g., Vidas, 2015; Whitmee, 2015).

Over the past decade, it has become one of the most intensively studied intervals of geological time with several new scientific journals launched, including *Anthropocene*, *The Anthropocene Review*, *Anthropocene Science*, *Anthropocene Coasts*, and *Elementa: Science of the Anthropocene*. As of 31st August 2023, "Anthropocene" appeared in the title in 9,592 publications recorded by Web of Science Core Collection since 2001. Given the acceleration in citing 'Anthropocene' in the scientific literature, formal definition clarifies and increases the utility of a term that is currently widely, but potentially ambiguously, used (Vidas *et al*., 2019; Zalasiewicz *et al*., 2021). In this sense the AWG has aimed to address the major task of commissions and subcommissions of the IUGS "*to establish standards in appropriate fields*" and "*to promote public awareness of the geosciences*"; and to follow the aims of IUGS as stated in the statues and bylaws, "*applying the results of these studies to sustain Earth's natural environment,...for the benefit of society in the attainment of their economic, cultural and social goals*".

The remit of the AWG from the outset was to analyse the Anthropocene as a potential chronostratigraphic/ geochronologic unit, using standard stratigraphic criteria to evaluate whether it would be comparable to other units of the GTS. If so, the concept can be consistently and unambiguously used in both geological and wider discussions. As part of this evaluation process, the AWG compiled several thematic volumes and a book summarizing the first decade of AWG analysis (Williams *et al*., 2011, Waters *et al*., 2014, Zalasiewicz *et al*., 2019, Waters *et al*., 2023) along with an additional ~30 multi-author AWG peer-reviewed publications, some of which are listed in the references.

The broad scope of AWG publications has undoubtedly contributed to the proliferation of use of the Anthropocene as a term, not least because it has been widely discussed and adopted as a concept by disciplines well outside of the Earth sciences, and ranging across the social sciences, humanities and arts (e.g., Biermann, 2014; Clark, 2014; Davis & Turpin, 2015). Interpretation has also expanded well beyond the original ESS meaning and its chronostratigraphic interpretation (which are essentially congruent: see Steffen *et al*., 2016; Zalasiewicz *et al*., 2017c) into a broader range of 'human-centred' meanings (Zalasiewicz *et al*., 2021). The term Anthropocene has even been applied to lunar geochronology, with suggestion of a Lunar Anthropocene commencing ~1959 CE (Holcomb *et al*., 2023).

These wider meanings of the term are mostly not consistent with a chronostratigraphic definition, for instance including a long and loosely constrained time range (e.g., 'early Anthropocene' interpretations stretching into the Holocene, and even into the Pleistocene), and/or having globally diachronous and vaguely defined limits reflecting the slow growth and spread of human colonization of the Earth over many millennia (e.g., Smith & Zeder, 2013; Ruddiman, 2013; Bauer & Ellis, 2018). Among suggestions as a potential GSSP was to use the ~1610 CE 'Orbis' spike 10 ppm fall in atmospheric CO_2, as recorded in an Antarctic ice core (Lewis & Maslin, 2015) as a marker for the effects associated with the arrival of Europeans in the "New World" in 1492, e.g., major human population loss, increased globalization of human foodstuffs, regional forest recoveries and associated carbon sequestration, and influx of neobiota. However, the Orbis spike is not correlatable in most geological archives and has questionable linkage to an anthropogenic cause. The magnitude of the Orbis dip in CO_2 is dwarfed by the later increase, particularly since the mid-20th century (see Zalasiewicz *et al*., 2015b), and associated proxy signals are diachronous over centuries.

A recent suggestion is for an informal 'Anthropocene event' (Gibbard *et al*., 2022a, b; Merritts *et al*., 2023), a human-focused (i.e., not geologically grounded), diachronous interdisciplinary phenomenon (somewhat similar to other diachronous developments of human culture, e.g., the Neolithic and Middle Ages) extending back variably some 50 millennia or more. The 'event' concept of Gibbard and colleagues is fundamentally different to the chronostratigraphic Anthropocene concept of the AWG, being formulated within a non-standard interpretation of event stratigraphy, atypical of how geological events are classified in Quaternary and many older strata. The 'event' suggestion obscures and minimises the clear mid-20th century transformation of the Earth System evident in sedimentary strata (e.g., fig. 1 of Gibbard *et al*., 2022a, b), a transformation that may be clearly and quantitatively expressed (Head *et al*., 2022c, 2023b; Waters *et al*., 2022, 2023b; see also Syvitski *et al*., 2020). Nevertheless, recognizing the slow unfolding of human history as an Anthropogenic Modification Episode (Waters *et al*., 2022), distinct from a chronostratigraphic Anthropocene that signals a geologically sudden and lasting change in the Earth System, is helpful in labelling how humans have progressively changed the planet.

These non-chronostratigraphic suggestions were triggered by disagreement with the brevity, ongoing nature, and novel and geologically unusual nature of many of the signals associated with the Anthropocene, while its 'human' and sociopolitical associations have attracted criticism from among both geological (e.g., Finney, 2014; Gibbard & Walker, 2014; Head & Gibbard, 2015; Walker et al., 2015; Finney & Edwards, 2016; Gibbard & Lewin, 2016; Swindles *et al*., 2023) and non-geological (e.g., Autin & Holbrook, 2012; Braje, 2016; Ruddiman, 2018; Bauer & Ellis, 2018; Nielsen, 2021, 2022) communities. All criticisms made to date have been effectively answered on stratigraphical grounds (Zalasiewicz *et al*., 2017b, 2018, 2023; Head *et al*., 2022, 2023): Table 1 in Appendix 3 lists some of the common criticisms of a potential chronostratigraphic Anthropocene and the corresponding responses published by the AWG.

3. REVIEW OF STRATIGRAPHIC MARKERS FOR THE ANTHROPOCENE

Abundant mid-20th century planetary-scale markers in the geological record represent a profound adjustment to the Earth System in response to rapid and massive increases in human population, energy consumption and greenhouse gas emissions, industrialisation, introduction of novel technologies, and globalisation (Syvitski *et al*., 2020; Head *et al*., 2021). Together, these Earth System responses were labelled the 'Great Acceleration' by Steffen *et al*. (2007), based on datasets that reveal marked post-1950 CE changes in socio-economic factors and biophysical processes as well as resulting environmental and climatic changes (Steffen *et al*., 2004, 2007, 2015). The scale of the Great Acceleration, seen against the wider context of the human planetary impact throughout the last 12,000 years (Syvitski *et al*., 2020), emphasises the profound novelty of the changes experienced since the 1950s, establishing humanity as an overwhelming Earth System force (albeit a force that is neither unified nor uniform) with an abrupt geological expression.

This section, largely sourced from Zalasiewicz *et al*. (2020) and updated with subsequent information, provides the basis of the investigations into the proposed GSSP/SABSs/reference sections discussed in Part 2. The key markers are described in the context of their causation and expression in geological successions, with key references (Table 1).

3.1 Particles of novel minerals and rocks

3.1.1 An unprecedented increase in Earth's mineral-like diversity

Lithostratigraphic criteria for the Anthropocene include a large and growing suite of novel anthropogenic 'inorganic crystalline mineral-like compounds'. These artificial chemical compounds have been specifically excluded from the mineral classification of the International Mineralogical Association (Nickel & Grice, 1998) – although not before 208 anthropogenic minerals had been formally defined and ratified. Nevertheless, the many subsequent novel inorganic crystalline compounds produced by industry and research are minerals in all but formal name, and through these the Anthropocene may be said to include a considerable and distinctive mineralogical signature.

The production of synthetic anthropogenic 'minerals' intensified with the Industrial Revolution and accelerated post-1950. For instance, as regards the purification of metals, aluminium, extremely rare in nature in native form, has seen cumulative production of >500 million tons, the vast majority since the mid-20th century when aluminium became the most produced non-ferrous metal, while the production of iron in that time has been ~30 times greater (Zalasiewicz *et al*., 2014a).

Table 1 [over page]. Some key stratigraphical markers for the Anthropocene and studies discussing the relevance of these proxies to the Anthropocene (from Waters et al., 2022; Zalasiewicz et al. in press). Abbreviations for key processes of formation (ordered with most important anthropogenic sources first): FFB–Fossil fuel burning, IP–Industrial pollution from multiple sources, M/S–mining/smelting, NT–Nuclear tests/energy/reprocessing, A/D–Agriculture/Deforestation, CC–Climate change/ acidification, and ST–Species translocations.

Type	Key markers	Key processes	References
Exogenic particles	Concrete	IP	Waters & Zalasiewicz (2017)
	Microplastics	IP	Ivar do Sul & Costa (2014); Zalasiewicz *et al.* (2016); Leinfelder & Ivar do Sul (2019)
	Fly ash (SCP/SAP)	FFB	Rose (2015); Swindles *et al.* (2015); Fiałkiewicz-Kozieł *et al.* (2016)
	Black carbon soot/microcharcoal	FFB, IP, A/D	Han *et al.* (2017, 2022, 2023)
	Glass microspheres	IP	Gałuszka & Migaszewski (2018)
Geochemical (organic & inorganic)	CO_2	FFB, IP, A/D	MacFarling Meure *et al.* (2006)
	CH_4	A/D, FFB	MacFarling Meure *et al.* (2006)
	S, SO_4^{2-}	FFB, IP	Mayewski *et al.* (1990); Fairchild (2019)
	C stable isotopes	FFB	Rubino *et al.* (2013)
	N_2O/nitrates	A/D	Wolff (2013)
	N stable isotopes	A/D	Hastings *et al.* (2009); Holtgrieve *et al.* (2011)
	Hg	M/S, FFB, IP	Hylander & Meili (2002)
	Heavy metals	M/S, IP, FFB, A/D	Gałuszka & Wagreich (2019)
	Pb isotopes	M/S, IP, FFB	Dean *et al.* (2014)
	Polycyclic aromatic hydrocarbons (PAH)	FFB, IP, M/S, A/D	Bigus *et al.* (2014); Kuwae *et al.* (2023)
	Polychlorinated biphenyls (PCBs)	IP	Gałuszka *et al.* (2020); Kuwae *et al.* (2023)
	Pesticides (e.g., DDT)	A/D	Gałuszka & Rose (2019)
Radiogenic isotopes	^{241}Am, ^{137}Cs	NT	Appleby (2008); Foucher *et al.* (2021)
	Pu isotopes	NT	Hancock *et al.* (2014)
	^{14}C	NT	Hua *et al.* (2021); DeLong *et al.* (2023)
	^{129}I	NT	Bautista *et al.* (2016); Han *et al.* (2023)
Climate / pH	Oxygen isotopes	CC	Masson-Delmotte *et al.* (2015)
	Element ratios (Sr/Ca)	CC	Tierney *et al.* (2015)
	Boron isotopes	CC	Waters *et al.* (2019)
Biotic turnover	Molluscs	ST	Hausdorf (2018); Himson *et al.* (2020); Williams *et al.* (2022)
	Coral reef ecological turnover	CC, IP, A/D	Hoegh-Guldberg (2014); Hughes *et al.* (2017); Leinfelder (2019)
	Diatoms	CC, IP, A/D	Wilkinson *et al.* (2014); McCarthy *et al.* (2023); Marshall *et al.* (2023)
	Benthic foraminifera	A/D, IP, ST, CC	Wilkinson *et al.* (2014); Jonkers *et al.* (2019)
	Ostracods	IP, A/D, ST	Wilkinson *et al.* (2014); Himson *et al.* (2023)
	Pollen	A/D, ST, CC	Wilkinson *et al.* (2014)
	Zooplankton	CC	Wilkinson *et al.* (2014); Jonkers *et al.* (2019)
	Dinoflagellate cysts	A/D, IP	Wilkinson *et al.* (2014)
	Testate amoebae	CC, IP	Fiałkiewicz-Kozieł *et al.* (2023)
	Pigments/ biomarkers	A/D, CC	Oleksy *et al.* (2020); Kuwae *et al.* (2023)

Such bulk production has been accompanied by a striking diversification of novel anthropogenic (synthetic) mineral-like compounds (Figure 2), such as tungsten carbide and novel synthetic garnets and now exceeds 200,000 (sources in Hazen *et al.*, 2017, updated). This explosion in diversity has been accompanied by redistribution of both natural and anthropogenic minerals and mineral-like compounds across the Earth, producing widespread, long-lived and distinctive stratigraphic markers. The first synthesis of the mineral-like compounds and their production on industrial scales is known from historical records, providing a constraint to their earliest possible presence in sedimentary successions (Figure 3).

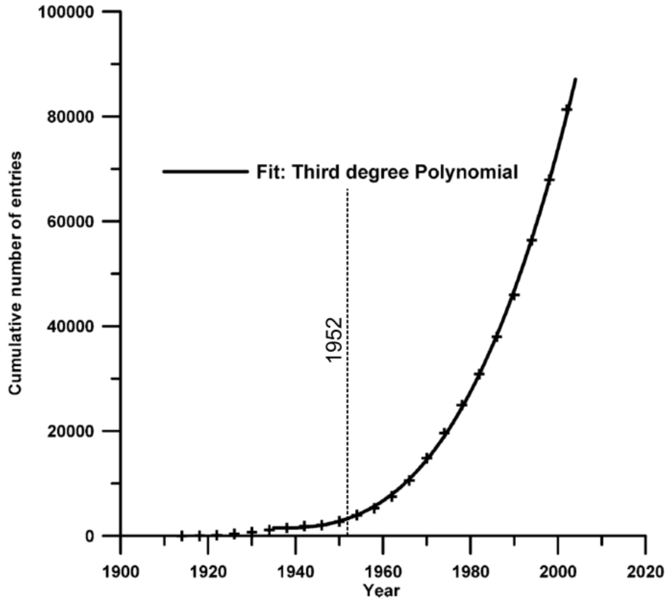

Figure 2. Cumulative number of new entries to the Inorganic Crystal Structure Database (ICSD). From Behrens & Luksch (2006). Note that since the production of this figure in 2006, the number of new 'synthetic minerals' has more than doubled.

3.1.2 Plastics

A range of novel anthropogenic organic compounds are represented by plastics, essentially a post-mid-20th century phenomenon, the production of which in 2015 was ~380 Mt/yr (since updated to 390.7 Mt in 2021), with cumulative production to 2015 of 8.7 Gt (Figure 4a; Geyer *et al.*, 2017). Most of the plastics produced are either still in use or are in landfills, though significant amounts have leaked into sedimentary systems on land and with ~0.5 Mt/yr riverine export of plastics to the seas (Strokal *et al.*, 2023). Most notably, synthetic fibres (Figure 4a), which can also be transported in the atmosphere, have become dispersed widely, and are already effective markers of deposits of recent decades, with microplastics now near-ubiquitous in marine sediments (e.g., Zalasiewicz *et al.*, 2016a, 2019: Peng *et al.*, 2018; Leinfelder & Ivar do Sul, 2019). The date of invention, and more importantly commercial production, of the various plastic polymers is well known and provides a basis for recognizing range zones for the various key polymers (Figure 3). Attempts to characterise the temporal variation of microplastic abundance as a stratigraphic tool in sedimentary successions have only commenced in the last few years, notably in Beppu Bay (Hinata *et al.*, 2023; Kuwae *et al.*, 2023) and East Gotland (Kaiser *et al.*, 2023), proposed SABSs and reference section, respectively (see Part 2) and in Xiamen Bay, China (Long *et al.*, 2022; Figure 4b). A marine sediment core from the Santa Barbara Basin off California shows exponential increases in microplastic abundance from 1945 to 2009 CE aligned with global plastic production figures (Brandon *et al*., 2019). However, this study also showed the difficulty in excluding contamination by microplastics during core collection and processing, with small amounts of microplastics present at anomalous levels older than possible for specific polymers.

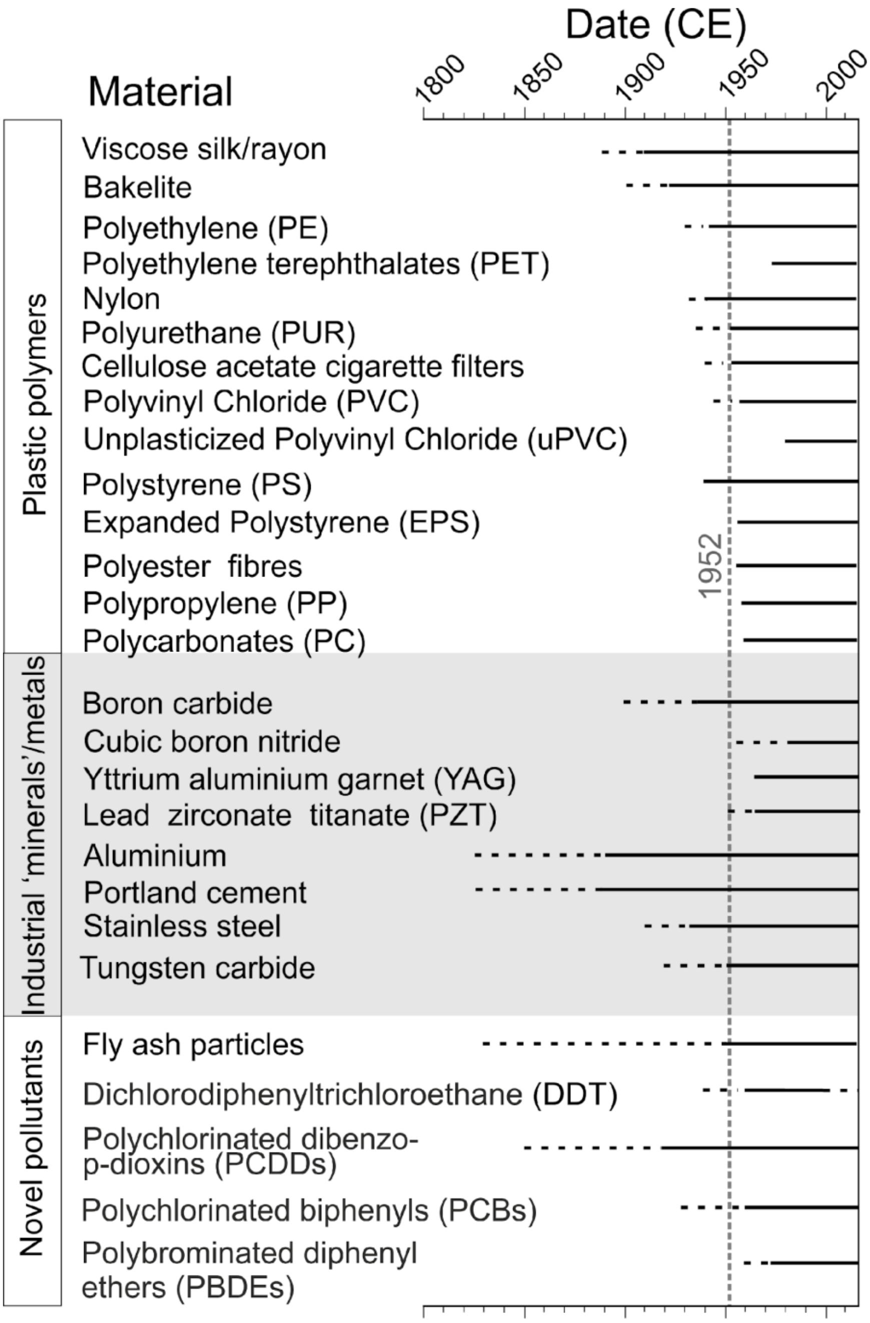

Figure 3. Range zones of common novel plastic polymers, synthetic mineral-like compounds, metals and industrial pollutants; dashed lines denote relative low abundances. NB dioxins occurred naturally before ~1850 CE but in low concentrations. From Waters et al. (2018b).

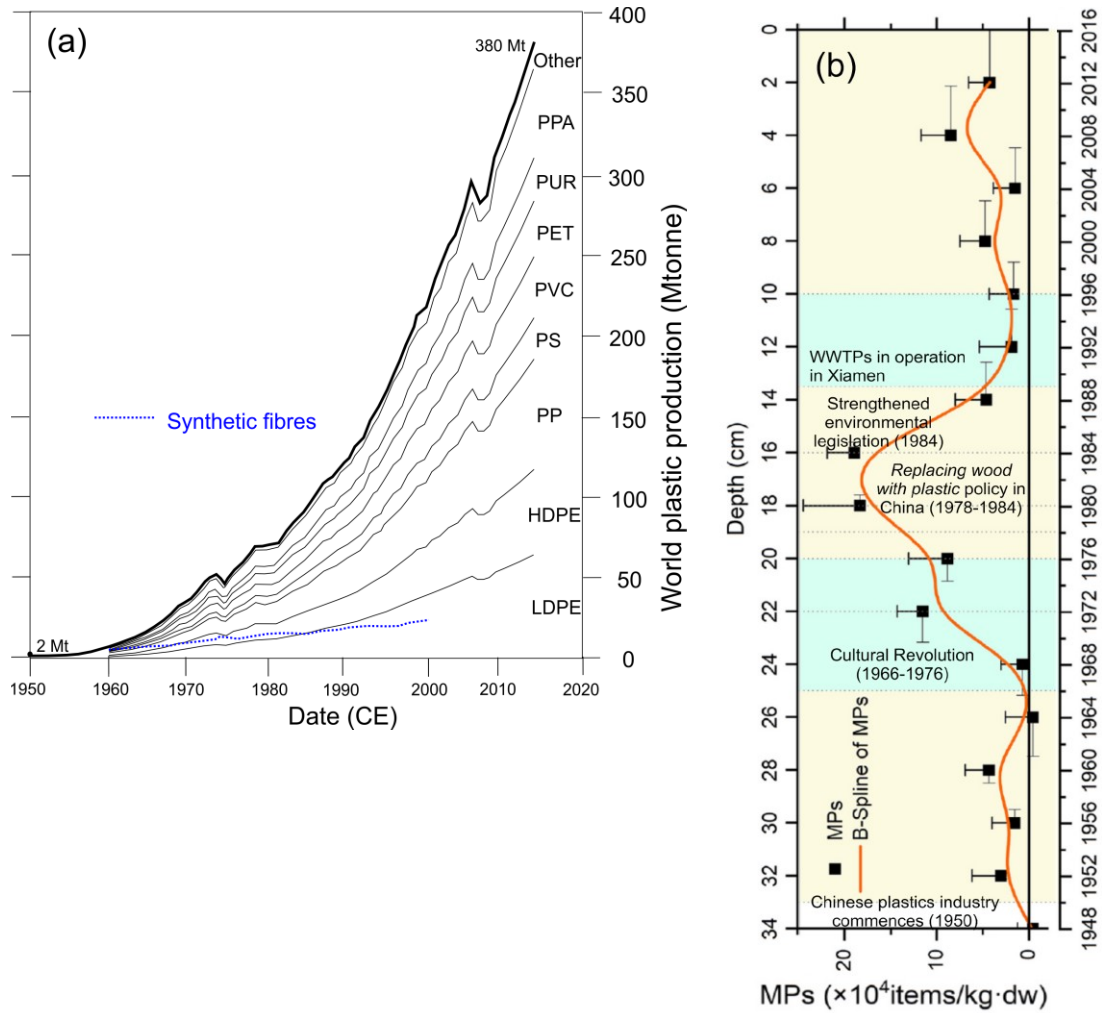

Figure 4. (a) *Cumulative production of plastic (from Geyer et al., 2017) and synthetic fibres from Thompson et al. (2004), reproduced from Zalasiewicz et al. (2020) and Zalasiewicz et al. (2016), respectively. Abbreviations for polymers are as shown in Figure 3, except: HDPE-high density polyethylene, LDPE-low density polyethylene, PPA-polyphthalamide; (b) profile of microplastic abundance in coastal sediments in Xiamen Bay, China, (adapted from Long et al., 2022, fig. 2a) showing variations reflecting regional economic changes. The first MPs occur in a layer deposited in 1952 CE, low MP abundances occurred during the Cultural Revolution (1966–1976) after which MP concentrations soared during increased industrialisation of the area, peaking in 1988 CE with a drastic decline to a low in 1996 CE related to increased regulation of emissions. Increasing MPs over subsequent decades may suggest that these mitigation measures are becoming less effective.*

3.1.3 Fly ash and other industrial combustion products

Fossil fuel burning has resulted in a global distribution in recent sediments of fly ash, both as spheroidal carbonaceous particles (SCPs; Rose, 2015; Swindles *et al*., 2015; Rose & Gałuszka, 2019), inorganic ash spheres (IASs; Rose, 1996) or spheroidal aluminosilicate particles (SAPs; Smieja-Król & Fiałkiewicz-Kozieł, 2014) and mullite (Smieja-Król *et al*., 2019; Fiałkiewicz-Kozieł *et al*., 2023); SCPs have been suggested as a potential primary marker for the Anthropocene (Rose, 2015; Swindles *et al*., 2015). SCPs and SAPs are only produced by the high-temperature combustion of coal-series and fuel oils, especially in thermal power stations, and mullite from high-temperature burning of coal. SCPs are small, up to tens of micrometres in diameter, inert, of high preservation potential, often with a distinctive pitted morphology, and can be readily counted after chemical extraction from sedimentary archives. A study by Rose (2015) in 76 lake successions around the world showed a common, though geographically variable, pattern of SCPs first appearing in the mid-19th century peaking in the 1970s to 1990s, but typically starting later in the southern hemisphere (Figure 5). The lake successions show a marked SCP upturn around the 1950s, providing a consistent marker globally, including during the study of the potential GSSP/SABSs/reference sections (McCarthy *et al*., 2023; Han *et al*., 2023; Stegner *et al.,* 2023; see Part 2). In addition, SCPs were shown to be promising markers in the Beppu Bay and East Gotland anoxic marine basins (Inoue *et al*., 2022; Kuwae *et al*., 2023; Kaiser *et al*., 2023), the Śnieżka Peatland (Fiałkiewicz-Kozieł *et al*., 2023) and were for the first time recorded in Antarctic ice (Thomas *et al*., 2023a, b) they are present in the Vienna anthropogenic deposits from the late 19th century, with elevated levels from 1945 to post-1959 CE (N.L. Rose, *pers. comm*., 3rd August 2023). SCPs do not accumulate in speleothems and have not been found in the coral sites (Zinke *et al*., 2023; DeLong *et al*., 2023).

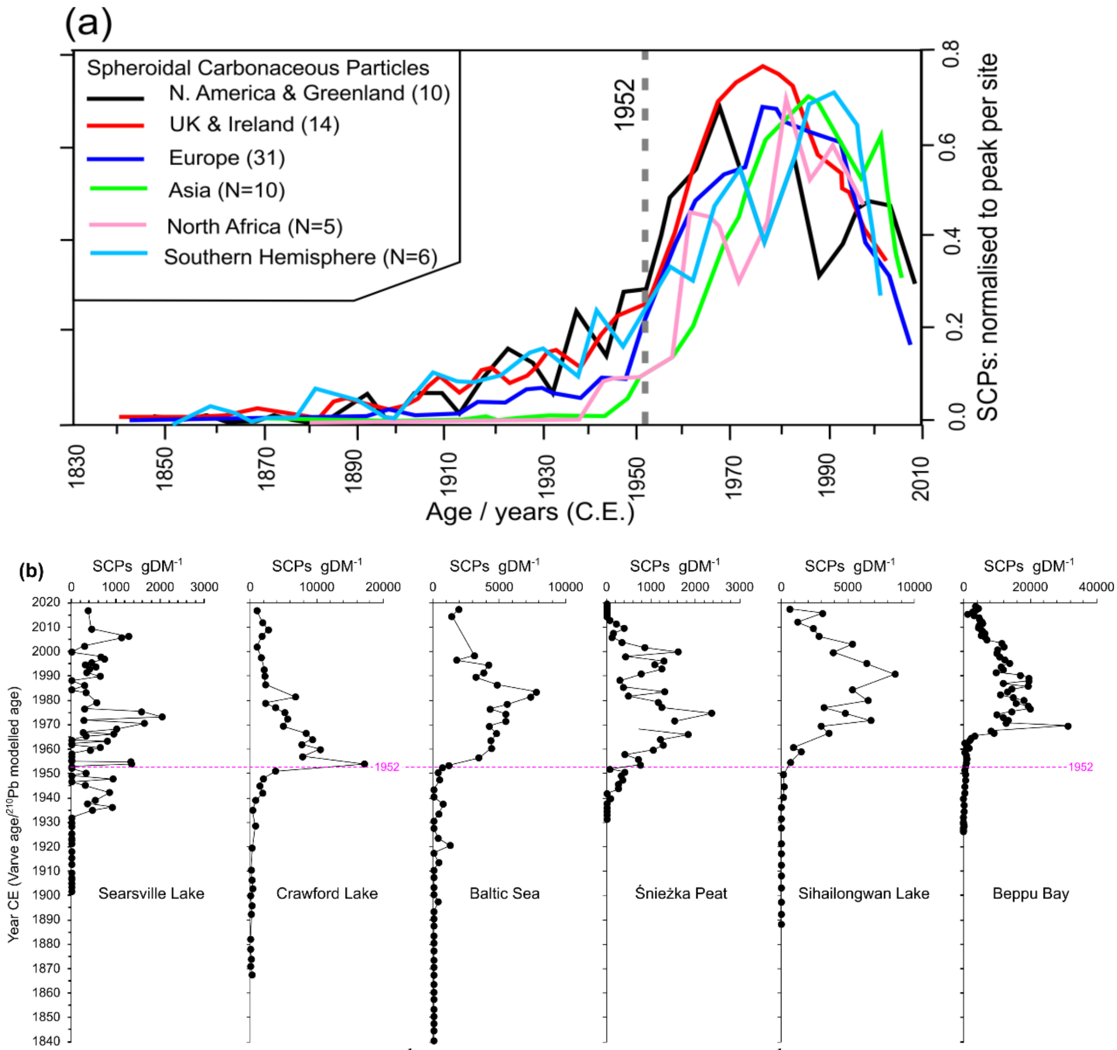

Figure 5. (a) Global mid-20th century rise and late 20th century spike in SCPs, normalised to the peak value in each lake core (from Waters et al., 2016, based on data from Rose, 2015); (b) Concentrations of SCPs (units: numbers of particles per gram dried sediment) in reference sites included in this study (see Part 2).

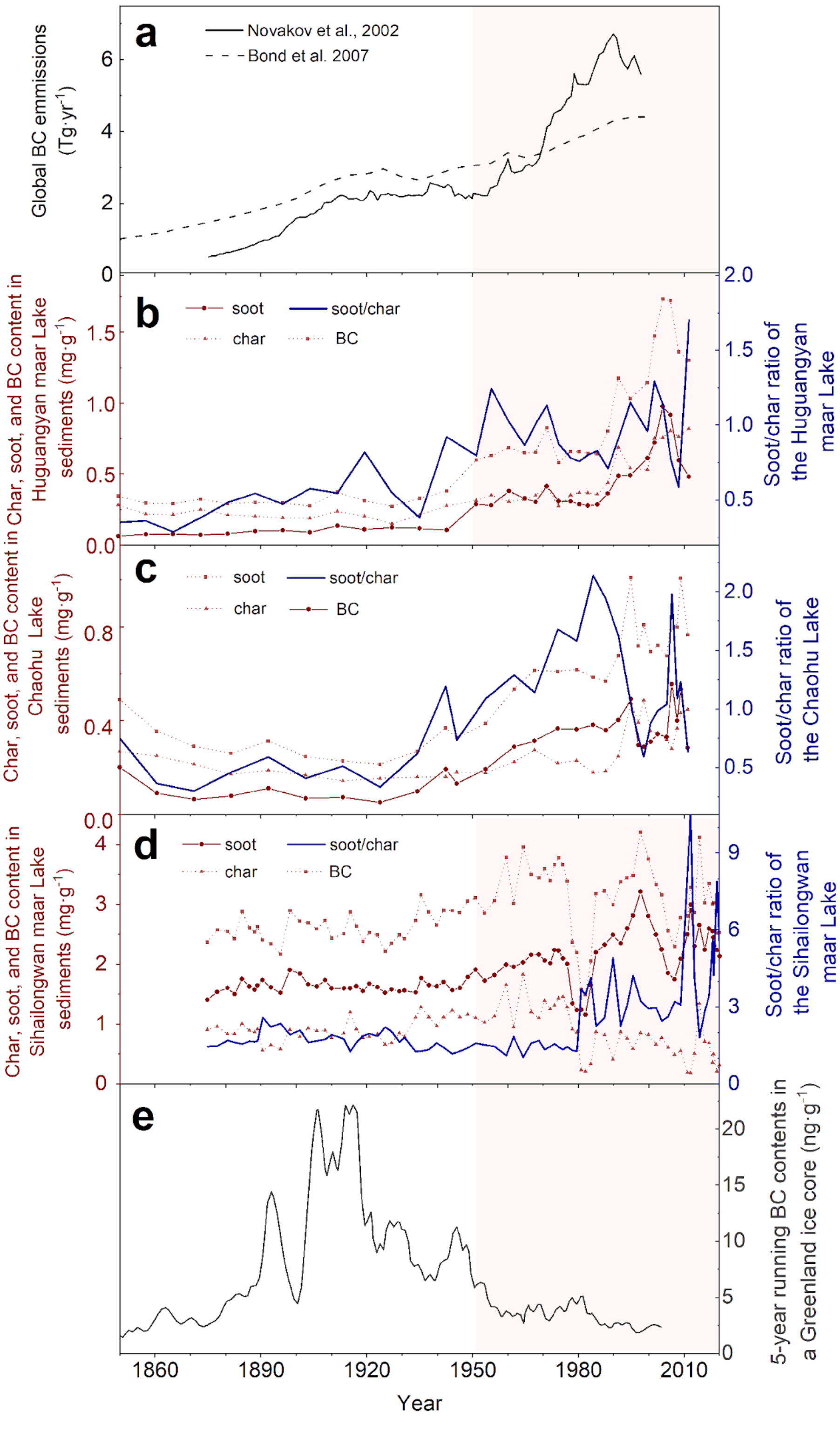

Figure 6. (a) Global black carbon (BC) for available annual fossil fuel-consumption data of 1875–1999 (from Novakov et al., 2003) and BC data of 1850–2000 (from Bond et al., 2007); Variations of concentrations and mass-accumulation rates of BC, comprising char and soot in (b) the Huguangyan Maar Lake, China and (c) Chaohu Lake, China (from Han et al., 2016) and (d) the SABS site of Sihailongwan Maar Lake, China (Han et al., 2023); and (e) Black carbon concentrations (5-year running means) in Greenland ACT2 ice core from 1772 to 2003 CE (McConnell & Edwards, 2008).

SCPs are one component of a spectrum of black carbon (BC), composed of refractory carbonaceous particles produced by the incomplete combustion of biomass and fossil fuels; like SCPs, other BC particles are inert with high preservation potential (Waters & An, 2019). BC includes two carbonaceous subtypes, soot (relatively high-temperature combustion condensates) and char (relatively lower temperature combustion residues which can retain original structure). Soot particles are smaller than char, of submicron scale, and are easily transported on regional scales (Han *et al.* 2017, 2022) with short atmospheric lifetimes of days to weeks (Waters & An, 2019). Fossil-fuel combustion typically produces higher soot/char ratios than biomass burning (Han *et al*., 2017). Approximations have been made of the increasing global atmospheric load of BC from combustion of fossil fuels and biofuels (Novakov *et al*., 2003; Bond *et al*., 2007; Figure 6a). Variations in concentrations and mass-accumulation rates of BC, comprising char and soot in Chaohu Lake and Huguangyan Maar Lake, China, show clear increases from 1950 CE, suggesting rising fossil fuel and biomass combustion at this time (Han *et al*., 2016; Figure 6b, c). BC soot analysed at Sihailongwan Maar Lake SABS site (Han *et al*., 2023) shows an upturn in concentrations around 1950 CE (Figure 6d; see also Part 2). Greenland BC, though, shows peak concentrations in early 20th century and markedly lower concentration from the mid-20th century reflecting reduced emissions from North America (McConnell & Edwards, 2008; Figure 6e).

3.1.4 Glass microspheres

Glass microspheres are commercially produced durable spherical glass particles (1–1,000 μm diameter) that include solid glass microspheres (glass microbeads) and hollow glass microspheres (microballoons or microbubbles). Industrial-scale production of the first solid glass microspheres started in 1914, while hollow glass microsphere production began in the 1950s (Gałuszka & Migaszewski, 2017; Rose & Gałuszka, 2019). They are now widely used as fillers in composite polymer materials and as additives in paints and coatings, especially on roads from which microspheres are commonly washed into river sediments via storm-water runoff (Gałuszka & Migaszewski, 2017; Irabien *et al*., 2020). Although glass microspheres provide excellent potential as a persistent marker in Anthropocene sediments, no work has detailed the stratigraphic profiling of this marker in sedimentary successions.

3.1.5 Novel anthropogenic rocks

The mineral diversification described above has been accompanied by a growth in the range and bulk of anthropogenic rock types. Some, including bricks and ceramics, have been made and used throughout much of the Holocene. Concrete, although intermittently made since Roman times, has since the mid-20th century been produced in increasingly prodigious amounts, and may be said to be a signature rock of the Anthropocene: some 27 Gt/yr (billion tons per year) are estimated to have been produced by 2015 CE (Figure 7) and cumulatively >500 Gt – the equivalent of a kilogram of concrete for each square metre of the Earth's surface – about half of which between 1995 and 2015 (Waters & Zalasiewicz, 2018). As clasts within the artificial ground that underlies urban areas, concrete my help broadly identify deposition during the Anthropocene (Terrington *et al*., 2018).

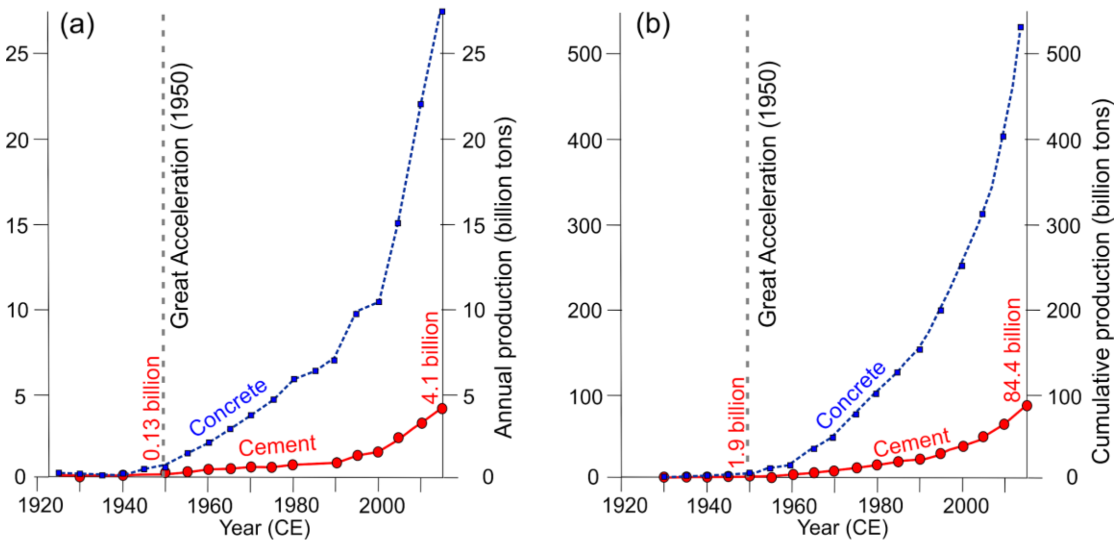

Figure 7. (a) annual global production and (b) cumulative production of cement and estimated concrete production (from Waters & Zalasiewicz, 2018).

3.1.6 Anthropocene erosion/sedimentation patterns

Anthropogenic sedimentation and erosion, associated with forest clearance, farming and urbanisation, took place through the Holocene, with profound acceleration from the mid-20th century. Several studies have indicated that movement of rock and soil by humans now exceeds natural rates of sedimentation and erosion, by an order of magnitude or more (Wilkinson & McElroy, 2007; Hooke *et al*., 2012). Since 1950, soil erosion rates are estimated to have tripled from 25 Gt/yr to 75 Gt/yr, while total sediment load has more than tripled (Syvitski *et al*., 2022; Table 2). Meanwhile, during the same interval the flux of sediment transported from land to ocean, including by rivers, wind, coastal erosion and glaciers, has decreased from 22.4 to 17.3 Gt/yr, in part due to the sequestration of sediment in reservoirs developed behind large dams, which increased in numbers from 7000 in 1950 to ~50,000 by 2015 (Syvitski *et al*., 2020). This markedly impacted sedimentation in coastal zones (see Subsection 4.3). Taking another perspective, a collation of global statistics on mineral (and overburden) production and construction estimated annual global anthropogenic sediment production to have risen from ~10 Gt in 1950 to 316 Gt in 2015; the latter figure is ~18 times greater than the rate of sediment supply by rivers, wind and glaciers to the world's oceans (Cooper *et al*., 2018).

Table 2 [over page]. A comparison of sediment loads for two representative years: 1950 and 2010. Natural transport processes play an ever-decreasing part in the movement of sediment on Earth during the Anthropocene. Adapted from Syvitski et al. (2022).

1950 (Gt/yr)	Sediment load type	2010 (Gt/yr)
25	Soil erosion	75
22.4	Land to sea flux	17.3
2.8	Reservoir sequestration	65
7.5	Construction	22.5
10.0	Coal and mineral mining	101
1.6	Aggregate mining	50
0.7	Dredging	9.8
2.9	Trawler fishing	22
0.1	Sand and gravel mining (rivers & coast)	2
1.7	Other consumption	54.1
70.2	**Total sediment load**	**299.6**

3.2 Geochemical (organic and inorganic)

Sen & Peuckner-Ehrenbrink (2012) calculated that the anthropogenic fluxes of up to 62 elements now exceed their natural fluxes, via activities such as mining, construction, fossil fuel burning and deforestation. This change underlies a further array of proxy signals that help characterise, and define, the Anthropocene.

3.2.1 Carbon cycle changes: carbon dioxide and methane

The carbon cycle has been affected by the accumulation in the atmosphere of ~1.1 trillion tons of anthropogenic carbon dioxide (CO_2), equivalent to a global layer of the pure gas at normal atmospheric pressure a little over a metre thick (Zalasiewicz *et al*., 2016b, updated). This is largely from the burning of fossil fuels, but with significant components from deforestation and related soil carbon changes, cement manufacture, and other processes. Atmospheric CO_2 levels started to rise significantly, from ~280 ppm in 1800 CE to ~310 ppm by 1950 CE (Etheridge *et al*., 1996; MacFarling-Meure *et al*., 2006; Rubino *et al*., 2013) and then more steeply to ~410 ppm by 2018 CE (Ritchie *et al*., 2020; Figure 8) and ~420 ppm today. As a marker for the base of the Anthropocene, this prominent upturn in atmospheric CO_2 concentrations is only directly recorded in glacial ice below firn levels. However, useful indirect markers of this rise exist as, for instance, changed carbon isotope patterns (see Subsection 3.2.2).

The rise in atmospheric methane (CH_4) levels, similarly recorded in polar ice, has been more pronounced than that of CO_2 (Zalasiewicz & Waters, 2019). Concentrations began to rise in the early 18th century (Wolff, 2014; Figure 9), and have continued rising to their annual level (2022 CE) of 1911 ppb (NOAA, 2023a). Carbon isotope patterns suggest that this rise was largely driven by fossil fuel-related emissions until ~2006, with a sharp subsequent change to surging emissions from wetlands that may reflect 'global reorganization of the planetary climate system' (Nisbet *et al*., 2023). As with the direct CO_2 record, the pronounced upturn in CH_4 concentrations is a marker for the base of the Anthropocene only in glacial ice below firn levels (e.g., Thomas *et al*., 2023).

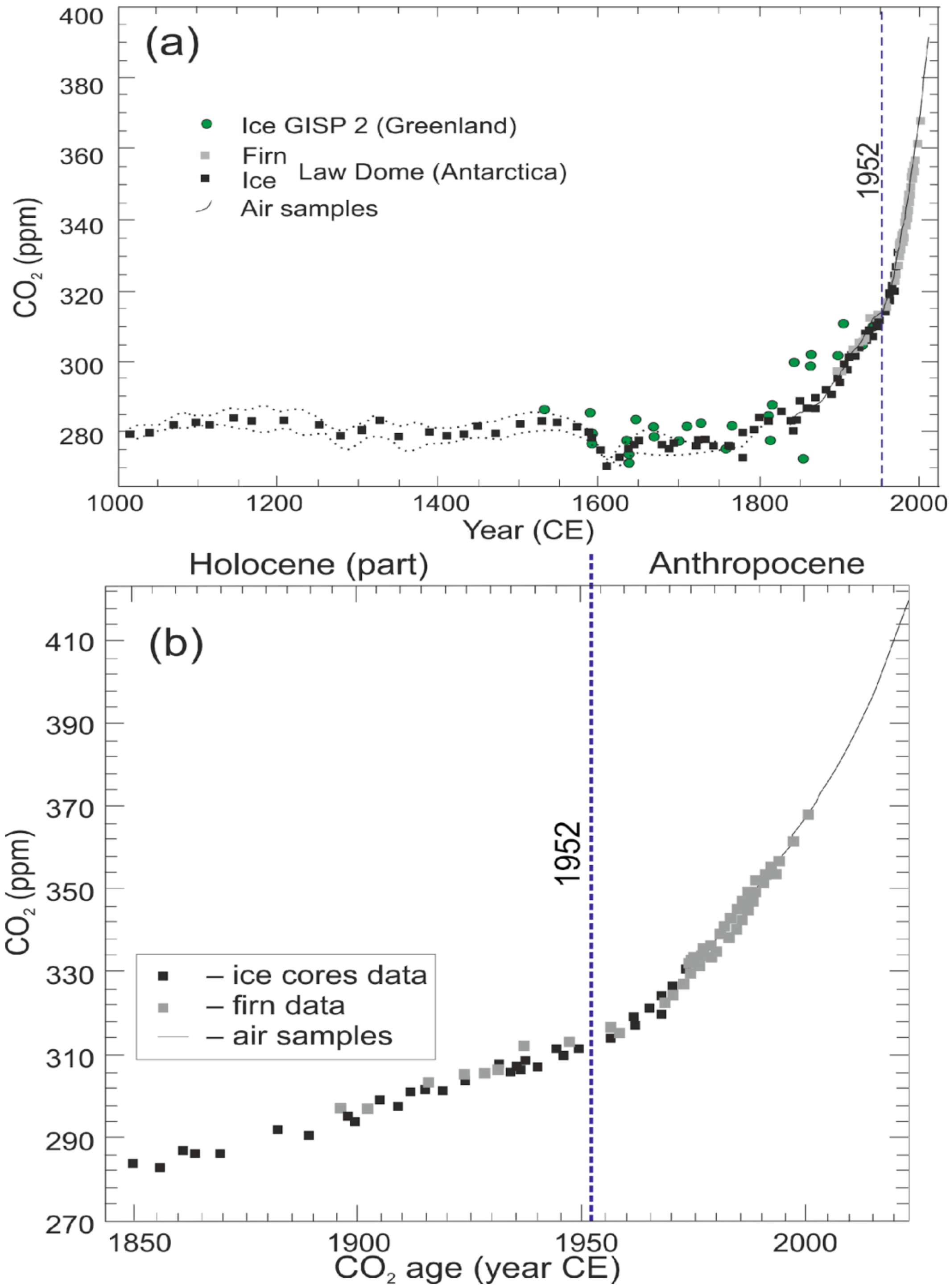

Figure 8. Atmospheric CO_2 records: (a) since 1000 CE from the Antarctic Law Dome ice core (Rubino et al., 2013) and Greenland GISP 2 ice core (Wahlen et al., 1991); reproduced from Zalasiewicz et al., 2020); (b) since 1850 CE from Antarctic Law Dome ice core, firn data and air samples (from Rubino et al., 2013, modified from Waters et al., 2016, and updated with data from Mauna Loa Observatory, Hawaii, from NOAA Climate.gov.).

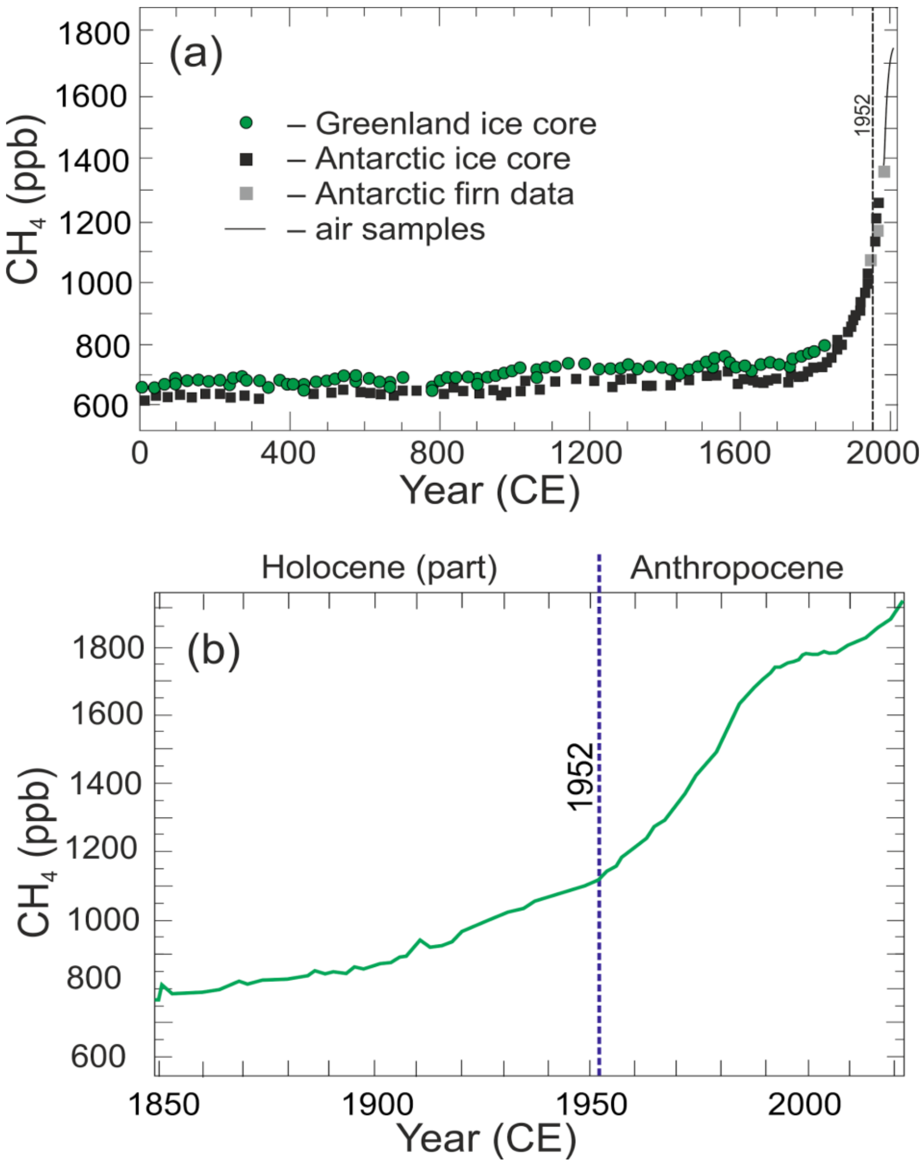

Figure 9. Atmospheric CH_4 records: (a) in ice core from Greenland GISP 2 (Mitchell et al., 2003) and Antarctic Law Dome ice core, firn data and air samples (Ferretti et al., 2005); reproduced from Zalasiewicz et al. (2020); (b) since 1850 CE in Antarctic Law Dome ice core, firn data and air samples (Ferretti et al., 2005, updated with data from Mauna Loa Observatory Hawaii from NOAA Climate.gov.).

3.2.2 The Anthropocene carbon isotope anomaly

Fossil fuel burning releases excess ^{12}C and causes 'lightening' of the composition of the surface carbon reservoir via the Suess effect (Zalasiewicz & Waters, 2019). This ongoing change in stable carbon isotopes is recorded directly in glacial ice as a ~2‰ decrease in $\delta^{13}C$ (Schmitt *et al*., 2012; Figure 10a). This contrasts with a slight tendency towards heavier carbon of <0.5‰ during the Holocene. The signal is also indirectly evident in stratigraphic components such as marine microfossils including foraminifera, tree rings (Figure 10b), peat, and coral skeletons (see Waters *et al*., 2018a; Figure 10c). Decreases, initiating in the late 18th century, show rapid downturns in the mid-20th century (Swart *et al*., 2010; Figure 10c). The reference section West Flower Garden Reef coral (Gulf of Mexico) shows a prominent decrease in $\delta^{13}C$ at 1956 CE (DeLong *et al*., 2023), compared to 1970 CE in the Flinders Reef coral off the Queensland coast

(Zinke *et al*., 2023) (see Part 2). The pattern across the other sites was inconsistent, with a decrease in 1950 CE at the Sihailongwan Maar Lake SABS site (Han *et al*., 2023), but an increase in the East Gotland Basin reference section in 1952 ± 4 CE (Kaiser *et al*., 2023) due to locally high primary production during post-1950 CE eutrophication. Typically, the stable carbon isotope signal is most clearly resolved in environments where the carbon is sourced from the atmosphere, with minimal input from sources of 'ancient' recycled organic carbon.

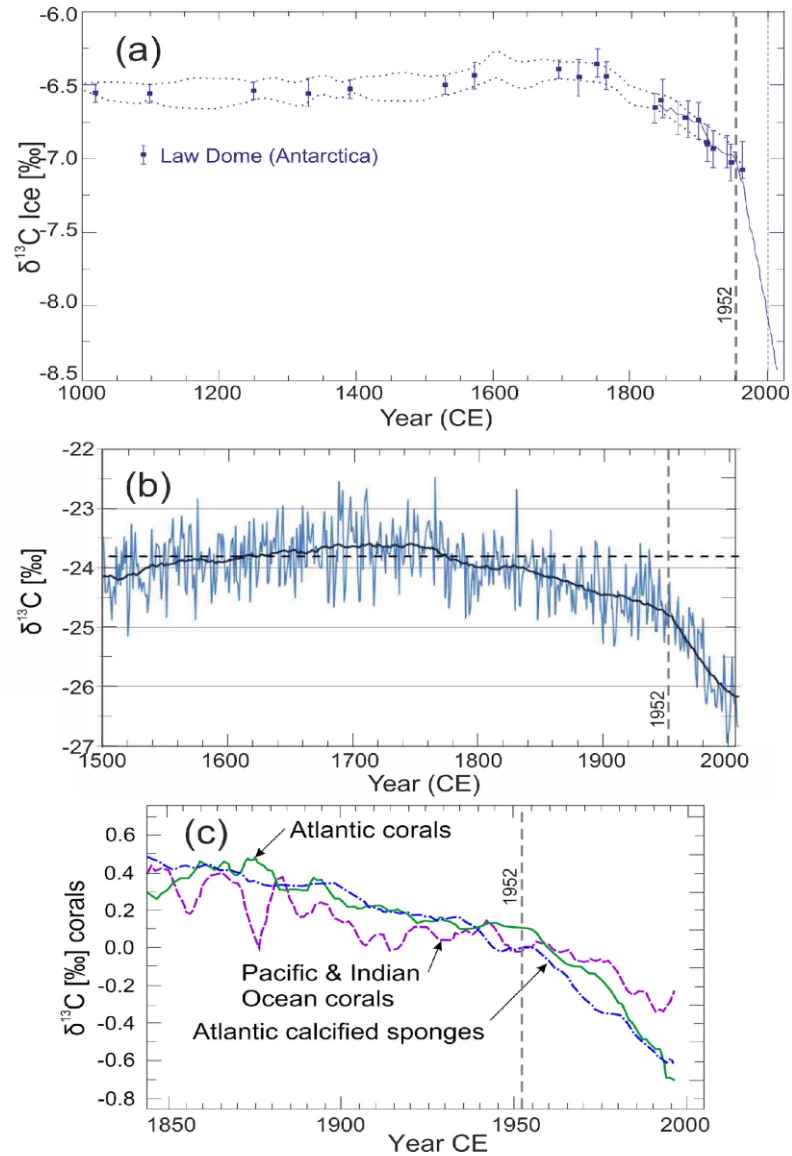

Figure 10. (a) δ^{13}C variability in the Antarctic Law Dome ice core (Rubino et al., 2013); (b) δ^{13}C variability for a composite tree ring chronology developed using Pinus sylvestris *trees from northern Fennoscandia (Loader et al., 2013). Fine blue line represents annually-resolved δ^{13}C variability, solid black line presents the annual data smoothed with a centrally-weighted 51-year moving average. Dashed line represents the mean δ^{13}C value for the "pre-industrial" period 1500–1799 CE; and (c) changes in δ^{13}C from Atlantic and Pacific/Indian ocean corals and Atlantic calcified sponges, shown as a five-year running mean (Swart et al., 2010). Reproduced from Zalasiewicz et al. (2020).*

3.2.3 Nitrogen and phosphorus cycle changes

Fossil fuel burning has increased concentrations of N_2O in polar ice, initiated ~1850 CE with an upturn from ~1950 CE (Figure 11a; Wolff, 2013), and the flux of nitrates recorded within Greenland glacial ice (Hastings *et al*., 2005, 2009), but not in Antarctic ice (Figure 11c). Unlike N_2O, nitrates accumulate in glacial ice rather than in air bubbles within the ice and so there is no lag between the age of the signal and the age of the ice. Other stratigraphic proxy signals include a prominent mid-20th century inflexion to lower $\delta^{15}N$ values in far northern lake deposits (Holtgrieve *et al*., 2011; Figure 11b) and Greenland ice cores (Figure 11c; Hastings *et al*., 2009). The inflexion is likely the result of far-travelled aerosols, which, with associated changes in diatom assemblages, have been suggested as an Anthropocene indicator (Wolfe *et al*., 2013; see Section 3.5). Marine successions, especially corals, record complex $\delta^{15}N$ patterns reflecting variable sources of underwater nutrients, including from nearby river systems bringing agricultural fertiliser runoff and animal and human wastes (e.g., Kaiser *et al*., 2023; DeLong *et al*., 2023).

Surface phosphorus levels have also doubled (Filippelli, 2002) but have not left such a clear signal, as phosphorus only has one stable isotope. Increased flux of phosphorus and nitrogen to coastal waters, in particular from the 1960s, has caused seasonal anoxic ‘dead zones’ to develop, which now cover an area of >250,000 km worldwide (Diaz & Rosenberg, 2008), and are recorded *inter alia* as changes in dinoflagellate cyst, ostracod and foraminiferal assemblages (Wilkinson *et al*., 2014).

3.2.4 Sulfur cycle changes

The sulfur signal during the Anthropocene is derived primarily from aerosols sourced from burning of sulfur-rich coal, and since ~1950 from industrial processes such as oil and gas refining and metal smelting (Fairchild, 2019), with peak emissions in the second half of the 20th century (Hoesly *et al*., 2018; Figure 12a). It is preserved in sedimentary archives as sulfate. This anthropogenic signal is superimposed on a natural background that also has strong spatial variations and that can change dramatically after volcanic eruptions that provide near-globally distributed pulses of sulfur dioxide to the atmosphere, providing useful chronological control for ice cores (e.g., Thomas *et al*., 2023a). Fossil fuel burning has led to increased sulfates in northern hemisphere glacial ice (Mayewski *et al*., 1990; Sigl *et al*., 2015; Figure 12a), though not in Antarctica (Sigl *et al*., 2015). Speleothems commonly record a decadal-scale lagged response compared with the atmosphere (Fairchild, 2018; Figure 12b). Industrially produced sulfate aerosols have a short residence time in the atmosphere and hence reflect local or regional pollution (Fairchild, 2019). As with nitrates, sulfates accumulate passively into snow and the record is determined from ice and not trapped air bubbles. Greenland ice cores show the increasingly industrial origins of sulfur from 1860 to 1970 CE by progressively lower $\delta^{34}S$ values (Patris *et al*., 2002), a trend also observed in the Ernesto Cave reference section (Figure 12b; Borsato *et al*., 2023) and in fir trees near to the cave (Figure 12c; Wynn *et al*., 2014). Total sulfur concentrations show upturns at the Beppu Bay SABS site in 1969 CE (Kuwae *et al*., 2023) and in 1960 ± 2 CE at Ernesto Cave (Borsato *et al*., 2023) (see Part 2).

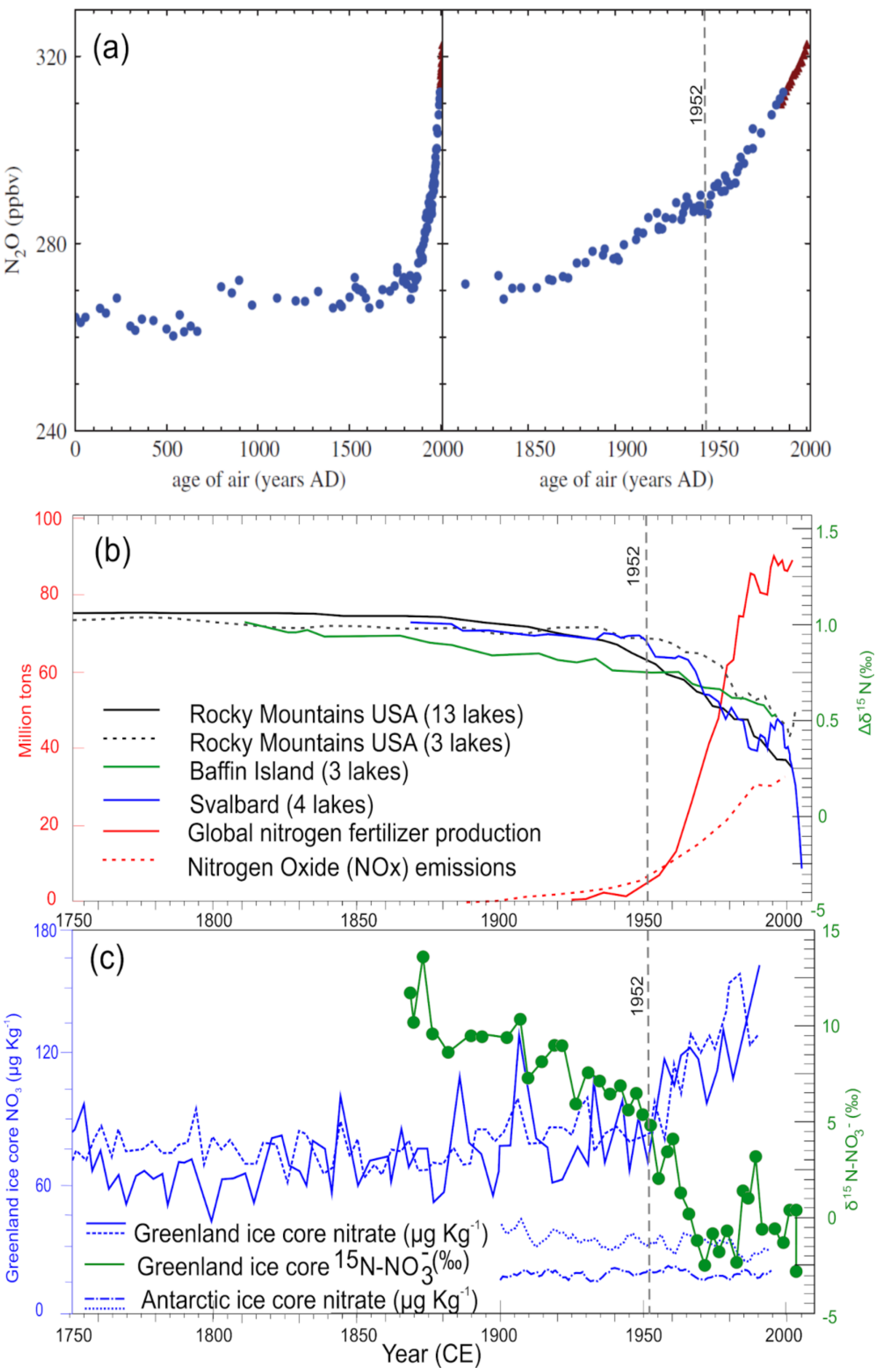

Figure 11. (a) N_2O concentrations in the Law Dome ice core (and firn (blue circles) over the last 2000 years and 200 years and annual averages for South Pole air (red triangles) (Wolff, 2013, fig. 1); (b) relative departures ($\Delta\delta^{15}N$) from mean pre-1900 CE $\delta^{15}N$ in Northern Hemisphere lakes (Wolfe et al., 2013), alongside annual rates of reactive N production from agricultural fertiliser and NOx emissions from fossil fuel combustion (Holland et al., 2005); (c) Coevolution of ice core NO_3 and $\delta^{15}N$ for NO_3 from GISP 2 Greenland ice core (Hastings et al., 2009) and nitrate concentrations from Law Dome and Siple Dôme Antarctic ice core (from Wolff, 2013).

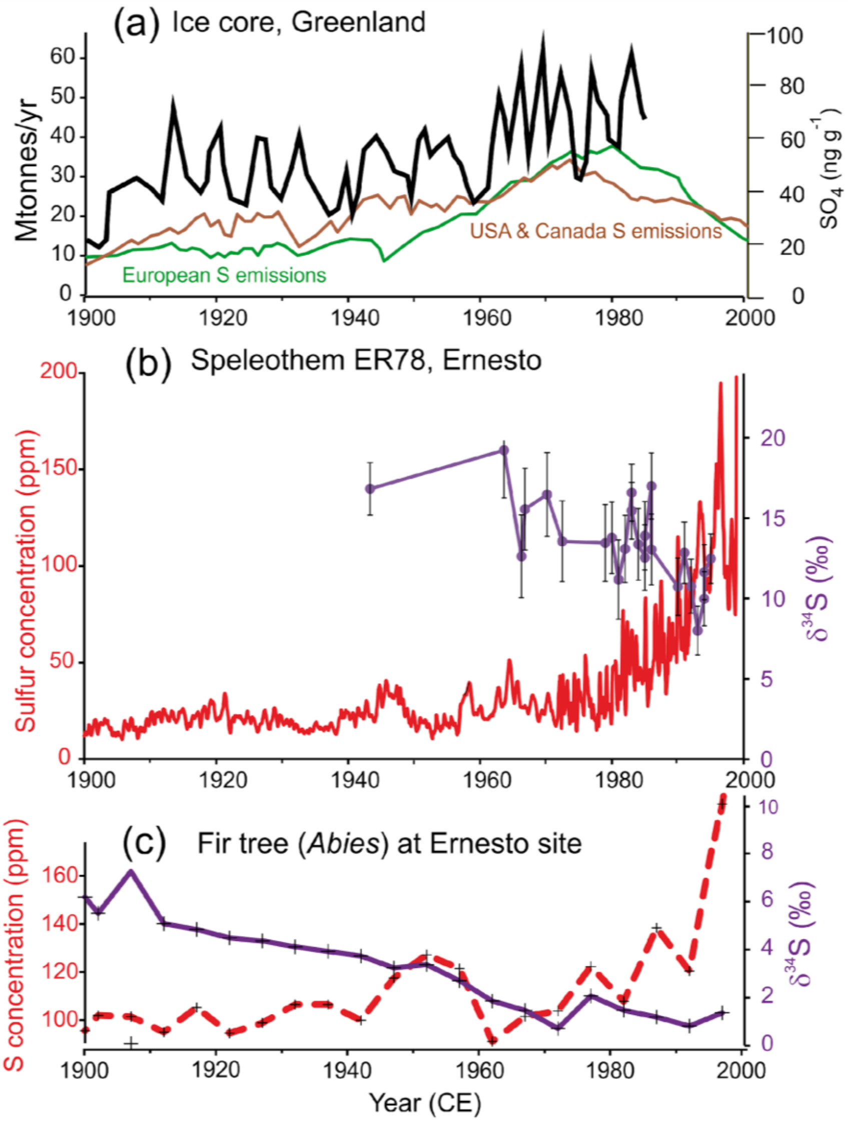

Figure 12. (a) Sulfate concentrations in Greenland ice core (Mayewski et al., 1990), and sulfur emissions from N. America and Europe (from Hoesly et al., 2018); (b) S concentration and δ^{34}S from Ernesto cave, Italy (Frisia et al., 2005; Wynn et al., 2010; Borsato et al., 2023); and (c) S concentrations and δ^{34}S in Abies alba *from NE Italy (Wynn et al., 2014).*

3.2.5 Metal stratigraphic signals

Greatly increased, and increasingly globalised extraction and use of metals such as lead, zinc and copper has left widespread signals of enhanced concentrations and changed isotope ratios across both hemispheres; although complex in detail, an upturn can often be seen around the mid-20th century (Gałuszka & Migaszewski, 2018; Gałuszka & Wagreich, 2019; Figure 13). The rise in Pb concentrations associated with the gasoline additive tetraethyl lead (Nriagu, 1996; Gałuszka & Wagreich, 2019) forms a prominent short-lived event in the 1940s–1980s (Figure 13), its stratigraphic expression shaped by subsequent rapid falls following bans on this additive in the late 20th century. This commonly overprints more regional or smaller signals from sources such as mining and coal-burning, e.g., Shotyk *et al*. (1998). Lead stable isotope ratios are widely used for the determination of pollution sources, particularly discriminating them from natural sources, with ratios of $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{208}Pb$ most commonly reported (Dean *et al*., 2014).

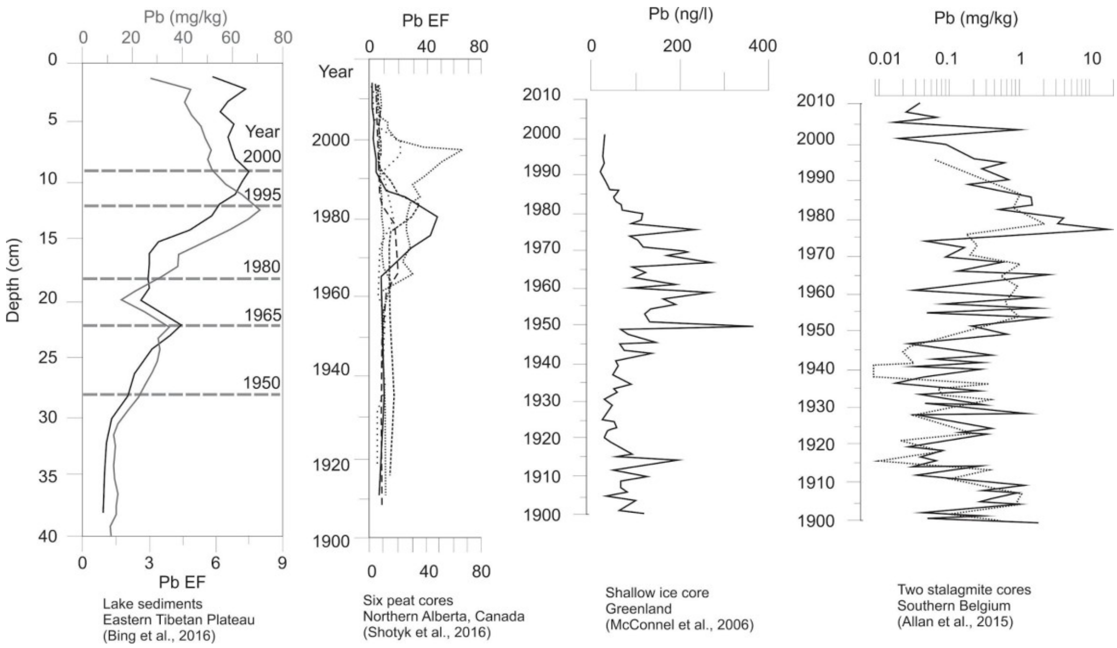

Figure 13. Examples of temporal changes in lead levels in different natural archives during the 20th century (from Gałuszka & Wagreich, 2019 and references therein). EF- enrichment factor.

Global patterns of mercury production and consumption (Hylander & Meili, 2002; Horowitz *et al*., 2014; Zhang *et al*., 2016; Streets *et al*., 2019) show a major increase in Hg deposition over the last century, especially related to increased coal combustion, notably present in the East Gotland Basin reference section (Kaiser *et al*., 2023). Comparable marked increases in molybdenum and vanadium have been found in Alpine ice cores sourced primarily from increased combustion of oil- and coal-burning, respectively (Arienzo *et al*., 2021).

3.2.6 Persistent organic pollutants and polycyclic aromatic hydrocarbons

Recognition of the mid-20th century can be seen unambiguously among a large and diverse group of novel persistent organic pollutants (POPs), which have long residence times in sediments. These include the organochlorine pesticides, e.g., dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin, aldrin, and hexachlorocyclohexane isomers (HCH), and industrial compounds such as polychlorinated biphenyls (PCBs). In the atmosphere they can be transported far from areas of production and use, including to polar regions via the so-called ‘global distillation’ processes. They have left clearly detectable residues widely identifying a post-1950 CE stratal interval in terrestrial (lake) and marine sediments, and in glacial ice (see Gałuszka & Rose, 2019 and references therein; Figure 14). Persistent organochlorine pesticides were first commercially manufactured in the 1940s (Figures 3 & 14d), showed a marked upturn in emissions in 1950 CE, clearly seen in the sedimentary record (Figure 14a-d), and peaked in the 1960s–1990s. Although emissions have subsequently declined, environmental signals have been slow to fall to pre-1950 CE levels. The first appearance of DDT occurs in 1950 ± 4 CE in East Gotland Basin reference section (Kaiser *et al*., 2023) and 1953 CE in the Beppu Bay SABS (Kuwae *et al*., 2023) (see Part 2). PCBs were first used in 1929 (Figures 3 & 14f) and commercially produced through to the 1980s (Bigus *et al*., 2014) with peak environmental concentrations in the 1960s–1970s before bans were introduced (Gałuszka *et al*., 2020). Upturns in PCB abundances were recorded in Lochnagar lake sediments (Scotland) in 1950 CE (Figure 14f) and in the AWG study sites in 1963 CE in Beppu Bay (Kuwae *et al*., 2023) and around 1962 CE in Searsville Lake (Stegner *et al*., 2023) (see Part 2). Brominated flame retardants such as polybrominated diphenyl ethers (PBDEs), widely used since the 1960s (Figure 3), show elevated concentrations from ~1980 CE in Lochnagar lake sediments (Muir & Rose, 2007; Figure 14g).

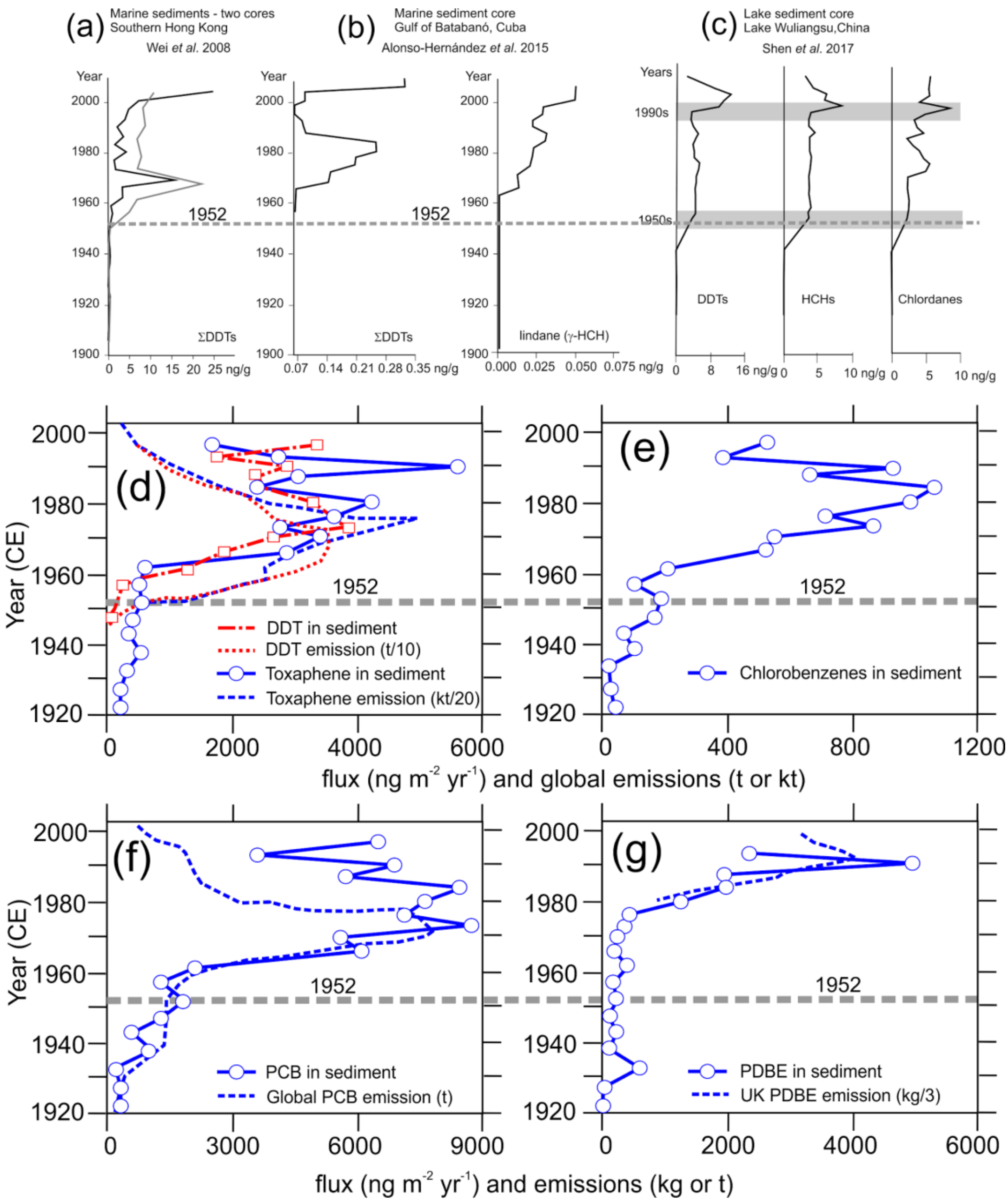

Figure 14 [previous page]. Examples of stratigraphic changes in persistent organic pollutant concentrations in dated sediment cores: (a) to (c) trends of selected organochlorine-pesticide concentrations (from Gałuszka & Rose, 2019; references therein). Contamination record in Lochnagar sediments (Scotland) demonstrating appearances as post-mid-20th century markers (from Muir & Rose, 2007; redrafted and published in Waters et al., 2018a): (d) the chlorinated pesticides DDT and toxaphene from core collected in 1997 CE related to emissions data; (e) chlorobenzenes; (f) total PCBs related to global emissions; and (g) PDBEs related to UK emissions. DDT: dichlorodiphenyltrichloroethane; HCH: hexachlorocyclohexane isomers; PCB: polychlorinated biphenyls; PDBE: polybrominated diphenyl ethers.

Polycyclic aromatic hydrocarbons (PAHs) are produced from any organic combustion, including natural sources such as forest fires. More specifically, high molecular weight PAHs, sourced from burning fossil fuel, have been produced since human coal-burning began, but show peak abundance in the 1940s–1980s (Bigus *et al*., 2014), with an upturn in abundance in 1953 CE in the SABS sites of Beppu Bay (Kuwae *et al*., 2023) and 1952 CE in Sihailongwan Maar Lake (Han *et al*., 2023) (see Part 2).

3.3 Radiogenic isotopes

The sharpest chemical signal associated with the Anthropocene is that from artificial radionuclides, mostly as the 'bomb spike' of plutonium, caesium, americium, strontium, iodine and enhanced radiocarbon from above-ground nuclear detonations, augmented by more recent accidental releases, such as from Chernobyl and Fukushima (Waters *et al*., 2015). This dispersal started with the Trinity bomb test of 16th July 1945, followed by wartime use at Hiroshima and Nagasaki, the first of these mooted as a possible Anthropocene GSSA (Zalasiewicz *et al*., 2015). However, radionuclide dissemination in these fission (A-bomb) devices was comparatively small and regional, and major global fallout spread started with the much larger (high yield) thermonuclear tests soon after detonation of the first 'Ivy Mike' H-bomb test on 1st November 1952 (Figure 15). The period following the Ivy Mike test through to the end of 1958 saw an upsurge in the number of tests (40% of the total) and fallout of radioactive products from these tests (Cundy *et al*., 2022). This was interrupted in 1959–1960 when there was a nuclear weapons testing moratorium by the major nuclear powers, resulting in a commonly observed dip in radionuclide activities in high-resolution plutonium profiles, including the Crawford Lake GSSP proposal (McCarthy *et al*., 2024), the Beppu Bay SABS proposal (Kuwae *et al*., 2023) and the West Flower Garden Bank (DeLong *et al*., 2023) and Searsville Lake (Stegner *et al*., 2023) reference sections (see Part 2). Testing resumed and quickly accelerated in 1961 with the number of tests peaking in 1962, with about a fifth of all atmospheric detonations and a third of the estimated explosive yield occurring in that year (Cundy *et al*., 2022), with global dispersal resulting in a peak signal commonly observed in geological materials in 1963 CE. The subsequent implementation of a Limited or Partial Test Ban treaty in 1963 limited test detonations of nuclear weapons to those conducted underground, and hence greatly reduced atmospheric spread of radionuclides. Although radionuclides were dispersed globally, the magnitude of fallout varied latitudinally, being heaviest in the mid-latitudes of the Northern Hemisphere with an equivalent, though smaller, maximum in the mid-latitudes of the Southern Hemisphere (Waters *et al*., 2015).

Table 3. Commonly used radiometric dating techniques and their applicability to dating Anthropocene deposits/artefacts. Adapted from Waters et al. (2018b).

Isotope	Half-life (years)	Acceptable residence	Sources	Environments of accumulation	Solubility/reactivity
^{3}H	12.32	1950 CE – Present	Natural sources, e.g., self-powered lighting; anthropogenic sources fallout, nuclear power and reprocessing plants	Glacial ice	Very soluble in sediments
^{14}C	5700	present – 60 kyr	Natural sources through cosmic radiation reacting with atmospheric ^{14}C; anthropogenic sources mainly from above-ground nuclear detonations	Found in organic material, e.g., wood, peat, charcoal, soil, organic sediments, bone, shells, coral, speleothem etc.	Risk of biotic recycling of carbon, so preferred use where signal is via direct uptake from atmosphere.
^{137}Cs	30.17 ± 0.03	1954 CE– Present	Anthropogenic sources, e.g., fallout, nuclear power plants, borehole wireline tools	Soils, peats, lake and sea-bed deposits, coral and tree rings, and glacial ice	Soluble / low reactivity (depends on ionic strength of local aqueous environment and presence of illite and other clays)
^{90}Sr	28.79	1950s – Present	Anthropogenic sources, e.g., fallout, nuclear power plants, medical radiotherapy	Soils, peats, lake and sea-bed deposits, coral and tree rings, and glacial ice	Soluble /very low reactivity
^{99}Tc	211,000	10 kyr– 1 Myr	Anthropogenic sources, e.g., fallout, nuclear power plants		Highly soluble / very low reactivity
^{241}Am	432.2	?	Anthropogenic sources, e.g., fallout, nuclear power plants, smoke detectors	Soils, peats, lake and sea-bed deposits, coral and tree rings, and glacial ice	Low solubility / high reactivity
^{129}I	15,700,000	Several Myrs	Natural sources; anthropogenic sources fallout, nuclear power plants	Lakes and sea-bed deposits, coral and tree rings, and glacial ice	Soluble/ very low reactivity. Possible migration due to degradation of organic matter and changes in redox conditions
^{239}Pu	24,110	<100 kyr	Natural sources (very rare); anthropogenic sources fallout, nuclear power plants	Soils, peats, lake and sea-bed deposits, coral and tree rings, and glacial ice	Low solubility / high reactivity
^{240}Pu	6563	<30 kyr	Anthropogenic sources fallout, nuclear power plants	Soils, peats, lake and sea-bed deposits, coral and tree rings, and glacial ice	Low solubility / high reactivity

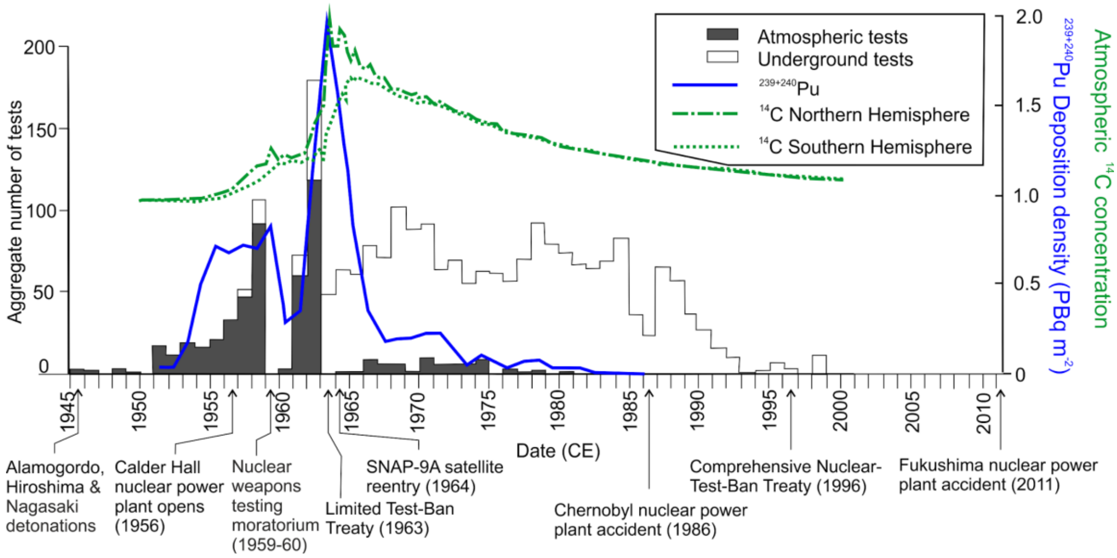

Figure 15. Timeline of key events that have influenced anthropogenic radiogenic signatures. The frequency of above-ground and underground nuclear weapons testing is compared with the fallout signals detected for plutonium and radiocarbon (^{14}C). Note that fallout follows the aggregate number of tests, with a time lag of 6 months–2 years, with the ^{14}C peak lagging and at reduced levels in the Southern Hemisphere compared with the Northern Hemisphere. Data on aggregate test numbers sourced from UNSCEAR (2000), atmospheric ^{14}C concentrations from Hua et al. (2013) and for Pu from Hancock et al. (2014). From Cundy et al. (2022), modified from Waters et al. (2015).

The less mobile and longer-lived (longer half-life) isotopes produced during the period of atmospheric nuclear weapons testing, including ^{241}Am, ^{129}I, ^{14}C, and various Pu isotopes (Table 3), provide a long-term marker of this global fallout which has been incorporated or locked into geological materials such as ocean and lake sediments, corals, and ice (Cundy *et al.*, 2022). Similarly, radioisotopes such as ^{241}Am, ^{137}Cs and ^{90}Sr are useful time markers that can be linked to bomb-spikes associated with fallout from nuclear detonations, but also to specific time-constrained emissions, such as accidental releases from nuclear power plants, e.g., Chernobyl in 1986 and Fukushima in 2011 (Figure 15). However, their short half-life (Table 3) means that in areas of low fallout these radionuclides may already be approaching their limits of detection.

3.3.1 Plutonium

Long-lived isotopes, such as ^{239}Pu and ^{240}Pu (Table 3), are considered the most suitable markers, and importantly these reactive radioisotopes bind strongly to soil and sediment particles, providing an immobile signal in most environments. Pu isotopes are produced in different ratios in fallout, depending on the design of the weapon and the parameters of the test. This can make it possible to distinguish the source of the Pu (Wu *et al.*, 2011), potentially to the level of an individual nuclear test (e.g., Lindahl *et al.*, 2012), and differentiate bomb fallout from other sources such as reprocessing facilities and nuclear reactor accidents (Cundy *et al.*, 2022).

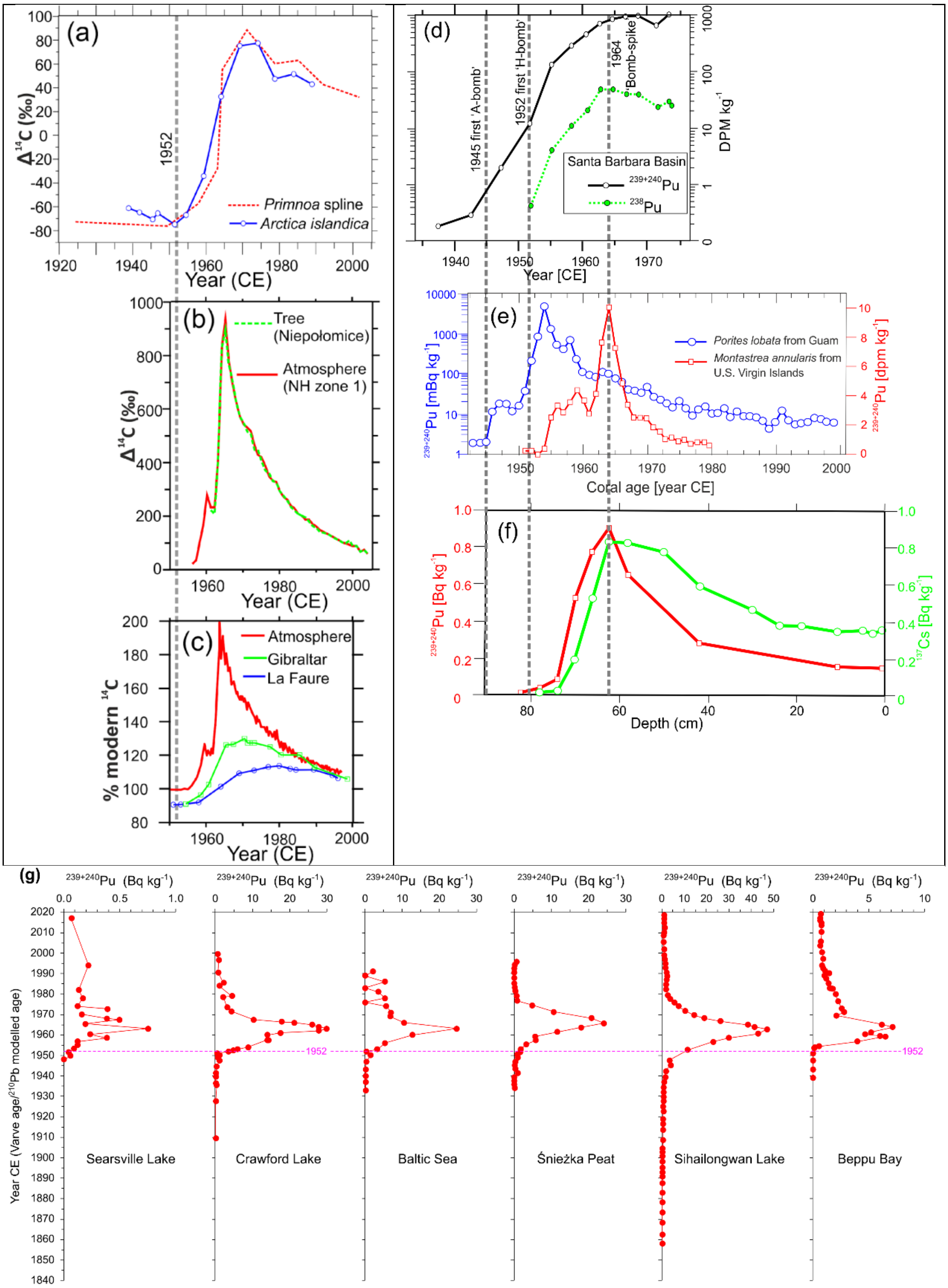

Figure 16. Examples of ^{14}C, Pu and ^{137}Cs signals within different environments. (a) Spline for seven different colonies of the deep-sea gorgonian coral Primnoa resedaeformis *and the bivalve mollusc* Arctica islandica *(Sherwood et al., 2005); (b) $\Delta^{14}C$ in tree rings (*Pinus sylvestris*) at Niepołomice (Poland) compared with Northern Hemisphere atmospheric values (Rakowski et al., 2013); (c) comparison of Northern Hemisphere atmospheric $\delta^{14}C$ values with speleothems from La Faurie Cave, southwest France and Lower Saint Michael's Cave, Gibraltar (Fairchild & Frisia, 2014); (d) $^{239+240}Pu$ and ^{238}Pu signals in the Santa Barbara Basin, USA (Koide et al., 1975), note*

*that these deeper water sediments show a delay in the recovery following the 'bomb-peak' signal; (e) $^{239+240}Pu$ in coral annual growth bands from Guam in the Pacific (Lindahl et al., 2011) showing early onset and peak Pu signals due to proximity to the Pacific Proving Grounds, whereas the US Virgin Islands in the Caribbean (Benninger & Dodge, 1986) shows a profile typical of global signals; (f) Radiogenic signature in a sediment core from Lake Victoria, Australia (Hancock et al., 2011); dpm kg^{-1} = decays per minute per kilogram; mBq kg^{-1} = megabecquerel per kilogram. From Zalasiewicz et al. (2020). (g) Correlation of $^{239+240}Pu$ in reference sites included in this study (*see Part 2*) showing a strong correlation between sites for the onset and peak Pu records.*

The longer half-life and greater abundance of ^{239}Pu makes it a preferred chronometer, and in many regions the signal is likely to be detectable in sedimentary deposits for 100,000 years or longer, subsequently decaying to the isotope ^{235}U, with a half-life of ~703.8 myr; hence the bomb-spike signal will be durably preserved. ^{239}Pu essentially only occurs as a human-generated radioisotope, first appearing in sedimentary archives after the Trinity bomb test of 16th July 1945 and its abundance markedly increased worldwide soon after detonation of the first H-bomb on 1st November 1952 (Figure 16d–g). Plutonium shows a rapid reduction in most environmental archives following cessation of the main phase of above-ground testing from 1963, with the exception of areas impacted by discharges from nuclear fuel reprocessing sites; 'pulsed' discharge can provide useful local chronological markers relating to specific emission events (Waters *et al*., 2022). Further fallout of the isotope ^{238}Pu, mainly in the Southern Hemisphere, occurred following the atmospheric burn-up of the nuclear-powered SNAP 9A satellite in 1964.

Because the fallout products from the thermonuclear tests from 1952 through to 1963 CE are globally distributed over 18 months to two years, they form a more reliable primary marker for a potential Anthropocene GSSP than the earlier fission tests from 1945 to 1952 CE that are associated with regional signals in geological archives (Waters *et al*., 2015, 2018; Figure 15). Plutonium isotopes, and specifically a marked upturn in $^{239+240}$Pu activity, are considered optimal as a candidate primary marker for defining the base of the Anthropocene in most sites analysed in this study (Waters *et al*., 2023). They are recorded within many distinct environments (Table 3), though not evident in speleothems and little studied in tree rings (Waters *et al*., 2018a). The GSSP/SABS/reference sections have used the combined $^{239+240}$Pu signal and ^{240}Pu/^{239}Pu isotopic ratio as the main marker (Figure 16g; see Part 2). Some sites emphasised the first appearance of a measurement above background levels, e.g., just before 1950 CE in Crawford Lake (McCarthy *et al*., 2023, using the updated age model in McCarthy *et al*., 2024), 1953 ± 4 CE in East Gotland Basin (Kaiser *et al*., 2023), 1946–1947 CE in Searsville Lake (Stegner *et al*., 2023), 1945 CE in the Palmer ice core (Thomas *et al*., 2023) and 1945 CE in the Karlsplatz anthropogenic deposits (Wagreich *et al*., 2023). Other sites noted the first prominent upturn in the signal, e.g., 1952 CE in Crawford Lake (see Part 2), 1953 CE in Sihailongwan Maar Lake (Han *et al*., 2023), 1954 CE in Beppu Bay (Kuwae *et al*., 2023) and wider NW Pacific (Yokoyama *et al*., 2023), 1956 CE in West Flower Garden Reef (DeLong *et al*., 2023) and 1952 CE in the Śnieżka peat (Fiałkiewicz-Kozieł *et al*., 2023).

3.3.2 Radiocarbon

A bomb-spike of excess ^{14}C can be used to identify a clear global marker in archives, such as tree-rings, with a typical ~1955 CE start culminating in a late ~1964 CE peak signal (Figures 15, 16b). The 'peak signal' of 1964 CE for atmospheric radiocarbon from annual tree-rings was one of the dates proposed by Lewis & Maslin (2015) and by Turney *et al*. (2018) as the primary marker for the onset of the Anthropocene. However, as radiocarbon occurs naturally and is part of the global carbon cycle, the atmospheric signal has a greater lag than plutonium, particularly in the southern hemisphere. The ^{14}C peak is commonly slightly time-transgressive depending upon latitude (Hua *et al*., 2021; Figure 15) and water depth in the case of many sedimentary archives, through settling lags in water bodies (Figure 16a), and so it is not as consistently correlatable as is the prominent upturn in the ^{14}C signal (Waters *et al*., 2018a). This ^{14}C upturn is recorded in many of the candidate GSSP/SABS/reference sections (see Part 2), with diachroneity of only a decade: mid-1950s in Crawford Lake (McCarthy *et al*., 2023), 1953 CE in Sihailongwan Maar Lake (Han *et al*., 2023), 1956 ± 4 CE in East Gotland Basin (Kaiser *et al*., 2023), 1963 CE in Beppu Bay (Kuwae *et al*., 2023), 1958–1959 CE in Flinders Reef (Zinke *et al*., 2023), 1957 CE in West Flower Garden Reef (DeLong *et al*., 2023), 1960 ± 3 CE in Ernesto Cave (Borsato *et al*., 2023) and 1951 ± 6 CE in the Śnieżka peat (Fiałkiewicz-Kozieł *et al*., 2023). There is insufficient organic carbon in ice cores for this marker to be useful, and in Searsville Lake the sediment contained old carbon, preventing measurement of a suitable profile (Stegner *et al*., 2023).

3.3.3 Americium

^{241}Am was recorded in two of the reference sections (see Part 2), with an upturn at 1953 ± 4 CE in East Gotland Basin and a peak signal in 1963 ± 4 CE (Kaiser *et al*., 2023), and a clear ^{241}Am signal was detected in the Karlsplatz anthropogenic deposits (Wagreich *et al*., 2023). However, this isotope was not detected in the two coral locations (DeLong *et al*., 2023; Zinke *et al*., 2023) and similarly had activities too low in San Francisco Estuary and Searsville Lake to provide a useful marker (Himson *et al*., 2023; Stegner *et al*., 2023). The relatively short half-life (Table 3) and variable record across different environments limits the use of this isotope, particularly as a tool for recognising the Anthropocene in the future.

3.3.4 Iodine

^{129}I does occur naturally with low activities, and in addition to having a bomb-spike signal, shows a secondary global peak associated with the Chernobyl accident in 1986, and maintains a high signal subsequent to the bomb-spike that is associated with emissions from nuclear fuel processing activities. There are suggestions that iodine can migrate in sediments due to degradation of organic matter and changes in redox conditions (Aldahan *et al*., 2007), but no such migration was observed in the proposed SABS cores at Sihailongwan Maar Lake and Beppu Bay (see Part 2). Han *et al*. (2023) considered the absence of migration in the Sihailongwan Maar Lake sediments potentially linked to the anoxic conditions and high organic matter content. A rapid increase in ^{129}I concentrations and in $^{129}I/^{127}I$ ratio from ~1950 CE are recorded at Sihailongwan Maar Lake (Han *et al*., 2023) and increase in $^{129}I/^{127}I$ at 1953 CE (Kuwae *et al*., 2023), consistent with global fallout sources from early nuclear weapons testing, and show the use of this marker for recognising the base of the Anthropocene. Subsequent, post-bomb-spike sediments are shown at Sihailongwan Maar Lake to contain ^{129}I mainly from European nuclear fuel reprocessing plants through marine transport and long-distance atmospheric deposition (Han *et al*., 2023). Anthropogenic ^{129}I has also been observed in sediment cores in western Europe, and East and South Asia (Aldahan *et al*., 2007; Fan *et al*., 2016; Zhang *et al*., 2018), ice cores, corals and tree rings (e.g., Bautista *et al*., 2016, 2018; Zhao *et al*., 2019).

3.4 Climate / ocean pH

3.4.1 Climate change to date

Since the end of the 19th century there has been a change from the typically stable climate regime of the later Holocene (see Section 5) to a regime in which global warming has unambiguously commenced, increasing rapidly from the mid-1970s onwards (Figure 17a). There have been sharp increases in the levels of greenhouse gas climate drivers (CO_2, CH_4, N_2O and O_3), described in Subsection 3.2. The associated warming has forced a parallel increase in water vapour (another greenhouse gas) to further exacerbate global warming (Summerhayes, 2020). Although their regional effects on temperature and sea-level changes are complex, these greenhouse gases have caused Earth's climate to develop a marked energy imbalance (i.e., energy emitted is less than energy received) (von Schuckmann *et al*., 2023) that is increasing as emissions trends continue upwards (Hansen *et al*., 2023). Most of the extra heat is warming the oceans (Yan *et al*., 2016).

Global temperature and sea level are lagging these changes in the Earth System state, although on an upwards, if stepped, trajectory (Summerhayes, 2019; Cearreta, 2019 Figure 17a). Palaeoclimate records show that industrial era-warming of the tropical oceans first developed during the 19th century, nearly synchronously with continental warming in the Northern Hemisphere, but that the warming appears to have been delayed in Southern Hemisphere palaeoclimate reconstructions (Abram *et al*., 2016; Summerhayes, 2019). A 'pause' in warming in the 1950s and 1960s, at a time when greenhouse gas emissions were rising rapidly, appears to have been the result of massive emissions of reflective aerosols from enhanced industrial output in the years before aerosols emissions were controlled by clean air legislation (Summerhayes, 2019, 2020), though at least some of the stasis then may be attributable to increased uptake of heat energy by the global ocean, which also accounts for the pause in the rate of temperature rise between 2000 and 2014 (Yan *et al*., 2016). Global mean surface temperatures showed a rapid rise of 1°C from 1975 to 2020 CE, at 0.02° C/yr (Sippel *et al*., 2021). This warming is largely due to: (i) increases in anthropogenic greenhouse gas emissions (see Section 3.2); (ii) evaporation of water vapour from the warming ocean (atmospheric water vapour increases by 7% for a 1ºC temperature rise); (iii) the reduction in albedo caused by (delayed) melting of especially Arctic sea ice and land ice; and iv) the decrease in aerosols (recently exacerbated by new legislation requiring shipping to burn cleaner fuel).

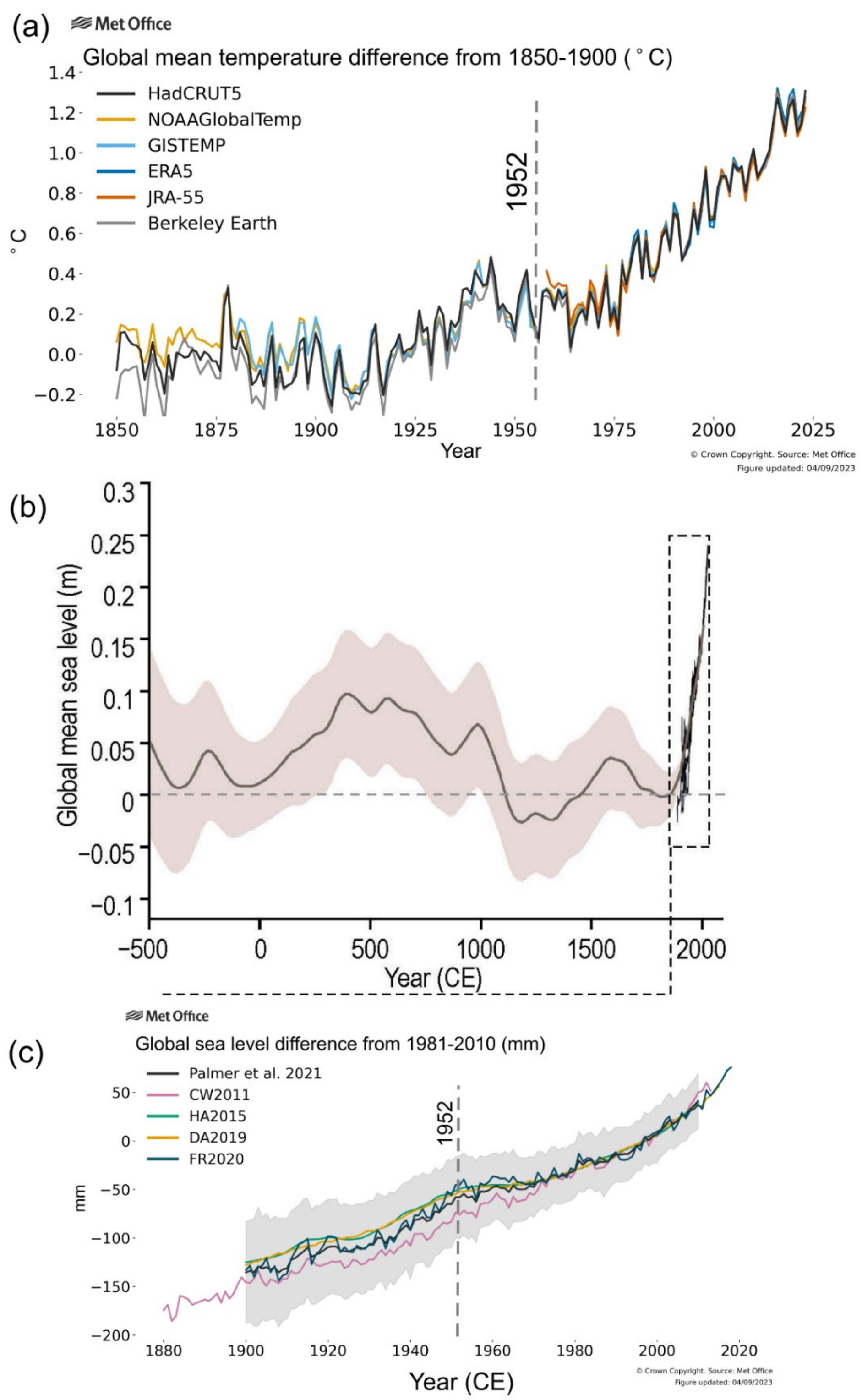

Figure 17. Changes in global temperature and mean sea level. (a)Annual global mean temperatures expressed as a difference from pre-industrial conditions using different data sets (from Met Office 2023 https://climate.metoffice.cloud/temperature.html); (b) reconstructions for the last 2500 years based upon a range of proxy sources with direct instrumental records superposed since the late 19th century (from IPCC, 2021, fig. 2.28); (c) annual global mean sea-level from 1870-present expressed as a difference from the average for 1993-2010. A number of longer tide gauge-based records are shown (from Met Office 2023 https://climate.metoffice.cloud/sea_level.html).

Significant deflection of oxygen isotope trends in polar ice, long not observed above the decal 'noise' (Masson-Delmotte *et al.*, 2015; Thomas *et al.*, 2023), has recently been detected (Casado *et al.*, 2023). Coral $\delta^{18}O$ by itself is not a marker for the Anthropocene but informs of the climate system's complex response to anthropogenic forcing (DeLong *et al.*, 2023). In the Flinders Reef coral reference section the proxies for sea-surface temperature (SST) (Sr/Ca; Calvo *et al.*, 2007; Zinke *et al.*, 2023), salinity ($\delta^{18}O$; Calvo *et al.*, 2007; Zinke *et al.*, 2023) and pH ($\delta^{11}B$; Pelejero *et al.*, 2005) are dominated by prominent centennial, multidecadal and decadal variability, most likely related to Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO) variability (Calvo *et al.*, 2007; see Part 2). The coral Sr/Ca record at the Flower Garden Bank coral reference section reflects a temperature increase of 1.1°C since 1932 CE, in a pattern similar to the global warming trends (DeLong *et al.*, 2023).

3.4.2 Global sea-level rise

Global sea level started to rise from the mid-19th century and since 1850 CE there has been ~30 cm eustatic rise (Figure 17b, c). This rate of rise has been increasing since ~1970 CE (IPCC, 2021) to 3.2 ± 0.4 mm/yr between 1993 and 2010 CE (Church *et al.*, 2013) and to 4.62 mm/yr in 2013–2022 CE (WMO, 2022). Sea level rise lags the rise in both CO_2 and temperature because while the ocean surface warms (and thus expands) rapidly it takes considerable time for warm surface water to make its way to deeper depths; it now reaches depths of 2 km or more in many parts of the ocean.

3.4.3 Ocean acidification

Modern oceanic pH values have only been routinely observed for less than a couple of decades, with a pattern of decreasing sea-surface pH with rising atmospheric CO_2 levels being evident. To infer the earlier seawater pH record (Waters *et al.*, 2019), a commonly used proxy exploits the isotopic fractionation of the two isotopes of boron, ^{11}B and ^{10}B, which can be measured from their ratio in seawater, marine carbonates, corals and planktonic foraminifera tests and recorded as $\delta^{11}B$ (Pagani *et al.*, 2005). Data from a *Porites* coral in the Great Barrier Reef covering an interval from 1800 to 2004 CE shows a strong positive correlation from 1940 to 2004 CE of increased acidification with the $\delta^{13}C$ Suess effect (Wei *et al.*, 2009). From 1940 to 2004 CE, the $\delta^{11}B$ signal decreased, representing a decrease in pH of about 0.2–0.3, though with some marked annual oscillations (Wei *et al.*, 2009). Further analysis of *Porites* from Japan and Tahiti shows a clear decrease in $\delta^{11}B$ after 1960 CE, consistent with increased acidification (Kubota *et al.*, 2015). However, annual to decadal variability often obscures the underlying signal attributable to changes in anthropogenic CO_2 (Waters *et al.*, 2019), as evident in the Flinders Reef (Pagani *et al.*, 2005; Zinke *et al.*, 2023). On average the oceanic pH signal has decreased by 0.1 units since the start of the Industrial Revolution, representing an increase in acidity (hydrogen ion content) of 30%.

3.5 Biostratigraphic signals

Biosphere change since Late Pleistocene times has been complex (see Section 5), and many potential biostratigraphic indicators of more recent change that might help characterise or define an Anthropocene geological time unit need careful assessment. Not least, the very short time scales involved preclude use of 'normal' evolutionary changes. However, there have been rapid changes to biological assemblages driven by intensifying anthropogenic pressures over the last century or so, and these do provide biostratigraphic potential.

3.5.1 Assemblages modified by ecological degradation

A range of signals is associated with industry- and agriculture-related chemical pollution, most clearly seen in many lake successions. By means of tracking 'ecological degradation' (Wilkinson *et al.,* 2014), a post-1950 CE interval can commonly be widely recognised in lake strata (see also Smol, 2008; Wolfe *et al*., 2013; Pla *et al*. 2009; Figure 18). Changes in diatom assemblages are expressed at the Crawford Lake GSSP candidate site by a decline in the planktonic diatoms *Lindavia michiganiana* and *Fragilaria crotonensis* that dominated prior to 1950 CE and sharp increases in non-planktonic taxa such as *Achnanthidium* spp. (McCarthy *et al*., 2023; Marshall *et al.,* 2023). Significant change was also noted around 1950 CE in the scaled chrysophyte record, with several species of *Synura* dominating assemblages between the late 1940s and early 1970s (McCarthy *et al*., 2023; Marshall *et al.,* 2023; Figure 19). Pollen analysis from this site shows the rapid decline in *Ulmus*, marking the effects of Dutch elm disease, regionally identifying the base of the proposed Anthropocene series (McCarthy *et al*., 2023).

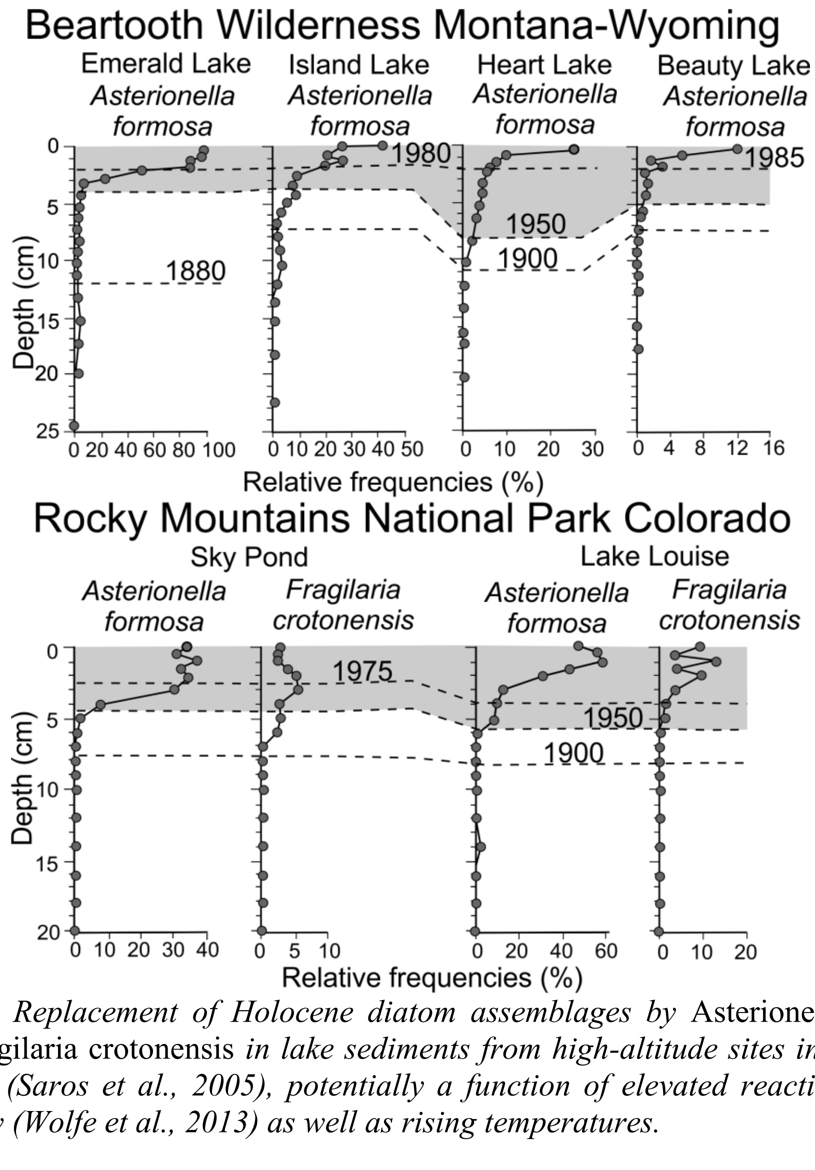

Figure 18. Replacement of Holocene diatom assemblages by Asterionella formosa *and/or* Fragilaria crotonensis *in lake sediments from high-altitude sites in USA since ~1950 CE (Saros et al., 2005), potentially a function of elevated reactive nitrogen availability (Wolfe et al., 2013) as well as rising temperatures.*

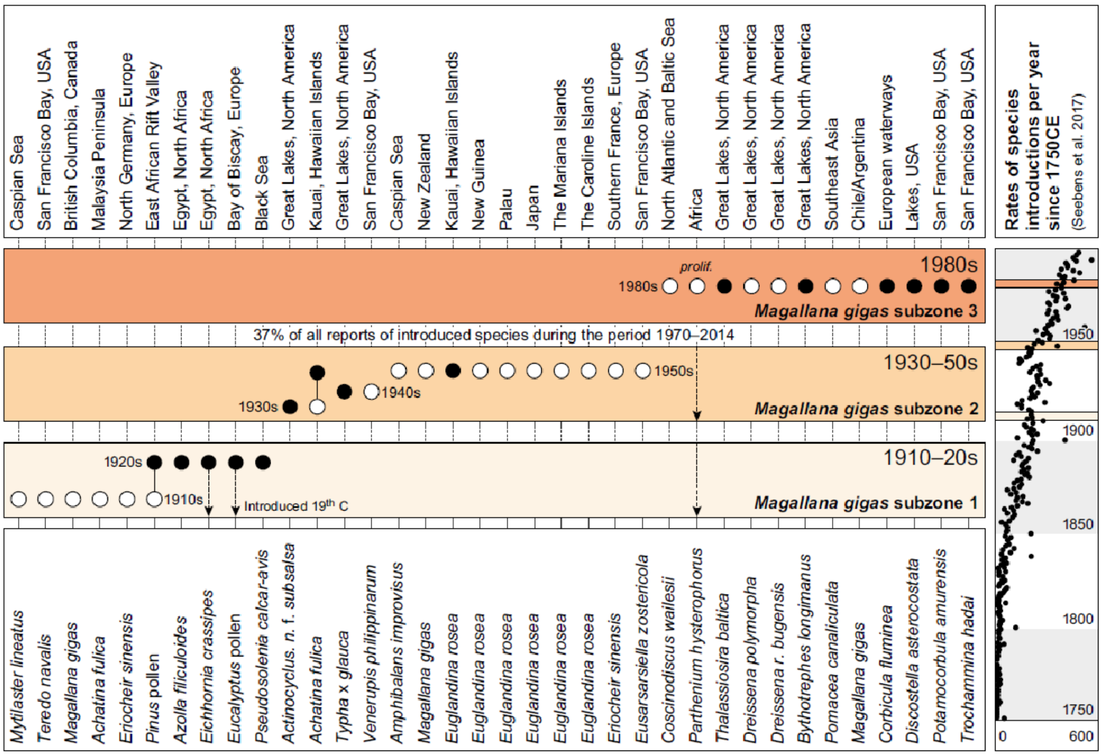

Figure 19. Potential web of palaeontological correlation for three intervals of the 20th century (from Williams et al., 2022 and sources therein). White circles are earliest recorded introductions for a specific region; black circles indicate introduced taxa with confirmed palaeontological records ('lowest occurrence datums') in their area of introduction. 'Prolif.' Means proliferation, noted from human observation of ecologies. The 20th century global spread of Magallana gigas *(Pacific oyster), a species with a fossil range in its native area, is used to suggest a theoretical biozone. Three subzones might be defined within this biozone, with the ability to correlate between marine and non-marine successions at sub-decadal level. Of these, subzone 2 of the* M. gigas *biozone would correlate with the suggested mid-20th century start of the Anthropocene. Right side of figure shows the recorded rates of global species introductions since 1750 CE (0–600 per year), reported by Seebens et al. (2017): 37% of all such records of introductions occurred between 1970 and 2014 CE.*

Such examples can provide functional local biostratigraphies. San Francisco Estuary, for example, is one of the world's most heavily invaded coastal regions, with assemblages commonly dominated by non-native species (Himson *et al*., 2023; Figure 20). Analysis of introduction dates has yielded a local range chart of exotic mollusc and foraminifera taxa across the last 150 years, from which local biozones have been established (Williams *et al*., 2019). These biozones may be used to constrain an Anthropocene boundary and correlated with comparable local biostratigraphies established elsewhere, and with more remote regions such as Hawaii (Williams *et al*., 2018, 2022), and so provide effective biostratigraphic constraint. In the nearby Searsville Lake site, the ~1952 CE level coincides with the first appearance datum (FAD) of the ostracod *Physocypria globula* and the last appearance datum (LAD) of *Ilyocypris* cf. *gibba* (Stegner *et al*., 2023; Figure 20). In the Śnieżka peat section, the FAD of pollen from the neobiotic plant *Ambrosia artemisiifolia* (common ragweed) in 1956 ± 3 CE (Fiałkiewicz-Kozieł *et al*., 2023) provides a marker close to the base of the proposed Anthropocene base. This plant has expanded across Europe since 1940 CE via contamination of crop seeds (Chauvel *et al*., 2006).

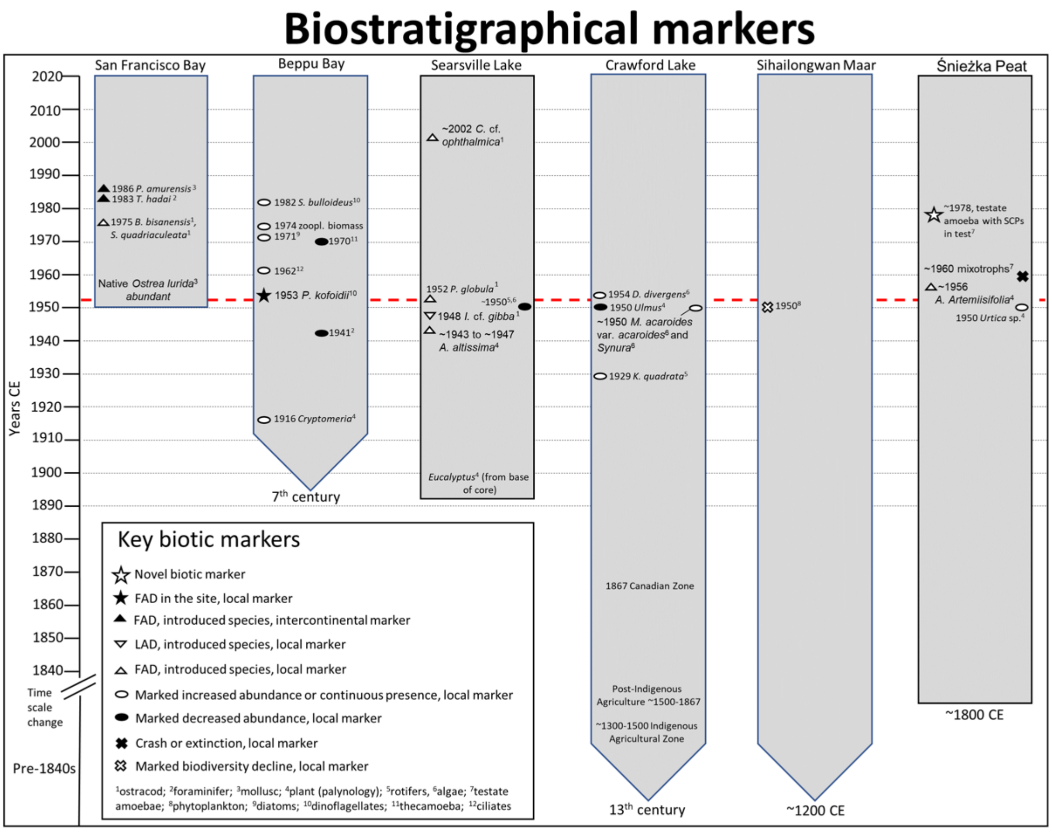

Figure 20. Comparison of key biotic markers present in the candidate GSSP site (Crawford Lake) and other SABS and reference sections considered during this study (see Part 2). *Details are provided as follows: San Francisco Bay (Himson et al., 2023); Beppu Bay (Kuwae et al., 2023); Searsville Lake (Stegner et al., 2023); Crawford Lake (McCarthy et al., 2023); Sihailongwan Maar Lake (Han et al., 2023); and Śnieżka peat (Fiałkiewicz-Kozieł et al., 2023).*

3.5.3 Novel taxa or morphospecies

There are even a few examples of completely novel taxa on such a highly abbreviated timescale. The marbled crayfish, the result of a chance mutation from the slough crayfish of the SW USA in the late-20th century, is morphologically distinct (significantly larger), reproduces parthenogenetically and is spreading quickly in the wild across the USA, Europe and on other continents (Vogt *et al*., 2015), commonly outcompeting native crayfish.

Among domesticated species, the modern broiler chicken is, via an intensive selective breeding programme since the 1950s, a clearly different morphospecies from both its wild ancestor (the red jungle fowl) and from earlier domesticated varieties, with sharply distinct skeletal morphology and genetic and isotopic composition (Bennett *et al*., 2018). Now by an order of magnitude the most common and short-lived bird in the world, with a >20 billion standing population continually replaced on a ~6-week cycle, its bones, discarded casually and in landfills, are adding to the biostratigraphic characterisation of the Anthropocene.

3.5.4 Climate change

Anthropogenic global warming is beginning to alter species ranges, both on land and, yet more markedly (because of narrower thermal tolerances), in the oceans. For instance, planktonic foraminifera globally have already shifted into new biogeographic patterns, distinct from those of pre-industrial times, to make up novel assemblages that have been explicitly referred to the Anthropocene (Jonkers *et al*., 2019). There is northward shift in mid-latitude Northern Hemisphere Atlantic plankton and fish (herring and cod) towards the Arctic, e.g., Steiner *et al*. (2019), along with the northward migration of land plants and an extension of the growing season.

4 RECOGNITION OF THE ANTHROPOCENE SERIES IN A RANGE OF ENVIRONMENTS

The wide array of stratigraphic proxy markers for the Anthropocene described in Section 3, and their equally wide combined distribution across all major sedimentary facies (including glacial ice and coral bioherms) mean that, for practical purposes, a potential Anthropocene Series is amenable to wide recognition across the globe.

The range of environments in which a GSSP may be located, and hence representatives of a potential Anthropocene Series identified, was assessed by Waters *et al*. (2018a) and includes lakes, marine anoxic basins, estuaries and deltas, speleothems, glacial ice, annually banded coral, and tree rings. All of these have the potential for annual (or subannual) resolution within successions that extend from the present to at least several centuries back. Peat provides an important terrestrial record, especially in that its surface is in direct contact with the atmosphere which may transfer signals to the peat without lag, though it lacks the annual lamination important for ensuring the ultra-high-resolution definition regarded necessary to define a mid-20th century boundary. Anthropogenic deposits are particularly widespread and include associations with cities, roads, railways, dams etc., these deposits usually being complex, discontinuous and rich in datable technofossils (Zalasiewicz *et al*., 2014c).

4.1 Lake Deposits

Lakes cover about 3.7% of the ice-free land surface, notably within boreal and arctic latitudes (Verpoorter *et al*., 2014), and their bottom sediments commonly comprise continuous, vertically aggraded, high-resolution stratigraphic records. Potential lake reference sites for the Anthropocene, including Crawford Lake (Canada), Lochnagar (Scotland), Lilla Öresjön (Sweden), Huguangyan Maar Lake (China) and Maha'ulepu Lake of Kauai (Hawaii) were suggested by Waters *et al*. (2018a).

The highest temporal resolution among lacustrine records are those with annual laminae (varves) (Waters *et al*., 2018a), common in glacial lakes (e.g., Holtgrieve *et al*., 2011; Wolfe *et al*., 2013). Varves also occur in hypoxic lakes with seasonally varying clastic/biotic input. Hypoxia in lake sediments, particularly resulting from increasing nutrient release, has developed extensively since the mid-19th century, about a century earlier than widespread coastal zone hypoxia (Jenny *et al*., 2016). Hypoxia can change the behaviour of trace elements and radionuclides, by either increasing or reducing their mobility, and hence may affect their use as chemostratigraphic markers. Small hypoxic lakes with limited or no fluvial input produce the most suitable environments for preserving clean atmospheric signals, e.g., the proposed SABS of Sihailongwan Maar

Lake in China (Han *et al*., 2023), and Huguangyan Maar Lake (Han *et al*., 2016), also with varves. Saline lakes develop varves due to seasonal precipitation of evaporite minerals, though are more prone to have missing annual laminae; no such site was investigated as a potential GSSP host. Seasonal lamination can also be preserved in artificial reservoir sediments, seen in the cores studied from the reference site Searsville Lake, California, as distinct lithologies associated with wet and dry seasons (Stegner *et al*., 2023).

There are also ~16.7 million artificial reservoirs worldwide, ranging from 0.0001 to 100,000 km^2 surface area (Lehner *et al*., 2011). In the USA, 48% of all lakes are human-made reservoirs (EPA, 2021), one example being the reference site Searsville Lake, presently ~0.8 km^2 (Stegner *et al*., 2023). Reservoirs may be associated with very rapid rates of sediment accumulation and hence thick developments of Anthropocene deposits (a 3.54 m interval accumulated in Searsville Lake since 1952 with a mean sedimentation rate of ~15.6 cm/yr; Stegner *et al*., 2023).

Within most, perhaps nearly all, of these lake deposits, an interval of Anthropocene age may commonly be distinguishable, based on a range of dating methods and proxy signatures. In addition to lamina counting, Anthropocene successions can be independently dated using ^{210}Pb (Waters *et al*., 2018b), in lakes in which deposition rates are moderately constant, e.g., Crawford Lake and Sihailongwan Maar Lake. This chronology can be supported by distinct radiogenic spikes and known pollution, storm or other local events (e.g., Stegner *et al*., 2023). Common geochemical signals include radiogenic fallout (Waters *et al*., 2015; Figures 15, 16), nitrates and stable nitrogen isotopes (Holtgrieve *et al*., 2011; Wolfe *et al*., 2013; Figure 11), fly ash and black carbon (Rose, 2015; Han *et al*., 2016; Figures 5 and 6b–d), microplastics (e.g., Corcoran *et al*., 2015; Turner *et al*., 2019), persistent organic pollutants (Gałuszka & Rose, 2019; Muir and Rose, 2007; Figure 14) and anthropogenic lead and Pb isotopes (Reuer & Weiss, 2002; Figure 13), commonly allowing a mid-20th century boundary to be correlated across continents.

Lakes are prone to rapid influx of and domination by introduced biota (e.g., the zebra mussel and quagga mussel, at the cost of endemic species (see Subsection 3.5.2). Diatom assemblages in remote Northern Hemisphere lakes show a common pattern of declining Late Holocene benthic diatoms and concurrent rise of planktonic diatoms during the Anthropocene, reflecting elevated reactive nitrogen availability and rising temperatures (Wolfe *et al*., 2013; Figure 18). Changes in planktonic and benthic diatom and chrysophyte assemblages around the mid-20th century provide a significant marker at Crawford Lake, along with marked changes in abundances of pollen and non-pollen palynomorph species (McCarthy *et al*., 2023; Figure 20).

4.2 Marine successions, especially anoxic basins

Oceans cover about 70% of the Earth's surface, and marine successions are among the Anthropocene SABS (Beppu Bay, Japan) and reference sections (East Gotland Basin, Baltic Sea) described in Part 2. The level of stratigraphic resolution *vis-à-vis* recognising an Anthropocene interval varies. Deep-ocean oozes typically show very low sedimentation rates – the Anthropocene interval commonly being less than a millimetre thick – and preserve few calcareous microfossils where below the calcite compensation depth (CCD); they are typically oxygenated and hence bioturbated, too, blurring the stratigraphic record (Waters *et al*., 2018a; Zalasiewicz *et al*., 2020). Trawling on the upper continental slope and continental shelf (e.g., Martin *et al*., 2015) has become a typical Anthropocene sedimentary signal, though one of extensive disturbance, of sediments that are in any case also prone to bioturbation. Marine anoxic basins have most potential for detailed records of the Holocene–Anthropocene transition (Waters *et al*., 2018a). Here, sedimentation accumulation rates may be relatively high through a combination of enhanced biological productivity in the photic zone and nearby terrestrial sediment sources, while varve preservation is favoured by oxygen-deficient bottom waters limiting bioturbation (Schimmelmann *et al*., 2016). Locations for potential reference successions include long-lived marine anoxic basins such as the Santa Barbara Basin (California), Cariaco Basin (Venezuela) and the enclosed Black Sea, and large marine inlets such as the Saanich Inlet and Saguenay Fjord (Canada) (Waters *et al*., 2018a). Stratigraphic signals are also being produced by the burgeoning seasonal marine 'dead zones', the number of which has approximately doubled each decade since the 1960s (Diaz & Rosenberg, 2008).

In the East Gotland Basin of the Baltic Sea, anoxic seabed conditions developed around 1956 ± 4 CE at the reference core site (see Part 2) (Kaiser *et al*., 2023). Another small isolated marine anoxic basin is the Beppu Bay site off the coast of Kyushu Island, Japan (Kuwae *et al*., 2023), which also shows a prominent colour change above the 1953 CE flood layer, consistent with increased anoxia from that time.

Anthropocene successions in these settings can be dated by lamina counting (if present), by ^{210}Pb dating, by radiogenic fallout signals and by known basinal events. Many useful signals can be recognised in such marine successions; the Beppu Bay study analysed 99 distinct stratigraphic proxies (Kuwae *et al*., 2023). Land-derived microplastic beads and plastic fibres have spread throughout the oceans (e.g., Ivar do Sul & Costa, 2014; Zalasiewicz *et al*., 2016a; Brandon *et al*., 2019; Long *et al*., 2022; Figure 4b). SCPs have not been routinely analysed in marine sediments, but show much promise for correlation. Both the East Gotland Basin and Beppu Bay provided clear microplastic and SCP event markers (Kaiser *et al*., 2023; Kuwae *et al*., 2023). Other important signals include organic and inorganic chemical contamination (including DDT residues), effects associated with atmospheric CO_2 increase and warming such as variations in pH, dissolved oxygen content and δ^{13}C, and resultant biological changes.

Pu isotopes and metal contaminants also form Anthropocene markers, though their use may be complicated by the potential decadal time delay for them to reach the seabed. Typically, the onset of the signal is little affected, but peak signals can show significant lags and prolonged elevated values rather than a distinct peak (Waters *et al*., 2018a; Figure 16d). The East Gotland Basin and Beppu Bay sites, nevertheless, preserve stratigraphically useful patterns of these signals (Kaiser *et al*., 2023; Kuwae *et al*., 2023). These Anthropocene signals differ from those in latest Holocene strata: e.g., clinker from coal combusted to power steam-ships, was extensively dumped on the seabed from ~1800 to ~1950 CE (Ramirez-Llodra *et al*., 2011).

4.3 Estuaries and deltas

Most modern estuaries and deltas developed during the Early Holocene sea-level rise and flooding of river or glacial valleys. Rates of sea-level rise during the Northgrippian and Meghalayan reduced greatly, allowing estuaries to fill with sediments and deltas to build seawards, enhanced by increased sediment flux resulting from early deforestation and agricultural expansion. Subsequently, the trapping of sediment behind major dams, constructed on nearly all major rivers, has greatly reduced sediment flux to the coast since the 1950s (Syvitski & Kettner, 2011; Syvitski *et al*., 2022; Table 2). This, along with current and projected sea-level rises, is expected to preserve transgressive, diachronous sequence-stratigraphic systems in these environments. River estuaries record evidence of anthropogenic impact of the entire catchment, but are prone to bioturbation and gaps in succession (Waters *et al*., 2018a). Continuous Anthropocene records are likely to be concentrated in areas of mud deposition in front of major estuaries and in prodelta settings, where moderate sedimentation rates of 1–5 mm/yr are typical (Hanebuth *et al*., 2015). However, this environment is prone to omission surfaces (both through natural erosion and anthropogenic dredging), so many Anthropocene records here will be incomplete (although vegetated systems such as saltmarshes may show more complete records). Many of the geochemical markers and independent dating possibilities found in lakes and marine basins are also found in estuaries and deltas, with such markers enhanced near to urban and industrial developments, as in San Francisco Estuary (Himson *et al*., 2023).

Estuaries and deltas are particular foci for introduced species (Wilkinson *et al*., 2014), often associated with marked declines in indigenous species. San Francisco Estuary, for instance, spectacularly demonstrates that a neobiota-based high-resolution biostratigraphy can be effectively used in such successions (Himson *et al*., 2023). Changed species assemblages have also resulted from aquaculture of fish, shellfish and shrimps in estuaries, especially during the late 20th and early 21st centuries, bringing eutrophication, the spread of pathogens and parasites and destruction of coastal mangrove systems (Martinez-Porchas & Martinez-Cordova, 2012).

4.4 Speleothems

Annually laminated calcareous speleothems (typically stalagmites) occur within natural cave systems of karst environments, in which growth is typically slow, of tens to hundreds of micrometres per year. Speleothems can also occur within artificial tunnels, where degradation of mortar in concrete linings contributes the calcium carbonate; these 'calthemites' can have faster growth rates of 10 mm/yr, though commonly with complex internal structures (Broughton, 2020). The Meghalayan Stage (Upper Holocene Subseries) is defined in a speleothem (Walker *et al*., 2018, 2019).

Principal signals that may be used to recognise a potential Holocene–Anthropocene boundary include (Fairchild & Frisia, 2014) shifts in atmospheric ^{14}C (Figure 16c) and sulfur (sulfate concentration and $\delta^{34}S$; Figure 12b). Superimposed upon these are local, more or less diachronous signals, that, include: 1) variations in growth rates of laminae and $\delta^{18}O$ which relate to air temperature and humidity; 2) $\delta^{13}C$ as an indicator of deforestation and/or introduction of C4 plants; 3) biomarkers such as changes in C27/C31 n-alkane ratios and increase in n-alkanols reflecting the local introduction of agriculture; and 4) shifts in trace elements and isotope ratios (Fairchild, 2018) (Figure 13).

The Ernesto Cave site, suggested (Waters *et al*., 2018a) and subsequently analysed for GSSP potential (Borsato *et al*., 2023), constitutes a highly useful reference for this setting, but with lagged and muted signals for sulfur concentrations (Figure 12b) and elsewhere through ^{14}C (Figure 16c).

Because these signals are transported through plants, soil and rock before incorporation, they are variably attenuated and delayed (Fairchild & Frisia, 2014; Fairchild, 2018). Speleothems are also insensitive to the large increases in atmospheric CO_2 concentrations and depletion in $\delta^{13}C$ over the past century (Fairchild & Frisia, 2014) and lack Pu isotope determinations. However, recently analysed annually laminated stalagmites from the Cook Islands, Oceania, where a barren, soil-free karst results in little or no lag of the signals (Faraji *et al*., 2023), show that such speleothem sites may more directly and immediately track Anthropocene signals, and may therefore provide potential for a SABS proposal in the future.

4.5 Glacial ice

Extensive, annually resolvable Anthropocene records are present in the continental ice sheets of Antarctica and Greenland. Records are present in mountain glaciers too, but these are prone to loss of annual laminae through seasonal and longer-term melting and consequent destruction of the signals. Ice accumulations offer strong correlative potential (Waters *et al*., 2018a), and were selected as GSSPs for the Holocene Series (Greenlandian and Northgrippian stages; Walker *et al*., 2018, 2019). The Greenland ice sheet is more contaminated by Northern Hemisphere industry, including pre-20th century signals, while Antarctic land ice is more pristine and shows a more attenuated but less locally influenced mid-20th century set of global markers (Waters *et al*., 2018a).

The Antarctic Palmer ice core, a reference section of this proposal (see Part 2), exemplifies this remote setting. The chronology is resolved through annual layer counting, determined through seasonal variations in non-sea salt sulfate, stable water isotopes and hydrogen peroxide (Emanuelsson *et al*., 2022) and is supported by well-dated volcanic horizons identified in the sulfate record, with an estimated dating error of <6 months (Thomas *et al*., 2023).

Stratigraphic markers in ice comprise: the ice itself and its isotopic compositions; a range of aerosol species that have fallen, and been preserved, with the snow layers; and trapped air bubbles, formed once air-filled snow and firn have compacted down into solid ice.

The air bubble record is the most iconic, preserving atmospheric variations in CO_2 (Figure 8), CH_4 (Figure 9) and N_2O (Figure 11a) that extend far beyond the instrumental record (Wolff, 2014; Figure ES1). However, the Anthropocene interval is mostly firn, where bubbles are not yet closed from connection to the atmosphere and hence their environmental signals – inherently younger than the enclosing ice – are not yet locked in. The depth and hence timing of the firn-to-ice transition is dependent upon the accumulation rate, and so sites with rapid accumulation rates, such as the Palmer ice core location, preserve a shorter air/ice lag. However, even here the point at which the air-bubbles become fully sealed (the close-off depth), is reached at 62.8 m, whereas the base of the proposed Anthropocene succession is 34.9 m (Thomas *et al*., 2023). In older ice records, the nitrogen isotopes in the air bubbles can be used to estimate the correct ages of the air bubbles, facilitating direct comparison with ice of the same age (Parrenin *et al*., 2013). This correction technique is not really applicable to the Anthropocene record; nevertheless, the fastest accumulating snow, with an ice/air difference of about 30 years, captures the beginning of the sharp upturns in greenhouse gases associated with industrialisation and the changes in their $\delta^{13}C$ composition due to the Suess effect (Figure 10a). The significance of the ice record is seen when splicing it with direct atmospheric measurements made since 1956 for CO_2 (and later for the other gases) to show the unprecedented scale and speed of the rise in these gases in the Anthropocene when placed against both a Holocene and a Quaternary context, as described above (Section 3.2.1 to 3.2.3 and Figures 8, 9, 10a, 11a).

Detecting a putative Holocene–Anthropocene boundary in oxygen isotope data from ice is hampered by climate change lagging atmospheric change, and by signal noise from decadal/multidecadal climate oscillations. Statistical analysis of the data, however, has detected industrial-era warming in Antarctica ice cores (Casado *et al*., 2023). The Palmer ice core has stable water isotopes showing a shift to warmer surface temperatures from ~1930 CE, coincident with snowfall rates becoming higher and more irregular (Thomas *et al*., 2023).

Anthropogenic signals derived from aerosols preserved within the ice are not affected by the discrepancy in air bubble age, and these provide the clearest markers for a Holocene/Anthropocene boundary. These include radionuclide signals from nuclear bomb testing (e.g., Pu, ^{14}C), increases in black carbon and metals such as Pb from industrial activity and automobile emissions, sulfate especially from coal combustion, and nitrate from fertilisers. SCPs were recorded for the first time in Antarctic ice in the Palmer ice core succession (Thomas *et al*. 2023a, b).

The most abrupt anthropogenic signal widely recognizable in ice is radioactive fallout from above-ground nuclear detonations. This is seen as a marked increase in beta radioactivity (e.g., ^{14}C, ^{90}Sr and tritium) initially in 1954 CE and peaking in 1966 CE, followed by slow decay towards natural background levels after the Partial Test Ban Treaty in 1963 CE (Wolff, 2014). The long-lived radionuclide ^{239}Pu typically has a higher activity in Arctic ice (by a factor of about three) than in Antarctic ice (Arienzo *et al*., 2016). However, despite lower activities in Antarctica, the Palmer ice core reference section has first detection of $^{239+240}Pu$ at 1945 CE (Thomas *et al*., 2023).

In Greenland ice, black carbon shows peak concentrations in the early 20th century (McConnell & Edwards, 2008; Figure 6e). The greatest rises in Pb concentrations are from the 1950s (Figure 13), peaking in the 1960s, mainly from the burning of alkyl-leaded gasoline (Murozumi *et al*., 1969; McConnell & Edwards, 2008), while in an ice core from Mt. Logan, Yukon, an unprecedented 1950s rise is thought to be sourced from increased coal-burning in Asia (Osterberg *et al*., 2008). At their peak, Pb levels in Greenland ice were about 200-fold above Holocene background levels, compared with Antarctic ice peak values from 1950 to 1980 CE at five times pre-Industrial levels (Wolff & Suttie, 1994).

Additional markers in Greenland ice include sulfate (SO_4^{2-}) concentrations (Mayewski *et al*., 1990; Figure 12a), ice nitrate concentrations (Fischer *et al*., 1998; Wolff, 2013; Figure 11a, d), and associated decreasing $\delta^{15}N$ trend (Figure 11a, d), coincident with a rapid rise in fossil fuel emissions (Hastings *et al*., 2009). Antarctic ice records show no equivalent elevated nitrate (Figure 11d) signatures, being more remote from anthropogenic contamination (Wolff, 2013, 2014).

4.6 Corals

Shallow-water coral reefs extend over only about 0.1–0.2% of the tropical oceans. Cold-water corals occupy a much wider range of latitudes and water depths, but these are typically smaller and grow more slowly than in tropical reefs. These deeper water coral skeletons have banding which, though, may not necessarily be annual, and some proxy signals (e.g., radiogenic nuclides, $\delta^{13}C$, heavy metals) can be affected by appreciable time lag during settling through the water column. Therefore, shallow-water corals most clearly exemplify stratigraphic patterns relevant to the Anthropocene, with two selected as reference sites (see Part 2): Flinders Reef in the Coral Sea (Zinke *et al*., 2023) and West Flower Garden Bank Reef in the Gulf of Mexico (DeLong *et al*., 2023).

An important factor is the current overall decline, and uncertain future, of this stratigraphic archive (Hoegh-Guldberg, 2014; Hughes *et al*., 2017). There has been a 50% reduction in the abundance of reef-building corals over the past 40–50 years, with potential collapse of whole reef systems in the next few decades, as happened during mass extinction events of the geological past (Hoegh-Guldberg, 2014; Leinfelder, 2019). The robust and fossilisable coral skeletons already formed, however, have good potential to preserve the Anthropocene-related signals already imprinted into them.

The most representative Anthropocene records are in long-lived coral colonies that show annual growth bands that can be independently dated using ^{230}Th and ^{14}C, as ^{210}Pb activities proved too low to date the Flinders Reef and West Flower Garden Bank Reef, while the ^{137}Cs and ^{241}Am bomb-peaks are typically not detected in corals (Zinke *et al*., 2023; DeLong *et al*., 2023). Key correlatory signals include Pu and ^{14}C radionuclide fallout, the ^{13}C Suess effect and uptake of pollutants, in particular heavy metals, while proxies of sea-surface temperatures (SSTs) and pH are regionally significant markers (Zinke *et al*., 2023; DeLong *et al*., 2023).

The Pu signal in corals typically has very high resolution, with only limited evidence of post-growth mobility (Lindahl *et al*., 2011). Pacific corals can show initial rises and peaks in Pu earlier than typical globally (Figure 16e), indicating an early local source of the signals from the Pacific Proving Grounds (Lindahl *et al*., 2011), consistent with the Pu record in the Flinders Reef core (Zinke *et al*., 2023). The Caribbean corals show a more globally representative Pu fallout pattern, with an initial 1954 CE rise and 1964 CE peak (Benninger & Dodge, 1986; Figure 16e). The West Flower Garden Bank Reef is consistent with this (DeLong *et al*., 2023) and Sanchez-Cabeza *et al*. (2021) proposed that sites far from nuclear testing grounds are potentially suitable to host a type section of the Anthropocene.

The West Flower Garden Bank and Flinders Reef corals show a pronounced radiocarbon bomb-spike commencing in 1957 and 1958 CE, respectively, with a slight lag as expected in the Southern Hemisphere record (Zinke *et al*., 2023; DeLong *et al*., 2023). The peak signals, in 1970 and 1980 CE respectively, are both significantly delayed compared with atmospheric ^{14}C concentrations (see Figure 15).

$\delta^{13}C$ in coral skeletons shows a marked decrease from about 1955 CE in Caribbean corals and sclerosponges (the ^{13}C Suess effect), with a more variable and less pronounced rate of change in the Indian and Pacific oceans (Swart *et al*., 2010; Figure 10c). This is consistent with the inflections to lower stable isotope ratios being pronounced from 1956 CE in West Flower Garden Bank, but less marked and later in the Flinders Reef in 1970 CE (DeLong *et al*., 2023; Zinke *et al*., 2023).

Pb signals in corals show strong regional influences. For instance, corals in Bermuda (Kelly *et al*., 2009) show a marked increase that began in the late 1940s due to increased consumption of leaded gasoline and peaked in the 1970s (Boyle *et al*., 2014).

Coral temperature proxies are strongly influenced by regional climate variations. Sea-surface temperature rises from the 1970s onwards have led to reduced annual band thicknesses in *Porites* colonies in the Great Barrier Reef (De'ath *et al*., 2009) and are linked with strong decrease in δ^{18}O and Sr/Ca ratios in the Caribbean (Hetzinger *et al*., 2010).

δ^{11}B isotopic records in corals provide a proxy for seawater pH. *Porites* coral in the Great Barrier Reef show a decreasing trend in pH of about 0.2–0.3 from 1940 to 2004 CE, though with marked annual oscillations (Wei *et al*., 2009). In the Flinders Reef there is strong decadal variability throughout the record with only a small, insignificant trend towards lower values (Pelejero *et al*., 2005; Zinke *et al*., 2023).

4.7 Peat

Peat deposits are extensive (Shotyk, 1992; Yu *et al*., 2010) and provide good environmental archives, particularly those that are ombrotrophic, receiving their nutrients solely from atmospheric inputs with naturally low concentrations of mineral matter (Waters *et al*., 2018a). Bog surface waters are acidic, with varying redox conditions, and so radioisotopes such as ^{137}Cs and metals such as U, Mn and Fe can be very mobile. Peat bogs are not varved and the most robust age-depth models use a combination of approaches, including ^{14}C and ^{210}Pb.

Waters *et al*. (2018a) noted Swiss peat deposits showing the greatest Pb flux in the late 20th century, reaching 1570 times the background value by 1979 CE associated with greatly decreased ^{206}Pb/^{207}Pb ratios. These patterns subsequently reversed following the introduction of unleaded gasoline and regional reduction in industrial Pb sources (Shotyk *et al*., 1998). Similar Pb enrichment is also recorded in northern Alberta, Canada (Shotyk *et al*., 2016; Figure 13). In the Swiss peats, the highest PCB concentrations date from 1960 to 1976 CE, while PAHs peak from 1930 to 1951 CE (Berset *et al*., 2001). Peak records of ^{241}Am activity mark the early 1950s to early 1960s bomb-spike, whereas maximum ^{137}Cs activity is in the uppermost living part of the profile, inferred to be sourced by the Chernobyl disaster of 1986 CE (Appleby *et al*., 1997).

Subsequently, the analysis of further proxy signals, including Pu isotopes, in peats from Śnieżka in the Sudetes mountains of Poland (Fiałkiewicz-Kozieł *et al*., 2020) led to a new core from this site being selected as a candidate SABS (Fiałkiewicz-Kozieł *et al*. 2023; see Part 2). Here, the $^{239+240}$Pu profile shows a marked increase from 1952 CE and a peak in 1965 ± 5 CE, consistent with the ^{14}C data. Other signals that help constrain the Anthropocene boundary include the lowest occurrence of spheroidal aluminosilicates (SAPs) and mullite, and an upturn in SCP abundance, while the introduction of ragweed (*Ambrosia*) is a clear neobiotic signal (Fiałkiewicz-Kozieł *et al*., 2023).

4.8 Trees

A precise dendrochronological timescale has been developed for the Holocene, for instance helping constrain a Medieval Climatic Anomaly (MCA) from 900–1200 CE, below average temperatures during the Little Ice Age (LIA) from 1200–1850 CE, and warming since 1850 CE (Esper *et al*., 2002; Wilson *et al*., 2016; Figure ES1). For the Anthropocene, tree rings provide a high-resolution archive of the radiocarbon bomb-spike, variations in stable carbon isotopes, sulfur concentrations and sulfur isotope values.

Trees provide a high-resolution record of the decrease in atmospheric $\Delta^{14}C$ by about 20.0‰ between 1890 and 1950 CE in response to the Suess effect of adding low-activity fossil carbon. This is followed by a marked radiocarbon bomb spike in response to nuclear weapons testing, peaking at double that of pre-1850 CE times (e.g., Rakowski *et al*., 2013; Figure 16b). A proposal suggesting a candidate tree GSSP in a non-native Sitka spruce (*Picea sitchensis*) from Campbell Island, New Zealand (Turney *et al*., 2018) was based upon ^{14}C as a single marker analysed between 1961 and 1967 CE, resolving the bomb-peak in October–December 1965 CE, their preferred base for the Anthropocene. However, sampling did not extend to the beginning of the bomb-spike. $^{239+240}Pu$ records in tree rings are less studied, but seem to show similar trends to those seen in lake sediment cores (Mahara & Kudo, 1995).

The change in tree ring carbon isotopic values resulting from global industrialisation is seen as a reduction of atmospheric $\delta^{13}C$ values by ~2‰ since the start of the Industrial Revolution ~1820 CE (the $\delta^{13}C$ Suess effect), with marked inflection at ~1950 CE (Loader *et al*., 2013). This effect, also observable in ringless trees in the tropics, is far greater than anything observed in the tree ring isotope record during at least the last thousand years.

4.9 Anthropogenic deposits

This category includes sedimentary successions that have accumulated through direct human deposition (artificial ground) or by human influence on natural systems, such as reservoir deposits that accumulate behind dams, described in Section 4.1 (Ford *et al*., 2014). There is a continuum from entirely natural through to entirely anthropogenic materials. Such anthropogenic deposits may show remarkably high accumulation rates, locally in excess of one metre per year, and rapidly incorporate novel anthropogenic signatures, which may be lithological, geochemical or biotic. This provides a highly resolvable succession in which artefacts and novel materials can provide time constraints to decadal resolution or better (Waters *et al*., 2018a; Zalasiewicz et al., in press) though such successions overall are typically marked by numerous internal erosion/hiatus surfaces separating intermittent depositional events, lack simple vertical accretionary patterns (e.g., the reference section at Karlsplatz, Vienna; Wagreich *et al*., 2023), and are commonly disturbed by 'anthroturbation' (Zalasiewicz *et al*., 2014b).. The pattern of such complex erosional/non-depositional surfaces is of great value for local correlation (Edgeworth *et al*., 2015).

Waters *et al*. (2018a) provided four examples of these extraordinarily diverse successions: Fresh Kills Landfill (New York), Teufelsberg (Berlin) and in Vienna (subsequently being proposed as a reference section by Wagreich *et al*., 2023), all of which are examples of artificial ground; and the Gorrondatxe-Tunelboca beachrock (northern Spain), a naturally formed succession comprising mainly artificial materials (furnace slags).

5. EVIDENCE FOR THE PROPOSED RANK OF SERIES/EPOCH

The hierarchical system of ranking chronostratigraphic and geochronological units implies that the higher the rank attributed to the Anthropocene, the greater the change that has occurred between it and the preceding stratigraphic unit (Gibbard & Walker, 2014). When Paul Crutzen first used the term Anthropocene (see Section 2) it was as an improvisation, not constructed with the technicalities of stratigraphic hierarchy in mind. However, Lyell's (1833) use of the "-cene" suffix has been followed consistently during the Cenozoic to denote epoch/series rank, and Crutzen's (2002) case was based on his assessment that the Holocene was no longer an adequate descriptor of the state of the Earth System. The evidence base assembled by the AWG led it to vote, both indicatively in 2016 (Zalasiewicz *et al*., 2017a) and as a binding vote in 2022 (Appendix 2) strongly in favour of the series/epoch rank, with Waters *et al*. (2016) providing the case, summarised below.

Previously defined geological epochs/series are highly variable in length, lacking a fixed duration. However, beginning with the Miocene, epochs become successively shorter, culminating in less than 12,000 years for the Holocene. The Anthropocene thus lies along a trend that reflects increasing resolution of the geological record as one approaches the present. Furthermore, Zalasiewicz *et al.* (2017b) suggested that the key issue is not how long epochs are, but whether the geological record that allows characterization and correlation of the Anthropocene is already sufficiently distinct, whether that record will persist for at least many millennia, and whether changes already in train will inevitably affect the future course of Earth history and therefore the pattern of the future stratigraphic record. All of those conditions are fulfilled for the Anthropocene.

5.1 Comparison of scales and rates of change related to stratigraphical markers

The observed signals of palaeoenvironmental change associated with the proposed base of the Anthropocene in the mid-20th century, and their range across diverse stratigraphic environments, are described in detail in Sections 2 and 3. Below they are described in assessment of the most appropriate rank for the Anthropocene.

One may compare the scales and rates of change across the Holocene–Anthropocene transition in those stratigraphical markers for which there are records extending from Pleistocene (or older) times to the present. These long-term records are discussed below:

5.1.1 Mineral and material diversity

The 'mineral evolution' of Earth, as assessed by Hazen *et al*. (2008), shows that mineral species grew from their number in pre-planetary asteroids and planetesimals (~250) to ~1500 on an early Earth with water, some form of plate tectonics and metamorphism (Figure 21). Once life emerged and, crucially, developed oxygenic photosynthesis, the number of minerals rose to >4000 around the Archean-Proterozoic boundary as suites of oxides and hydroxides formed. Further changes in ocean chemistry, climate and biological evolution added only modest numbers of minerals (some 5,300 are now recognised, most being extremely rare). Early anthropogenic mineral-like formation included separation of pure metals (rare in nature) and their combination into alloys, beginning with the Bronze and Iron ages. This process intensified with the Industrial Revolution and accelerated sharply in post-1950 times, a trend that continues; the number of synthetic (human made) mineral-like compounds now exceeds 200,000 (sources in Hazen *et al*., 2017, updated), exceeding by more than an order of magnitude the number of minerals (Figure 21) (Section 3.1.1). This increase in diversity is unique in Earth history and in itself suggests a rank for the Anthropocene of at least series/epoch. Many of the novel anthropogenic materials either first became evident in geological deposits around the start of the proposed Anthropocene (e.g., micro- and macroplastics, glass microspheres, titanium), or first accumulated slightly earlier in the 19th and early 20th centuries but show marked upturns in abundance since the mid-20th century (e.g., fly ash, black carbon, aluminium metal, concrete, tungsten carbide).

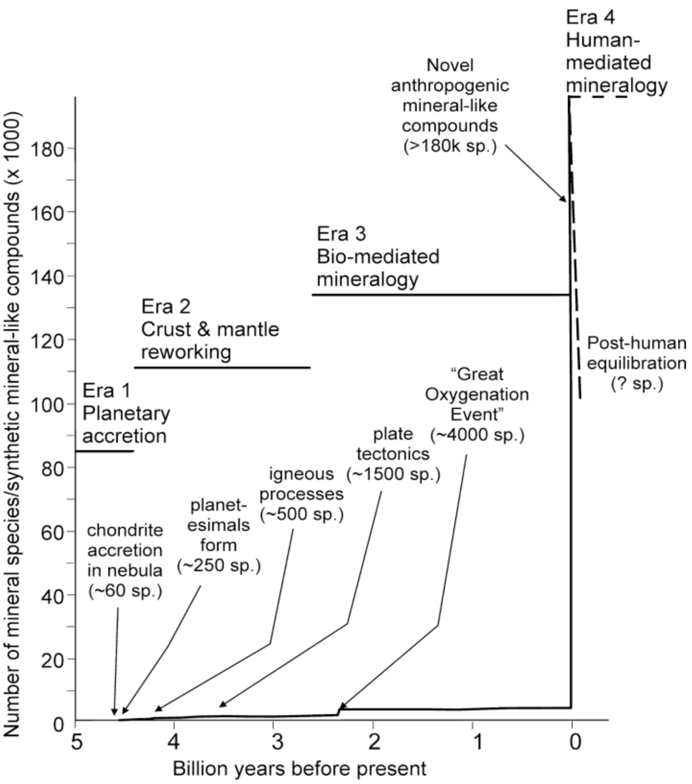

Figure 21. Earth's mineral evolution (after Hazen et al., 2008) modified to show the human addition (from Zalasiewicz et al., 2014a), the scale of which is here shown to be much greater than originally figured (see Hazen et al., 2017) and since has estimated to have increased to >200,000 mineral-like compounds. From Zalasiewicz et al. (2019a).

5.1.2 Carbon dioxide (CO_2)

During the proposed Anthropocene, atmospheric CO_2 concentrations have risen by 110 ppm (Figures ES1 and 22), at a peak rate of >2 ppm/yr. This rise is some 100 times faster than across the Pleistocene–Holocene transition (Waters *et al*., 2016). The start of the Northgrippian broadly coincides with a change from a slightly decreasing trend to a slight increase that persisted without further change through the start of the Meghalayan. This slight increase was attributed by Ruddiman (2003, 2013, 2018) to anthropogenic deforestation during early farming, though this interpretation remains controversial, with natural degassing from the oceans also suggested (see Zalasiewicz *et al*., 2019b, in press). Whichever interpretation is correct, the rise during the Anthropocene is >600 times faster than the 25 ppm rise from ~8000 yr BP to ~1750 CE and is unprecedented over at least 800 kyr, as shown by the ice-core records (Lüthi *et al*., 2008). Furthermore, the post-industrial rise (~140 ppm) already considerably exceeds the rise (76 ppm from Dome C ice core) associated with the Pleistocene–Holocene transition (Flückiger *et al*., 2002). Hence, atmospheric CO_2 concentrations in the Anthropocene are outside of the range of variability of the Holocene and probably the Quaternary too, and were last likely to have been at this level some ~3.3–3.0 million years ago during the Pliocene Epoch (Haywood *et al*., 2020; Rae *et al*., 2021). A significant component of this CO_2 will persist in the atmosphere for tens of millennia (Clark *et al*., 2016; Talento & Ganopolski, 2021), irrespective of future emissions or emission reductions (see Section 5.2).

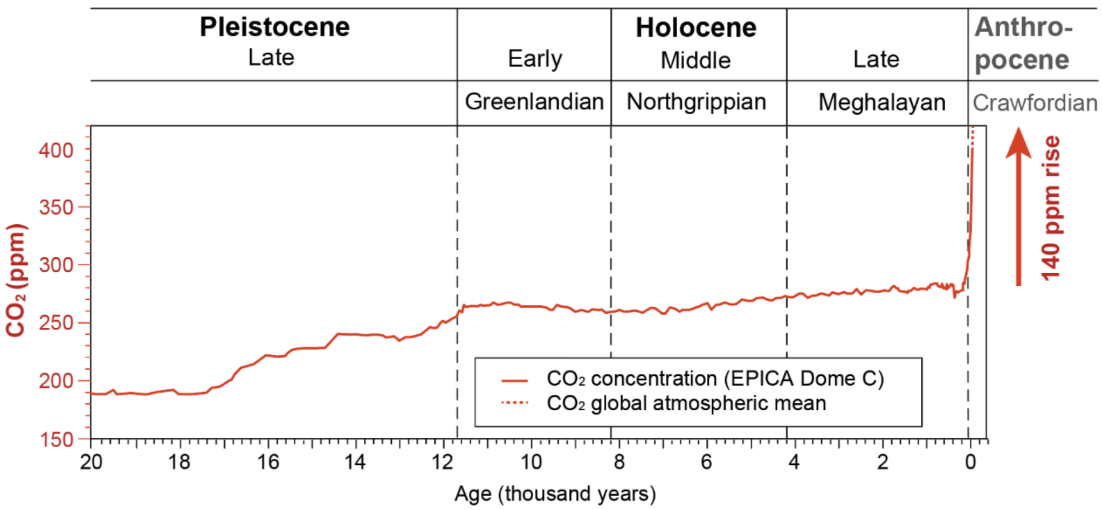

Figure 22. Atmospheric CO_2 records in Antarctic (EPICA Dome C) ice core over the last 20 kyr (Monnin et al., 2001), supplemented by observational data from Rubino et al. (2013).

5.1.3 Methane (CH_4)

During the proposed Anthropocene, atmospheric CH_4 concentrations have risen by >750 ppb (Figures ES1 and 23; Nisbet *et al*., 2023), in addition to a rise of ~360 ppb between 1875 and 1950 CE. Consequently, it is now more than double the maximum concentrations evident during the Holocene (when it fluctuated between 590 and 760 ppb). CH_4 levels have typically increased rapidly with rises of insolation from past glacials to past interglacials. This is the case during the Pleistocene–Holocene transition in which there was a rise of 306 ppb in the Dome C ice core (Flückiger *et al*., 2002), substantially lower than the scale of increase at the start of the proposed Anthropocene. Subsequently, during the Greenlandian and Northgrippian, CH_4 concentrations fell along with the decline in insolation, as they did also in previous interglacial intervals, then began to rise over the past 5000 years, plausibly in response to the development of rice farming in eastern Asia (Ruddiman *et al*., 2016). The average rate of rise of 10 ppb/yr or 0.5%/yr during the Anthropocene is ~500 times faster than the ~100 ppb rise from 5000 years ago to 1750 CE and the total rise is about three times the magnitude of increase recorded at the Pleistocene–Holocene transition. Current CH_4 concentrations greatly exceed those evident in ice core over at least the past 800 kyr and are hence outside of the range of variability of the Holocene and much, if not all of, the Quaternary.

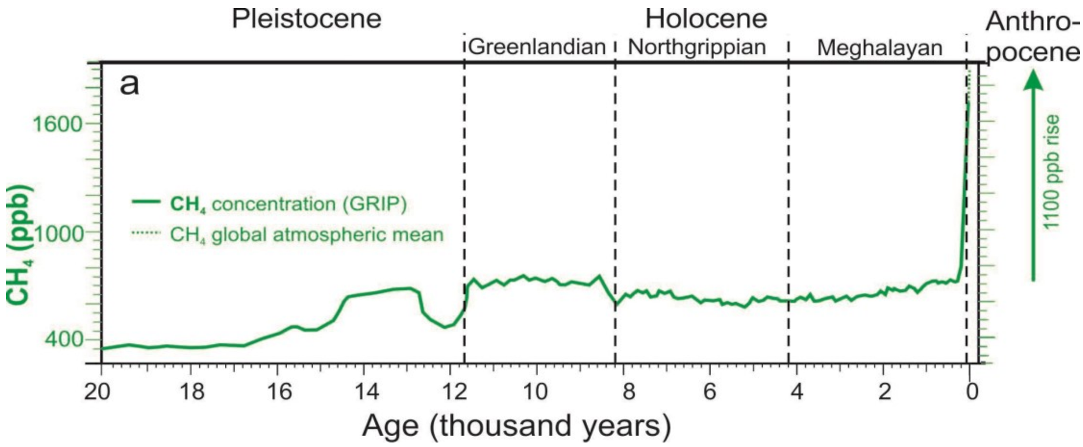

Figure 23. Atmospheric CH_4 records in ice core from Greenland GRIP (Blunier et al., 1995) and global atmospheric mean values (NOAA, 2023a).

5.1.4 Carbon isotope anomaly

During the proposed Anthropocene a ~2‰ decrease in $\delta^{13}C$ in Antarctic ice (Schmitt *et al*., 2012; Figures ES1 and 24) has greatly more depleted values than at any point in the last 24 kyr. This compares already in magnitude to major Cenozoic carbon isotope events such as the Monterey Event of the Miocene (Sosdian *et al*., 2020). It contrasts with a slow Greenlandian trend towards isotopically heavier carbon of <0.5‰ over ~4 kyr and subsequent static levels for much of the Northgrippian and Meghalayan. This Suess effect will continue as long as fossil carbon is combusted (Graven, 2015; Graven *et al*., 2020).

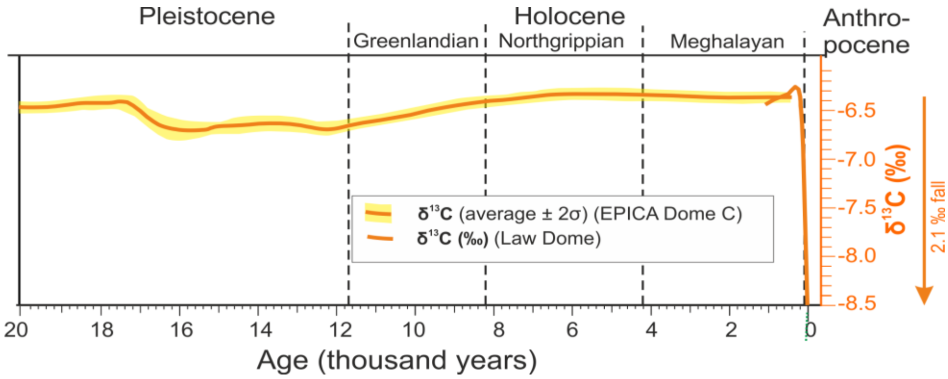

Figure 24 $\delta^{13}C$ variability over 20 kyr in the Antarctic EPICA Dome C (Schmitt et al., 2012) and Law Dome ice cores (Rubino et al., 2013).

5.1.5 Nitrogen isotopes, nitrous oxide and nitrates

Levels of chemically bound nitrogen have increased at the Earth's surface by some 120% relative to the Holocene baseline (Figure 25), following the invention of the Haber-Bosch process early in the 20th century (Galloway *et al*., 2008; Zalasiewicz, 2019). It has been inferred to be the greatest perturbation to the Earth's nitrogen cycle for 2.5 billion years (Canfield *et al.,* 2010).

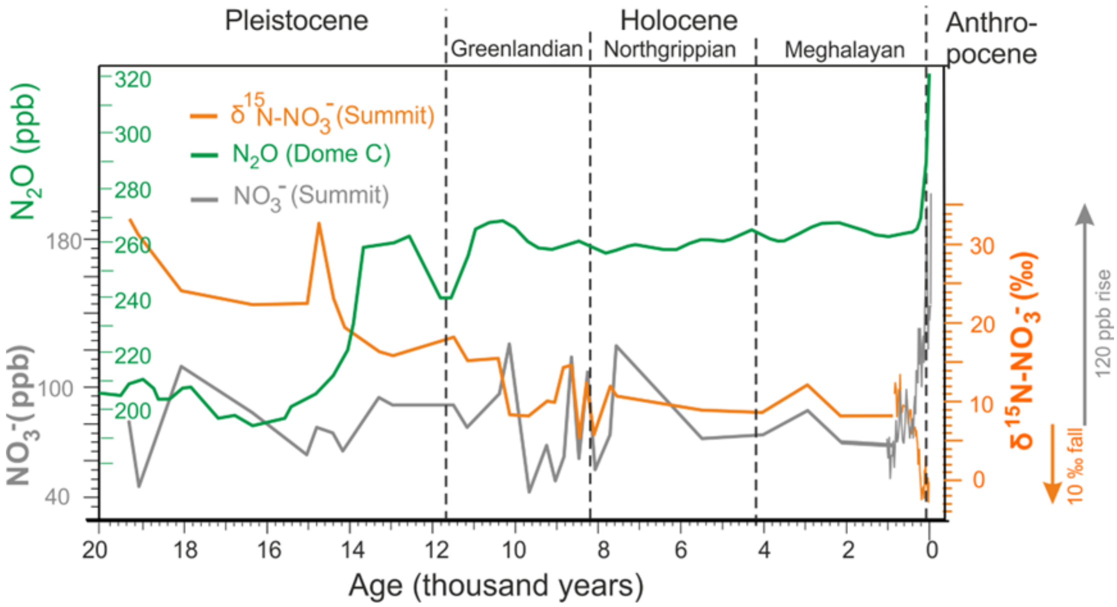

Figure 25. Ice core NO_3^- and $\delta^{15}N$ from Summit, Greenland (from Hastings et al., 2005, 2009 and Wolff, 2014, reproduced in Waters et al., 2016); N_2O curve from Antarctic Dome C ice core (Flückiger et al., 2002; Schilt et al. 2010b).

During the proposed Anthropocene, nitrate concentrations in Greenland ice show a peak increase of >100 ppb above a pre-1850 CE baseline of 73 ppb (Figure 11c) with a marked 1950s–1960s upturn and peaking at levels higher than over the past 100 kyr (Wolff, 2014). Nitrate perturbations occur around the base of the Northgrippian, but not Greenlandian and Meghalayan stages, although are subdued compared with the rise during the Anthropocene (Figures ES1 and 25).

N_2O concentrations for Antarctic ice core over the past 800 kyr shows a natural variability with high values during interglacials and low values for glacials, ranging between 202 ppb and 286 ppb (Schilt *et al*., 2010a), but during the Anthropocene has risen from ~290 ppb to the current figure of 334 ppb. The onset of the Holocene in Greenland ice core coincided with a marked increase in N_2O of 70 ppb (Schilt *et al*., 2010b; Flückiger *et al*., 2002), exceeding the rise at the start of the proposed Anthropocene, but over a ~5 kyr duration (Figure 25). However, this parameter shows little variability during the entire Holocene (10 ppb), but with a trend change from falling concentrations during the Greenlandian to slowly rising values during the Northgrippian and early Meghalayan (Flückiger *et al*., 2002).
A ~7.5‰ decrease in $\delta^{15}N$ values in Greenland ice cores commences with a marked inflexion, following an additional decrease of ~7.5‰ between 1875 and 1950 CE (Figures ES1 and 11c). Recent values are at least ~10‰ lower than over at least the past 36 ka, with Holocene values consistently higher than those in the Anthropocene, while Pleistocene values are consistently higher still.

5.1.6 Sulfate concentrations

Peak Greenland ice sulfate (SO_4^{2-}) concentrations are 2–5 times above pre-industrial values (Fischer *et al*., 1998), though not exceeding concentrations associated with large volcanic eruptions or during the Last Glacial Maximum (Wolff, 2014). Antarctic ice records show no equivalent elevated sulfate signatures, being more remote from anthropogenic contamination (Wolff, 2013, 2014).

5.1.7 Metal stratigraphic signals

Stratigraphic signals from metal extraction and working have a long history, early signals from Bronze and Iron Age lead smelting being recorded in archives such as European peat-bogs, Iberian lakes and Arctic ice-cores from ~3500 yr BP, with a more pronounced Roman peak at ~2000 yr BP (García-Alix *et al*., 2013; Figure 26), also recorded in Swedish lakes (Renberg *et al*., 2002). Suggested as potential markers to stratigraphically define an 'early' Anthropocene concept (Wagreich & Draganits, 2018), these signals are weaker, patchier and less sharply defined than signals associated with and post-dating the Industrial Revolution.

There are natural variations in Pb associated with crustal dust and volcanic emissions (Figure 26), although these are typically greatly exceeded by anthropogenic sources. However, the early mining signal seen in Europe is not evident in Mt. Logan (Yukon) ice and hence is very much regional, the signal of lead pollution being much weaker and appearing later in the Southern Hemisphere (Gałuszka & Wagreich, 2019). Coal-burning was considered the source of an abrupt, unprecedented increase in Pb from 1950 CE in ice core records from Mt. Logan, resulting in >10-fold Pb enrichment from 1981–1998 CE above natural background levels (Osterberg *et al*., 2008; Figure 26). In the Northern Hemisphere, peak enrichment factor values for Pb are typically >100 times and for the Southern Hemisphere 4 to 15 times background concentrations (Marx *et al*., 2016), though Pb flux values in 1979 CE of 1570 times natural background have been recorded in peat deposits in Switzerland (Shotyk *et al*., 1998).

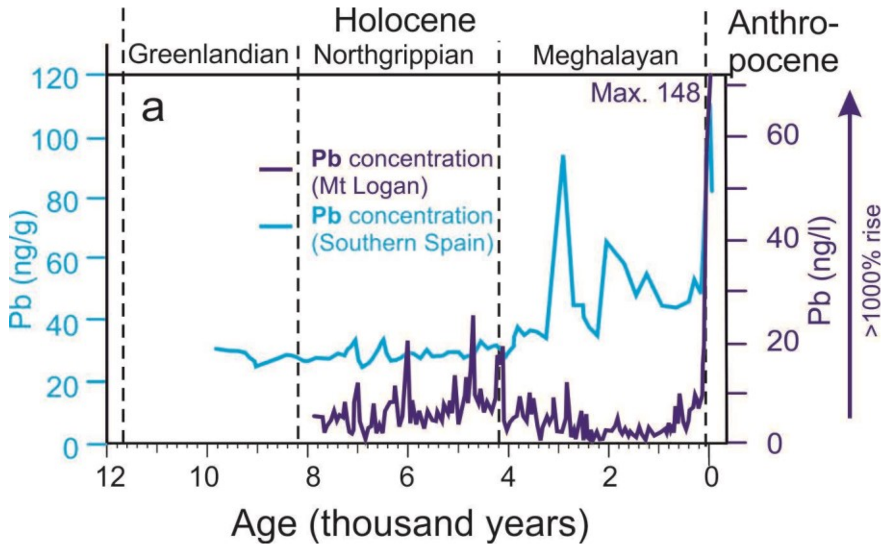

Figure 26. Variations in Pb concentrations in ice core from Mt. Logan, Yukon (Osterberg et al., 2008) and Laguna de Rio Seco, southern Spain (García-Alix et al., 2013).

5.1.8 Climate

The Quaternary Period and its subdivisions, excepting the recent tripartite subdivision of the Holocene (Walker *et al*., 2018), are broadly based on climate transitions, even if specific boundary levels use other markers, such as palaeomagnetic reversals. In the case of the Anthropocene, the dominance of orbital insolation controlling global climate has now been overwhelmed by anthropogenically sourced drivers and the Earth is clearly in a different climatic regime, outside of the Holocene climatic envelope (Waters *et al*., 2016; Summerhayes, 2019, 2020). Bova *et al*. (2021) show that during the past 11,700 years of the Holocene, the average global insolation trend was almost flat, with a very slight increase of about 1 W/m^2 over the past 7000 years. That very slight increase paralleled a slight rise of about 25 ppm in CO_2 (Ruddiman *et al*., 2016; see Section 3.2.1), leading Bova *et al*. (2021) to suggest that the Holocene climate should have warmed very slightly over the past 5000 years or so. This trend appeared to run counter to data from sediment cores and ice cores, especially from the Northern Hemisphere, which suggested that there had been a gradual global cooling over this interval (Marcott *et al*., 2013; Kaufman *et al.,* 2020; Figure 27). However, those data are now thought to represent summer insolation, which declined over the past few thousand years and was especially well developed in the polar regions (Crucifix, 2009; Beer & Wanner, 2012), leading to what came to be termed a 'neoglacial' climate of the past 4000–5000 years (e.g., McKay *et al*., 2018); as an example, the 'neoglacial' was characterised by a pronounced cooling in Greenland (Vinther *et al*., 2009). The cooling of this 'neoglacial' period was due to the Late Holocene growth of land and sea ice in the polar regions in response to declining summer insolation there. The combination of the slight growth in globally averaged insolation with the decline in polar summer insolation and consequential growth of ice led to overall flat average global temperature and sea level profiles for the Holocene.

Short-term climatic events at 8.2 ka and 4.2 ka provide useful guides for the subdivision of the Holocene into component stages and subseries, but the overall pattern is of a thermal maximum between 10 ka and 6 ka BP and subsequent gradual reductions in global temperatures until ~1850 CE (Figures ES1 and 27). Global mean surface temperatures showed a rapid rise of 1°C from 1975 to 2020 CE, at 0.02°C/yr (Sippel *et al*., 2021; Figure 17a), almost an order of magnitude faster than occurred at the Holocene onset. Bova *et al*. (2021) showed that the current global temperature has exceeded peak Holocene levels and probably approaches the warmth of the last interglacial period (128 ka to 115 ka BP).

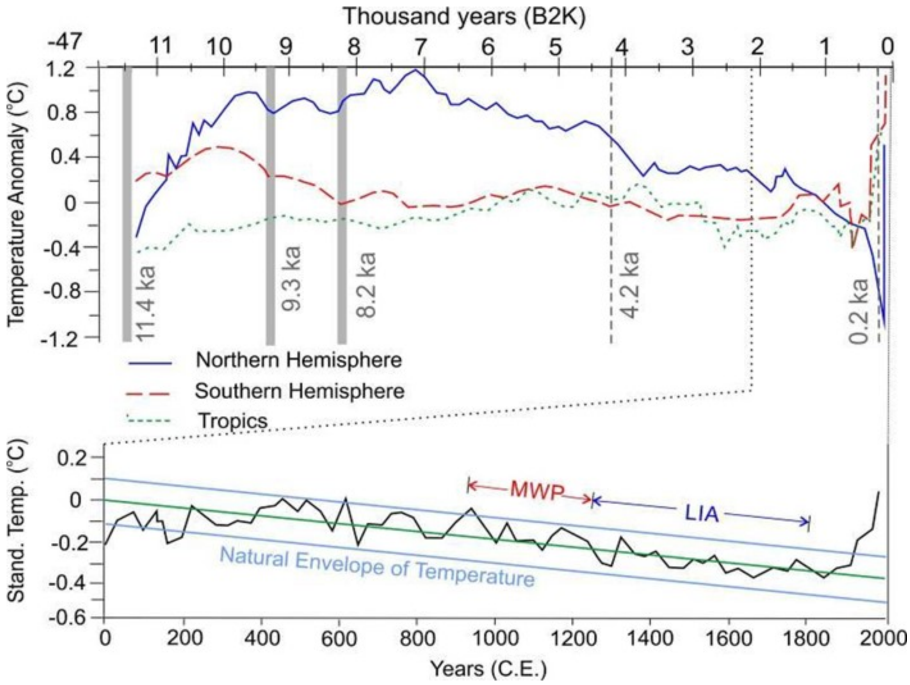

Figure 27. Upper figure shows mean temperature reconstructions for 60° latitude bands (Northern Hemisphere: 90–30°N; Tropics: 30°N–30°S and Southern Hemisphere: 90–30°S; based upon Marcott et al., 2013). Lower figure shows standardised global mean temperature for the past 2000 years, represented by 30-year means (from Pages 2k Consortium, 2013, redrawn in Waters et al., 2016), showing the natural temperature envelope for the past 2000 years; Little Ice Age (LIA) and the Medieval Warm Period (MWP) of the Northern Hemisphere are indicated.

Evidence from ^{14}C and ^{10}Be demonstrates that there were small fluctuations in solar output throughout the Holocene, with a periodicity of approximately 1500–2000 years (Steinhilber *et al*., 2012). Lower activity led to small advances in sea ice in the North Atlantic (Bond *et al*., 2001), associated with rainy climates and higher lake levels in western Europe (Magny, 2007). The most recent warm period was that of the so-called Medieval Climate Anomaly (or Medieval Warm Period, MWP) centred on about 1000 CE, while the most recent cold period was that of the Little Ice Age centred on about 1650 CE (during the Maunder Sunspot Minimum). These peak intervals extended over time frames of ~200 years. A recent analysis of tracheid anatomical measurements from *Pinus sylvestris* trees in Fenno-Scandinavia has provided high fidelity proxy measurements of instrumental temperature variability during the warm season that show the peak summer temperatures of the MWP were substantially cooler than those of the present period, in agreement with models of insolation (Björklund *et al*., 2023). Today's climate is indeed significantly warmer than was the MWP. Current solar measurements show that solar output declined significantly from a peak in 1980 to very low levels between 2019 and 2021 at the same time as global warming was ramping up. Solar energy is now increasing towards the next peak of solar cycle (25), which should be reached in about 2025 but will still be lower than the peak in 1980 (NOAA, 2023b). These changes are associated with very small changes in temperature that barely deflect the upward trajectory of climate change.

5.1.9 Sea level

Sea level is significantly lagging the marked upturns in atmospheric greenhouse gases and global temperature. The 4.62 mm/yr rise in 2013–2022 CE (WMO, 2022) greatly exceeds the mean rate of rise during the late Northgrippian to early Meghalayan (from 7–3 ka BP) of 0.5–0.75 mm/yr, with <0.1 m eustatic change inferred since ~3 ka in pre-industrial times (Onac *et al*., 2022). This recent rise is still short of the average rate of ~10 mm/yr from the start of the Holocene through to 7000 yr BP (Lambeck *et al*., 2002) or the 11 mm/yr during the rapid recovery from the extreme and local cooling event centred on the Arctic around 8.2 ka BP which marked the start of the Northgrippian Stage (Gehrels & Shennan, 2015), and likely resulted from the flooding into the Arctic of ice-cold water from the breaching of glacial Lake Agassiz. During the final stages of the melting away of the great Northern Hemisphere ice sheets between 11,700 and 7000 years ago, sea level rose by 45 m before flattening for the remainder of Holocene time (Clark *et al*., 2016). Such a rapid rate of rise would not be expected now because most Northern Hemisphere ice has disappeared. Nevertheless, significant near-future ice loss and sea level rise is now regarded as 'committed' given the Earth's present energy imbalance (e.g., Box *et al*. 2022; Naughton *et al*., 2023).

5.1.10 Biostratigraphic signals

Human impact on the biosphere extends back to human origins but became particularly evident in Late Pleistocene times, with the beginning of extinctions of terrestrial megafauna at ~50 ka BP, a wave of extinctions that peaked at ~10–12 ka BP. There has been a further acceleration of extinctions over the past few decades and into the present day (Koch & Barnosky, 2006), on a trajectory towards a Sixth Mass Extinction within a few human generations (Barnosky *et al*., 2011; Ceballos *et al*., 2015, 2017).

While there has been much debate as to the relative role of human causation versus climate/environment change as drivers for these Late Pleistocene–Early Holocene extinctions, they commonly coincide with the first entry of humans to continents, and the dominant human role is clear in well-dated examples of island-based extinctions, as on Madagascar and New Zealand. An anthropogenic driver is undisputed in more recent times (e.g., Barnosky *et al*., 2011, 2012; Ceballos *et al*., 2015, 2017). Human impact has also included the facilitation (overtly or accidentally) over millennia of non-native species introductions, which in turn led to a variety of secondary biological consequences, such as the decimation of island bird populations by rats which in turn affected adjacent reef productivity (Graham *et al*., 2018). Some of these changes have been explored biostratigraphically within the Holocene, as in the Santarosean and Santaugustinian land mammal ages of North America of Barnosky *et al*. (2014), reflecting human impacts on the North American biota at ~14 ka BP, and introduction of domesticated megafauna 500 years ago respectively.

There are marked, tightly clustered biostratigraphic changes of global correlatability, many novel in kind, around the base of the Anthropocene. These contrast markedly with the protracted anthropogenic biotic changes (mainly terrestrial) associated with the Pleistocene–Holocene transition, the transitions between the three Holocene stages/subseries, and the biostratigraphic changes associated with the Neogene–Quaternary boundary. Among the anthropogenic changes, the accelerating rate of species extinctions, now some hundreds to thousands of times higher than background levels (Pimm *et al*., 2014; Ceballos *et al*., 2015, 2017) has not yet led to a major mass extinction event, but threatens one over the course of at most a few centuries if current rates of loss are sustained (Barnosky *et al*., 2011, 2014), more immediately so if projected levels of climate warming (IPCC, 2018, 2021) take place. Furthermore, land-use alteration and increased predation have resulted in an average 69% decline in the relative abundance of monitored wild vertebrate populations around the world between 1970 and 2018, most drastically in freshwater species with a global decline of 83% (WWF, 2022). Translocations of terrestrial plant and animal species have accelerated markedly in the last century (e.g., Seebens *et al*., 2017) and, importantly, begun to change the character of marine biota too, which until recently was not as severely impacted as terrestrial systems have been (McCauley *et al*., 2015). This is accompanied by a now 98% dominance of terrestrial mammal biomass by humans and their domesticated mammals (Bar-On *et al*., 2018; Greenspoon *et al*., 2023). This sets the overall context, with practical Anthropocene biostratigraphic characterisation and correlation being based on specific taxa and assemblages associated with this overall trend, as recorded in strata, and as detailed above (Section 3.5; see also Williams *et al*., 2022).

Many of the above palaeoenvironmental signals are, in a geological context, essentially synchronous and globally distributed. The signals described above consistently exceed scales of change evident at the onset of the Middle and Upper Holocene subseries; although sea-level rates only exceed those of the onset of the latter. Many signals already exceed Holocene natural variability (Pb concentrations, global temperatures), and most likely exceed Quaternary variability (CO_2, CH_4, carbon isotopes, nitrous oxide, biostratigraphic signals) and some are unique either during the Phanerozoic or at any time in Earth history (reactive nitrogen, novel mineral-like compounds), starkly contradicting the opinion of Gibbard & Walker (2014, p. 32) concerning epoch-level change that "*…a change of this magnitude is not supported by the geological evidence*". Although the perturbations during the Anthropocene have so far been short-lived, it is clear that, as regards climate and biosphere change, they will have geologically long-term consequences. The AWG have concluded that it is both reasonable and conservative to consider the Anthropocene at a rank of epoch/series (Zalasiewicz *et al*., 2017b).

Would this be problematic for Quaternary (or indeed Phanerozoic) chronostratigraphy? Head and Gibbard (2015, p. 24) noted that the Anthropocene defined at the rank of series/epoch would truncate the Holocene, which "*has included modern deposits since its original inception in the late nineteenth century (Gervais, 1867–1869)*". This would cause the Holocene to lose its traditional and historical context as the geological time of the present, and would require stratigraphers to discriminate Anthropocene from Holocene strata. The Anthropocene defined at the rank of stage, or even substage, these authors suggested, would overcome such difficulties.

However, when Gervais introduced the term Holocene in 1869 he was living at a time soon after the end of the Little Ice Age, with environmental conditions occupying Holocene norms; he could not have foreseen the unprecedented changes occurring since the mid-20th century. Units of the Geological Time Scale, too, are defined by their base, the top of the Holocene having until now remained essentially undefined. Defining the Anthropocene at the rank of series/epoch would therefore complete formalisation of the Holocene (and that of the Upper Holocene Subseries and Meghalayan Stage) with a fixed top. The question of systematic recognition of chronostratigraphic units affects all of the geological column: where this is problematic, combined terms such as Permo-Triassic and Plio-Pleistocene have been widely used (Zalasiewicz *et al*., 2017b). As we have shown, the Anthropocene possesses a wealth of stratigraphic signals allowing its wide recognition and correlation.

5.2 Anthropocene: a brief reversible 'blip', or geologically long-lasting?

The case for the Anthropocene is based on the *elapsed* ~70 year record of Earth System change and the stratigraphic patterns that have resulted in an established history and in strata that already exist, and that can be sampled, analysed and correlated across a range of environments (see Section 4). However, a key criterion determining whether or not the Anthropocene has significance at the level of a geological epoch are the *implications* of these already-elapsed changes for the future unfolding of both Earth history and of the material stratigraphic patterns that reflect that history. If these elapsed changes are reversible by simply stopping the various kinds of anthropogenic forcing, then the Anthropocene might be regarded as a short-lived 'blip', following which conditions of the Holocene can soon return. In this case the Anthropocene would be inappropriate to be considered at the level of epoch. However, if the Earth System changes that have already occurred impose geologically long-lasting Earth System and stratigraphic repercussions, then the case for a formal Anthropocene Epoch is reinforced.

The pattern of change and resulting repercussions will undoubtedly be complex, but may be considered in three broad categories: physical, chemical/climatic, and biological.

5.2.1 Physical changes

These include the altered patterns of sedimentation associated with dammed rivers and land-use changes (Syvitski *et al*., 2020), and the introduction of novel materials such as plastics and novel 'rocks' such as concrete. They are likely to give rise to the least long-lasting signals, once their formation stops, and these materials are subject to weathering and erosion. Thus, as with any sediment layer that has formed in Earth history, equivalents in the Anthropocene, whether a landfill layer that is tens (or hundreds) of metres thick, or slowly accumulated lake sediments just centimetres thick, will either be buried over geological timescales or eroded away. Where buried and preserved, they can represent a brief 'event' layer, the Great Acceleration Event Array (GAEA) of Waters *et al*. (2022). Such Anthropocene 'event' strata (*sensu* Waters *et al*., 2022) may have a more extensive stratigraphic reach, though. Firstly, humans have burrowed deeply and extensively underground in 'anthroturbation' of various kinds, such as in mines, tunnels and boreholes, and in many of these structures will be lined with anthropogenic materials such as concrete and steel, thus placing them deep within more ancient rocks, far below the reach of erosion and therefore with excellent preservation potential (Zalasiewicz *et al*., 2014b; Waters *et al*., 2019b). A part-natural-analogue can be said to comprise the intrusive sills and dykes that lie below, and connect upwards into, an extrusive basalt province. Secondly, materials such as concrete, ceramics and plastics may be reworked by later erosion to become concentrated in subsequent deposits, much as Cretaceous flint clasts may locally dominate Quaternary gravel assemblages, and the common occurrence of reworked microfossils. This is a kind of stratigraphic 'halo' extending in time and space from the original level, but beyond that it has few impacts on the course of Earth history.

5.2.2 Climate change

The impacts of contemporary climate change are considerably longer-lasting. The current state in the Anthropocene is one of pronounced climate disequilibrium, in which sharply increased levels of atmospheric greenhouse gases including CO_2 and CH_4 (see Subsection 3.2.1) and N_2O (Subsection 3.2.3) are producing an Earth Energy Imbalance, in which the Earth will continue to heat up long-term, even after greenhouse levels eventually stabilise. Most of the additional heat is currently entering the ocean (which thus acts as a planet-scale storage radiator), with only a small part remaining in the atmosphere (Cheng *et al*., 2022; von Schuckmann *et al*., 2023). Even if greenhouse gases stabilise now at current levels (~420 ppm CO_2), this is 50% higher than pre-industrial levels. But once anthropogenic rises in other greenhouse gases are factored in, the 'carbon dioxide-equivalent' is now effectively doubled (Hansen *et al*., 2023). Estimates of the resulting equilibrium temperature to be attained, some centuries to millennia from now, as both short- and long-term feedbacks work through the Earth System, range from 3°C (IPCC, 2021) to as many as 10°C (Hansen *et al*., 2023) above pre-industrial temperatures.

Yet longer-term scenarios have been modelled (e.g., Talento & Ganopolski, 2021) based on the very long lifetime of CO_2 in the atmosphere. These indicate that the already accumulated emissions can affect climate for at least half a million years in the future, with glacial inception unlikely for the next 120,000 years. Realistically, hence, the Milankovitch cyclicity that has dominated Quaternary (and earlier) climate until very recently has been perturbed on a geological timescale, with further emissions increasing both the amplitude and duration of the perturbation. Even the 'best-case' scenario departs markedly from the Holocene pattern towards warmer conditions more typical of Pliocene (Burke *et al*., 2018) or Miocene (Steinthorsdottir *et al*., 2020) warmth and sea level. Post-industrial climate impacts already in train, therefore, are near-certain to persist over geological timescales – several Milankovitch cycles at least – before signature Quaternary patterns are resumed. Should the sequence of Northern Hemisphere glaciations be halted as a result of human actions, this could signal the end of the Quaternary Period/ System (Wolff, 2014).

5.2.3 Biological signals

Biological signals will have even longer-term repercussions that will be essentially permanent. A species, once extinct, cannot return and, of more immediate relevance to the Anthropocene, a species successfully transplanted away from its native range has a good chance of persisting and giving rise to successor species. This scale and extent of species reshuffling on Earth – simultaneously between every continent and within the global ocean – has been unique to Earth history, such that newly introduced species make up a large part, and locally the majority, of the biological association of any region. This reconfiguration of biotic components (that in itself independently gave rise to the concept of the Homogenocene: Samways, 1999) has put the Earth's biospheric evolution on to a new trajectory. This new biological trajectory is already evident in many stratigraphic records that have accumulated over the last few decades and means that the future biostratigraphic record will be permanently reconfigured too, away from

Holocene and earlier patterns. Biological effects are likely to become even more severe over coming decades and centuries (not least as intensifying climate change impacts are factored in) so that a period- or era-scale mass extinction event (with ~75% of species extinct) is a realistic possibility in the next few centuries (Barnosky *et al*., 2011, 2012; Ceballos *et al*., 2015, 2017), more quickly if global temperatures exceed Quaternary interglacial maxima. It has been mooted that the Anthropocene should be of period/system (or even era/erathem) rank (Bacon & Swindles 2016), which would then terminate the Quaternary Period/System. The previous mass extinction events form the basis for the Silurian, Carboniferous, Triassic, Jurassic and Paleogene periods/systems; two of these also coincide with the start of the Mesozoic and Cenozoic eras/erathems. If such a comparable mass extinction event does take place over the next few centuries, then – at that future time – consideration of a hierarchical level above that of epoch may well become appropriate, as addressed by Head et al. (2023a). Even now, though, the biological perturbation is sufficiently developed to give permanent repercussions that reflect planetary change of at least epoch scale.

As the final scale of the changes resulting from the transition from the Holocene to Anthropocene is unknown, some have argued to wait until the full effects are stabilised (Wolff, 2014). But, given that considerable, irreversible change has already taken place to the Earth System and to the stratigraphic record, with consequences persisting for hundreds of thousands of years climatically and being permanent biologically, there is *currently* a strong case to establish the Anthropocene formally, and conservatively, as a series/epoch.

6. SUMMARY

The Anthropocene Working Group (AWG) of the Subcommission on Quaternary Stratigraphy has, following 14 years of investigations, concluded that the Anthropocene possesses robust geological reality and its strata can be readily correlated worldwide. The AWG considers that the 'Anthropocene' needs a clear, consistent, formal chronostratigraphic definition for ongoing use by the wide range of communities for whom it has already become an indispensable term. A potential Anthropocene chronostratigraphic unit may currently be brief in geological deep-time terms, but the Earth System changes that are involved and the subsequent stratigraphic signals are of sufficient scale, global extent, rapidity and irreversibility to demonstrate that the Anthropocene is best considered as an epoch within the International Chronostratigraphic Chart. If the Anthropocene is adopted as such, this would mean that the Holocene Epoch has terminated, but that we remain within the Quaternary Period and Cenozoic Era. This action would then also increase the utility and geological integrity of the Holocene Epoch, restricting it to an interval of relative climatic stability, as prevailed at the time when it was originally conceptualised by Lyell (1833, his 'Recent') and Gervais (1868). Failing to formally recognize the Anthropocene as a geological series/epoch would mean that the Geological Time Scale would no longer accurately reflect Earth history.

Many of the signals of the Anthropocene are entirely new within Earth history, reflecting a proliferation of new forms of stratigraphic evidence. These include artificial radionuclides, microplastics, industrial fly ash, various kinds of synthetic persistent organic compounds and novel biostratigraphic signals, notably the rapid and near global spread of introduced species. The rapid development and wide (commonly global) dissemination of these signals have allowed a step change in stratigraphic resolution that, uniquely integrated with detailed observational process records, enable analysis of an Earth System undergoing transformation at an unprecedented rate, magnitude and manner. They amply enable, too, a precise and stable boundary as needed (Lucas, 2023) for the chronostratigraphic scale. Many of the proxies reflect the recent anthropogenic perturbation of patterns that extend back tens or hundreds of millennia, such as in ice CO_2, CH_4, N_2O, and more widely carbon/nitrogen isotopic ratios and heavy metal contents. These are consistent with concentrations far exceeding envelopes of variation in the Holocene, and in some cases the Quaternary, occurring with magnitudes and rates of change that far outpace those observed at the start of the component subseries of the Holocene, and at the start of the Holocene itself. On this basis, series/epoch rank is most justified for the Anthropocene and is consistent with the etymology of the name, with the inclusion of '-cene', used to denote a series/epoch of the Cenozoic.

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APPENDICES

APPENDIX 1: MEMBERSHIP OF THE ANTHROPOCENE WORKING GROUP

1.1 Current Working Group members

C.N. Waters* (Chair): School of Geography, Geology and the Environment, University of Leicester, Leicester, UK.
S.D. Turner* (Secretary): Department of Geography, University College London, London, UK
Z. An: State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China
A.D. Barnosky*: Jasper Ridge Biological Preserve, Stanford University, Stanford, California, USA[1]
A. Cearreta*: Departamento de Geología, Facultad de Ciencia y Tecnología, Universidad del País Vasco UPV/EHU, Bilbao, Spain
A.B. Cundy*: School of Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton, UK
I.J. Fairchild*: School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK
B. Fiałkiewicz-Koziel*: Institute of Geoecology and Geoinformation, Adam Mickiewicz University, Poznán, Poland
A. Gałuszka*: Institute of Chemistry, Jan Kochanowski University, Kielce, Poland
J. Grinevald: IHEID, Genève, Switzerland
P. Haff†: Nicholas School of the Environment, Duke University, Durham NC, USA
I. Hajdas*: Laboratory of Ion Beam Physics, ETH, Zurich, Switzerland
Y. Han*: State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China
M.J. Head*: Department of Earth Sciences, Brock University, St. Catharines, Ontario, Canada
J.A. Ivar do Sul: Leibniz Institute for Baltic Sea Research Warnemüende (IOW), Rostock – Germany
C. Jeandel: LEGOS, Université de Toulouse, CNES, CNRS, IRD, Toulouse, France
R. Leinfelder*: Department of Geological Sciences, Freie Universität Berlin, Berlin, Germany
F.M.G. McCarthy*: Department of Earth Sciences, Brock University, St. Catharines, Ontario, Canada
J. McNeill: Georgetown University Washington DC USA
E. Odada: Geology Department, University of Nairobi, Nairobi, Kenya
N. Oreskes: The Department of the History of Science, Harvard University, Cambridge, USA
C. Poirier: Normandie Université, UNICAEN, UNIROUEN, CNRS; Caen, France
D. deB. Richter: Nicholas School of the Environment, Duke University, Durham, NC 27708, USA
N.L. Rose*: Department of Geography, University College London, London, UK
Y. Saito*: Estuary Research Center, Shimane University, Shimane, Japan
W. Shotyk: Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada

C.P. Summerhayes*: Scott Polar Research Institute, Cambridge University, Cambridge, UK
J. Syvitski*: INSTAAR and CSDMS, University of Colorado, Boulder, Colorado, USA.
D. Vidas: The Fridtjof Nansen Institute, Lysaker, Norway
M. Wagreich*: Department of Geology, University of Vienna, Vienna, Austria
M. Williams*: School of Geography, Geology and the Environment, University of Leicester, Leicester, UK.
S.L. Wing*: Department of Paleobiology, Smithsonian Museum of Natural History, Washington, DC, USA
J. Zalasiewicz*: School of Geography, Geology and the Environment, University of Leicester, Leicester, UK.
J. Zinke*: School of Geography, Geology and the Environment, University of Leicester, Leicester, UK.

*Voting member
†Deceased following submission of the proposal
[1]Current address: Department of Integrative Biology, University of California, Berkeley, CA 94720, USA
n.b. P.L. Gibbard (Scott Polar Research Institute, Cambridge University, Cambridge, UK) resigned as voting member in July 2023. He voted in earlier rounds (see Subsection 2.1–2.4.

APPENDIX 2: MEMBERSHIP AND VOTING RECORD OF THE AWG

2.1 AWG Executive and organisation

The Anthropocene Working Group (AWG), was set up by Subcommission on Quaternary Stratigraphy (SQS) in 2009 with Jan Zalasiewicz as Chair and Mark Williams (subsequently Colin Waters from 2011) as Secretary. In 2020 the AWG entered a new formal cycle, with particular emphasis on identifying a candidate GSSP. The Chair's position moved to Colin Waters, and the Secretary's role to Simon Turner, who was also employed to manage the Haus der Kulturen der Welt's project analysing 12 candidate stratotypes (Rosol *et al*., 2023).

In preparation for subsequent binding votes, the AWG's structure also changed in 2020 to encompass 23 voting members (with expertise to assess detailed stratigraphic evidence of GSSP candidate sites, commensurate with the overall SQS mandate) and 15 non-voting members as of 1st January 2023 (to continue the wider exploration of the Anthropocene, and particularly how its geological application interfaces with its use in other disciplines).

The AWG has been able to meet in person at several venues, including Berlin (2014, 2021, 2022), Cambridge (2015), Oslo (2016), Mainz (2018), New Orleans (2019) and participated in an SQS-sponsored meeting 'AnthroFlor' in Florence (2022). Details of all of the meetings are available online in the annual AWG Newsletter downloadable from the AWG webpage:
(http://quaternary.stratigraphy.org/working-groups/anthropocene/)

2.2 Voting record of the AWG

2.2.1 2016 indicative vote reported by Zalasiewicz et al. (2017a)

At the 35th International Geological Congress in Cape Town, South Africa, on 29th August 2016, the AWG presented its preliminary findings and recommendations, as well as the range of voting opinion within the group on the major questions surrounding the Anthropocene (as summarised by Zalasiewicz *et al*., 2017a). It also mapped out a route towards a formal proposal on the Anthropocene: submission to the relevant ICS subcommission (the SQS), then to the full voting membership of ICS, and finally to the Executive Committee of the International Union of Geological Sciences (IUGS), and outlined the work that still needed to be done. Votes on all of the main current questions on the Anthropocene were taken by email ballot immediately prior to the meeting and involved all members of the group (then numbering 35). The votes were informal and non-binding, and were taken as an important indication of the range of opinion within the group, and as useful to guide future work (*n.b.* a vote could be divided between more than one option if the member thought that, at that stage, they had equal weighting).

The majority opinion of the group, as reported at Cape Town and detailed in Zalasiewicz *et al*. (2017a), was based on responses to the following questions on the email ballot form:

- *Is the Anthropocene stratigraphically real?* Voting result: in favour, 34; against, 0; abstain, 1.
- *Should the Anthropocene be formalized?* Voting result: in favour, 30; against, 3; abstain, 2.
- *Hierarchical level of the Anthropocene.* Voting result: era, 2; period, 1.5; epoch, 20.5; sub-epoch, 1; age, 2; sub-age, 0 (or 1 "if needed"); none, 1; uncertain, 3; abstain, 4.
- *When should the Anthropocene begin?* Voting result: ~7 ka, 0; ~3 ka, 1.3; 1610 Orbis, 0; ~1800, 0; ~1950, 28.3; ~1964, 1.3; diachronous, 4; uncertain, 0; abstain, 0.
- *Should the Anthropocene be defined by GSSP or GSSA?* Voting result: GSSP, 25.5; GSSA, 1.5; uncertain, 8.
- *What is the best primary marker for the Anthropocene?* Voting result: aluminium, 0; plastic, 3; fuel ash particles, 2; carbon dioxide concentration, 3; methane concentration, 0; carbon isotope change, 2; oxygen isotope change, 0; radiocarbon bomb spike, 4; plutonium fallout, 10; nitrate concentration/$\delta^{15}N$, 0; biostratigraphic extinction/assemblage change, 0; other (lead, persistent organic pollutants, technofossils), 3; uncertain, 2; abstain, 6.

There was virtually unanimous agreement that the Anthropocene concept, as articulated by Paul Crutzen and Eugene Stoermer in 2000, is geologically substantiated. The majority view was that, based on the evidence of actual and potential stratigraphic indicators gathered to date, a formal proposal on the Anthropocene should be prepared. Most of the AWG voted for assignation as an epoch/series. The majority view was that the start of the Anthropocene should coincide with the substantial and approximately globally synchronous changes to the Earth System which most clearly began or intensified in the 'Great Acceleration' of the mid-20th century. Majority opinion of the AWG was to seek and choose a candidate GSSP, as this is the most familiar and widely accepted method of defining formal geological time units. Given the large array of stratigraphic proxy indicators recognised to be useful in identifying Anthropocene strata there was no strong support for a particular marker, although plutonium fallout had the greatest support.

In summary, majority opinion within the AWG considered the Anthropocene to be stratigraphically real, and recommended formalisation at epoch/series rank based on a mid-20th century boundary, defined by a GSSP, but with more work to determine the preferred primary marker.

2.2.2 2019 results of binding vote by AWG

Following guidance from the Subcommission on Quaternary Stratigraphy and the International Commission on Stratigraphy, the AWG completed a binding vote (released on 21st May 2019) to affirm some of the key questions that were voted on and agreed at the IGC Cape Town meeting in 2016. The details, reported on the AWG website (AWG, 2019) and AWG Newsletter for 2019, are as follows:

No. of potential voting members: 34 No. required to be quorate (60%): 21 No. of votes received: 33 (97% of voting membership)

Q1. Should the Anthropocene be treated as a formal chrono-stratigraphic unit defined by a GSSP?

29 voted in favour (88% of votes cast); 4 voted against; no abstentions

Q2. Should the primary guide for the base of the Anthropocene be one of the stratigraphic signals around the mid-twentieth century of the Common Era?

29 voted in favour (88% of votes cast); 4 voted against; no abstentions

Both votes exceeded the 60% supermajority of cast votes required to be agreed by the Anthropocene Working Group as the official stance of the group and guided their subsequent analysis.

2.2.3 2022 binding vote on selection of rank for proposed Anthropocene chronostratigraphic unit

No. of potential voting members: 23 No. required to be quorate (60%): 14 No. of votes received: 23 (100% of voting membership).

Round 1 (concluded 17th December 2022): Epoch/series and corresponding stage 22 votes (95.7%)
Stage alone 1 vote (4.3%)
Other rank 0 votes
Abstentions 0

2.2.4 2022/2023 binding vote on selection of GSSP candidate

No. of potential voting members: 23 No. required to be quorate (60%): 14 No. of votes received: 23 (100% of voting membership).

Round 1 (concluded 17th December 2022): Crawford Lake 11 votes (47.8%)
Sihailongwan Lake 5 votes (21.7%)
Beppu Bay 4 votes (17.4%)
Searsville Lake 3 votes (13.0%)
All other sites 0
Abstentions 0

Round 2 (concluded 20th February 2023): Crawford Lake 11 votes (47.8%)
Sihailongwan Lake 8 votes (34.8%)
Beppu Bay 3 votes (13.0%)
Abstentions 1 (4.3%)

Round 3 (concluded 19th April 2023): Crawford Lake 14 votes (60.9%)
Sihailongwan Lake 7 votes (30.4%)
Abstentions 2 (8.7%)

Hence, the proposal is for an Anthropocene epoch/series and Crawfordian age/stage.

2.2.5 2023 binding vote on selection of candidate Standard Auxiliary Boundary Stratotypes (SABSs)

No. of potential voting members: 22 No. required to be quorate (60%): 13 No. of votes received: 21 (95% of voting membership).

Peer-review of the published data for the 12 candidate sites determined three sites should be considered reference sections: Ernesto Cave (Italy), Karlsplatz (Vienna) and San Francisco Estuary (USA). A non-binding vote was undertaken (completed on 4th July 2023) with 19 members voting, to determine relative support for remaining sites. The candidates with least support, East Gotland Basin (Baltic Sea), Flinders Reef (Australia) and Palmer ice core (Antarctica) were excluded from the SABSs vote and were considered to represent reference sections. The remaining five sites then were included in a formal vote.

Round 1 (concluded on 6th August 2023)
Beppu Bay, Japan 20 votes (95.2%)
Sihailongwan Lake, China 19 votes (90.5%)
Śnieżka Peatland, Poland 16 votes (76.2%)
Searsville Lake, USA 12 votes (57.1%)
West Flower Garden Bank, USA 9 votes 42.9%)
No vote 1
Abstentions 0

Hence, Beppu Bay, Sihailongwan Lake and Śnieżka Peatland all achieved greater than 60% support to be proposed as SABSs for the GSSP. Searsville Lake and West Flower Garden Bank Reef are included as reference sites.

2.2.6 2023 binding vote on the level (year) of the GSSP in the Crawford Lake core

No. of potential voting members: 22 No. required to be quorate (60%): 13 No. of votes received: 22 (100% of voting membership).

Following the binding vote on selection of Crawford Lake as the proposed site for the GSSP, a new core had been collected in order to carry out annual resolution analysis of the primary marker ($^{239+240}Pu$) and some secondary markers. Given that the Crawford Lake submission voted on by AWG members was on an earlier core and proposing 1950 CE as the level of the GSSP in that core (as outlined by McCarthy *et al*., 2023), it was necessary to confirm this in a binding vote. The results of the vote were concluded on 18th October 2023.

Q1. Can the preferred core from Crawford Lake be revised from CRA22-1FRA-3, as published in the original proposal McCarthy et al. (2023) in the Anthropocene Review Special Publication and selected by vote by the AWG, to the new core CRA23-BC-1F-A with annual-resolution Pu data?

Yes, 21 votes (95%)
No, 0 votes (0%)
Abstentions, 1 (5%)

Q2. What is your preferred level for the proposed Global boundary Stratotype Section and Point (GSSP) in the Crawford Lake core?

1950 CE[1], 4 votes (18%)
1952 CE[2], 18 votes (82%)

[1] Specifically, at the base of the calcite lamina in the varve level equivalent to 1950 CE, fixed at a convenient date close to a lithological boundary evident in the core and consistent with the common understanding of the onset of the Great Acceleration. For practical purposes to be taken as 1st January 1950 CE.

[2] Specifically to be taken at the base of the organic lamina in the varve level equivalent to 1952 CE, the varve in which the initial major increase in $^{239+240}Pu$ is recorded. For practical purposes to be taken midpoint between the two adjacent annual samples that show the biggest proportional increase within the run of samples that all have detectable Pu. At Crawford Lake this definition coincides in core CRA23-BC-1F-A with the Fall (October-December) 1952 CE closely coincident with the first thermonuclear detonation on 1st November 1952 CE. This option is conditional on selected 'YES' for question 1.

Hence, the Crawford Lake core CRA23-BC-1F-A has been selected as the host for the proposed GSSP, which is specifically taken in this core at the initial major increase in $^{239+240}Pu$ coincident with the boundary between the lower calcite and upper organic component of the varve level equivalent to 1952 CE at a depth of 16.2 cm.

2.2.7 2023/2024 binding vote on nominal start time for the Anthropocene epoch/Crawfordian age [added after submission to SQS]

No. of potential voting members: 22 No. required to be quorate (60%): 13 No. of votes received: 22 (100% of voting membership).

Q1. Can the preferred core from Crawford Lake be revised from CRA23-BC-1F-A (for which all material had been consumed during analysis) to the alternative CRA23-BC-1F-B which contributed Pu data to the annual analysis and for which intact core is preserved, as published in McCarthy et al. (2024) in the Anthropocene Review? The boundary will continue to be taken at the base of the organic lamina in the varve level equivalent to 1952 CE, the varve in which the initial major increase in $^{239+240}Pu$ is recorded.

Yes, 21 votes (95%)
No, 0 votes (0%)
Abstentions, 1 (5%)

Q2. Can a notional start of the proposed Crawfordian age/Anthropocene epoch be proposed at a specific date and time. Options are: a) 00.00 GMT 1 January 1952; b) 1st November 1952 coincident with detonation of first thermonuclear device, augmenting the proposed Global boundary Stratotype Section and Point (GSSP) in the Crawford Lake core present at the boundary between summer and fall 1952 CE varves? The Ivy Mike detonation occurred on 1 November 1952 at 07:15 local time (19:15 on 31 October, GMT); or c) 00.00 GMT 1 January 1953. Please select only one option.

a) 1st January 1952, 1 vote (5%)
b) 1st November 1952, 19 votes (86%)
c) 1st January 1953, 1 vote (5%)
d) Abstentions, 1 (5%)

Hence, the Crawford Lake core CRA23-BC-1F-B has been selected as the host for the proposed GSSP, which is specifically taken in this core at the initial major increase in $^{239+240}$Pu coincident with the boundary between the lower calcite and upper organic component of the varve level equivalent to 1952 CE at a depth of 17.5 cm. A nominal start for the Anthropocene is proposed to be 1st November 1952 coincident with detonation of first thermonuclear device (the Ivy Mike detonation) which occurred on 1 November 1952 at 07:15 local time (19:15 on 31 October, GMT), augmenting the proposed GSSP in the Crawford Lake core.

APPENDIX 3: COMMON CRITICISMS OF A CHRONOSTRATIGRAPHIC ANTHROPOCENE AND AWG RESPONSES

Table 1 [over page]. Common examples of criticism of a chronostratigraphic Anthropocene. Responses are presented in the following articles: [1] Zalasiewicz et al. (2017b); [2] Head et al. (2022b, 2023b) and Waters et al. (2022, 2023b); [3] Head et al. (2023a); [4] Head et al. (2022a); [5] Zalasiewicz et al. (2023), [6] Zalasiewicz et al. (in press); [7] Zalasiewicz et al. (2021). Abbreviation: AME=Anthropogenic Modification Episode of Waters et al. (2022).

Criticism	Key publications	Response
The anthropogenic signature is already the hallmark of the Holocene	Gibbard & Walker (2014)	Anthropogenic influence is not part of the definition of the Holocene or component stages, all based upon the expressions of natural climatic shifts [1]. The Anthropocene does not represent anthropogenic modification *per se* (that could be encompassed by the AME *sensu* [2], but a marked, in part irreversible Earth System response to post-mid-20th century sharply increased human forcing.
Origin of term is from outside of stratigraphy; The Anthropocene is a concept in search of a stratigraphic record	Finney (2014), Finney & Edwards (2016)	Origin from the Earth System sciences, but proposed as stratigraphic series/epoch [1] at least in part based on stratigraphic data from ice-core; the Quaternary and Holocene have similar conceptual underpinning [5]
There is imputed faulty etymology of the name	Walker *et al.* (2015)	The juxtaposing 'human' and 'new' is consistent with humans as the dominant force driving marked and globally near-synchronous changes to key Earth processes, and is consistent with use of the suffix '-cene' for all Cenozoic epochs, the most appropriate rank [1]
The 'Atomic' Age has priority over Anthropocene	Finney & Edwards (2016)	The "Atomic Age" neither conveys the meaning of the Anthropocene nor is formulated in a way that would make it acceptable as a formal chronostratigraphic term [1]
Formalization of the Anthropocene would cause truncation of the Holocene and sever it from its traditional context of 'modern' deposits	Head & Gibbard (2015)	The published origins of the Holocene pre-date the existence of the Anthropocene, which could not have been foreseen. The top of the Holocene can only be marked by definition of a younger unit; so, formulation of an Anthropocene does not change the existing definition of the Holocene but rather provides it with completeness. Unprecedented changes in the mid-20th century are of considerably greater scope and magnitude than those of the subdivisions of the Holocene and hence series/epoch rank is justified [1]
There is difficulty in discriminating Anthropocene and Holocene strata in geological mapping	Head & Gibbard (2015)	Geological mapping typically presents lithostratigraphical (not chronostratigraphical) units, and as elsewhere in the geological column it is possible to record Holo-Anthropocene undivided where necessary, but there are many proxies that help discriminate the two and many of these markers are recognised in numerous depositional settings [1]
Anthropocene successions are too thin, or 'minimal', 'negligible', 'marginal' and 'impoverished'	Walker *et al.* (2015); Finney & Edwards (2016)	They may be commonly thin, though are locally substantial (tens to even hundreds of metres thick) reflecting markedly increased sedimentation. They are laterally extensive, and can include rich stratigraphic detail with many unique Anthropocene proxy signatures [1]
There has not been a major transformation of sediment systems	Gibbard & Lewin (2016)	There has been an expansion of anoxic sedimentation in coastal marine and lake successions, with coastal and fluvial systems extensively modified by accelerated landscape change and dam construction. There have been order-of-magnitude changes of sediment erosion, transport and deposition related to agriculture, construction and mineral extraction, yielding abundant anthropogenetic and anthropogenically-influenced deposits [1]

Criticism	Key publications	Response
Anthropogenic isotope shifts in greenhouse gases have been rising for 100 years or more	Finney & Edwards (2016)	These isotope shifts (e.g., $\delta^{13}C$) show a clear mid-20th century inflection with a diachroneity of about a decade across the planet [1] They are accompanied by other isotopic shifts (e.g., $\delta^{15}N$) linked to the mid-20th century.
It is too short in duration	Finney & Edwards (2016)	The geological record already allows characterization and correlation of the Anthropocene and this distinction will likely persist over geological timescales [1] Formal units are defined by their base and no minimum duration is stipulated [4]
The Anthropocene cannot be consistently recognised or correlated and anthropogenic sediments show great complexity locally; there is no unambiguous and widespread 'golden-spike'	Edwards (2015); Edgeworth *et al*. (2023)	As with any geological boundary one would not expect *all* proxies to precisely coincide with a given boundary. Older deposits too can show great complexity yet are not excluded from stratigraphic analysis [1]. There are many stratigraphic indicators that can be used to trace the base of the chronostratigraphic Anthropocene with strikingly high precision, on a global scale, and in a wide range of sedimentary settings [3]
It is a product of the observational rather than stratigraphic record	Finney & Edwards (2016)	The Anthropocene is uniquely aided by the overlap of geological and historical time and instrumental records. The evidence provided is stratigraphic, but supporting information allows detailed analysis of how human drivers result in formation of signals in strata. Chronostratigraphy should not stop at some arbitrary point in the geological past and not be considered irrelevant to modern geological successions [1]
It is not necessary to use interpretative time scales when direct observations are available	Finney (2014)	The stratigraphic proxies within Anthropocene deposits contribute directly to identifying and calibrating this phase of Earth history. It is the comparison of the nature and rate of change of these proxies with those in earlier geological time, that enables assessment of the Anthropocene on both a planetary and deep time scale [1]
Many ratified GSSPs are at stratigraphic levels that do not represent major changes to the Earth System	Finney & Edwards (2016)	The criterion for justifying a geological time unit is not simply for example the first appearance of a fossil taxon, but because that proxy provides a readily correlatable surface close to fundamental changes to the biota and/or chemistry of the planet which justify the distinctiveness of the unit [1]
Focusing on the definition of the Anthropocene's start results in lack of consideration of its stratigraphic content and its concept	Finney & Edwards (2016)	The focus on defining the base of a chronostratigraphic unit is a fundamental aspect of the GSSP approach and the AWG does not differ from that taken elsewhere in the geological column. But AWG analysis also considers the nature of proxies through the entirety of the unit [1]
The Anthropocene is based upon predictions	Finney & Edwards (2016)	The case being made for the Anthropocene rests solely on evidence documented within existing strata that represent past events. Forward modelling may be used to demonstrate that the planetary changes related to the Anthropocene will be geologically long-lasting and not just a 'blip', but is not part of the definition [1] [6]

Criticism	Key publications	Response
The major anthropogenic impacts may lie ahead, or may be obliterated by subsequent natural events and so we should wait	Wolff (2014); Visconti (2014); Smil (2015); Gibbard & Lewin (2016); Swindles *et al*. (2023)	This appeals to the future consequences of possible trajectories of Earth history rather than to geological evidence. Epoch-scale change has already been recorded in strata [1] Future changes to the Earth System may lead to a higher rank than series/epoch being justifiable, but recognition of this would be eased, not hindered, by formal recognition of an Anthropocene epoch justified by the current AWG assessment [3] [6]
The Anthropocene lacks utility as a stratigraphic term	Walker *et al*. (2015)	The Anthropocene characterises a major, distinct and in part irreversible phenomenon marking a significant change in the Earth System with a distinctive stratal record. The term enables wide and effective communication, and formal recognition, of this planetary change [1]
The Anthropocene is a unit of human history not Earth history	Finney (2014)	The stratigraphic Anthropocene is founded on substantial changes to the Earth System that are reflected by an array of stratigraphic signatures. It is important to formalise this Anthropocene from other non-geological and very different concepts of the Anthropocene that have been proposed recently [1]
It is a cultural or multi-faceted diachronous event and should be maintained as an informal concept	Gibbard *et al*. (2022a, b); Swindles *et al*. (2023)	Most GSSPs are chosen strategically at points that are part of a complex evolving continuum. The coincidence of numerous geological markers around the mid-20th century is consistent with recognition as the onset of the Anthropocene. The concept of an 'event' encompassing 50 ka or more of human impact, is not consistent with the common usage of event and obscures the evidence of overwhelming Earth System change coincident with the Great Acceleration [2] Precision in terminology is far more desirable than vagueness, and promotes more productive communication [3]
It is a political statement, or of pop culture	Autin & Holbrook (2012); Finney & Edwards (2016);	The case for a formal stratigraphic Anthropocene unit rests upon stratigraphic evidence and much of the controversy may be driven by the imprecision in usage of the term in various communities. Many of the phenomena connected with the Anthropocene are of societal, and hence political, importance. However, this does not mean that they cannot be treated objectively and scientifically analysed [1]
Humans are not alone in affecting the environment	Baskin (2015); Walker *et al*. (2015);	All organisms alter their environments, but it is the scale, nature, pace and novelty of human impact that is significant to the Anthropocene and would be stratigraphically significant regardless of the cause [1]
There are different opinions over where the base of the Anthropocene should be set	Swindles *et al*. (2023)	Although there have been many alternative suggestions for the start of the Anthropocene, the only one that has withstood stratigraphic scrutiny by the AWG is the mid-20th century [3]

Criticism	Key publications	Response
A fixed ~1950 boundary 'excludes' much anthropogenic impact – and also much archaeological/ anthropological study – from the Anthropocene	Ellis *et al*. (2016); Gibbard *et al*., (2022a, b)	A chronostratigraphic Anthropocene commencing ~1950 CE definitionally excludes millennia of such earlier human influences, but includes it in the Holocene. This does not decouple it from its historical and causative links (e.g., much of 20th century history is rooted in 19th century and earlier events). The situation is directly comparable to many of the chronostratigraphic boundaries of older parts of the GTS, where a correlatable horizon occurs within a continuum of long-term change [7].
Some in the humanities prefer a fuzzy boundary to a precise one	Zalasiewicz *et al*. (2021); Swindles *et al*. (2023)	The original concept was clearly framed as a geological time unit and hence requires an isochronous base. It is unclear why such alternative fuzzy concepts should be labelled using a term rooted by its etymology in chronostratigraphy (as many alternative terms have been proposed rooted in the humanities), for confusion would inevitably result [5]
The Great Acceleration data cannot be used to support the beginning of the Anthropocene	Nielsen (2021, 2022)	The term was introduced to refer to rapid increases in numerous Earth System indicators around the mid-20th century and not in a precise mathematical sense. Nevertheless, the growth rates of most datasets fit hyperbolic trajectories up to ~1960 CE, after which many show decelerating (but still exceptionally fast) growth [4]
The Anthropocene series/epoch specifiable to a moment in time in the mid-20th century ignores the time-transgressive transformative complexity and progressively amplified development that is evident in the material records.	Walker *et al*. (2023)	(1) The stratigraphic record does not show "progressively amplified development" but essential stability of Holocene conditions, even as the anthropogenic record slowly grows and diversifies over millennia, followed by sharp change into an Anthropocene Earth System, most acutely and globally synchronously since the mid-20th century. (2) Virtually all chronostratigraphic boundaries are associated with "time-transgressive transformational complexity", e.g. the transition from late Pleistocene glacial conditions to Holocene interglacial conditions played out over ~13 kyr, from ~20 ka to ~7 ka, and its course differed strongly between the northern and southern hemispheres. This did not prevent a pragmatic and effective Pleistocene-Holocene boundary being defined and ratified at 11.7 ka. The Holocene-Anthropocene transition is far sharper – and globally synchronous.

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