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

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Abstract: This is the Executive Summary of a report produced by the membership of the Anthropocene Working Group as part of a submission to the Subcommission on Quaternary Stratigraphy to seek formalisation of the Anthropocene as an epoch of geological time. It summarises the content of two reports and their associated appendices which provide a background to: the history of usage of the term Anthropocene, when the proposed epoch started, the characterisation of the Anthropocene geological deposits and their stratigraphic value, the recognition of the Anthropocene in different sedimentary environments, the rank and duration of the Anthropocene, the proposed Global boundary Stratigraphic Section and Point and supporting Standard Auxiliary Boundary Sections.

EXECUTIVE SUMMARY

Part 1

Section 1 – Background: Paul Crutzen in 2000 (Crutzen & Stoermer, 2000; Crutzen, 2002), working in the context of Earth System science (ESS) and the International Geosphere-Biosphere Programme (IGBP), proposed that changes to the Earth's atmosphere, ocean, climate and biosphere since the Industrial Revolution were sufficiently profound to have effectively terminated the relatively stable Earth System, including climatic, conditions of the Holocene Epoch. He proposed a new geological epoch, the Anthropocene, to represent this recently transformed planetary state. The term was quickly adopted by the IGBP/ESS community as a *de facto* new epoch: a key framing concept widely used in their publications (e.g., Meybeck, 2001; Steffen *et al.*, 2004), though it had not gone through the formal analysis, voting process and ratification necessary to become an official unit of the International Chronostratigraphic Chart (ICC), the basis for the Geological Time Scale. Initial geological examination of the term (Zalasiewicz *et al.*, 2008) led to an invitation from the Subcommission on Quaternary Stratigraphy (SQS) to form a working group, the Anthropocene Working Group (AWG) to analyse the Anthropocene regarding potential inclusion in the ICC. Since 2009 the AWG has worked to this end, and this document, in two parts and with associated appendices is the final submission of the AWG.

Section 2 – The start date of the Anthropocene: Crutzen (2002) had suggested the beginning of the Industrial Revolution, but the AWG found the geological signals from early industrialization to be too widely scattered in time and space to allow systematic recognition of the Anthropocene in strata. By contrast, the more profound and globally synchronous changes associated with the 'Great Acceleration' of population growth, industrialization and globalization in the mid-20th century (Steffen *et al.*, 2007, 2015) left a wide array of stratigraphic proxy signals that allow an Anthropocene chronostratigraphic unit to be precisely delimited and widely identified and correlated. This level was subsequently agreed by majority vote (AWG, 2019) and forms the basis of this proposal. A wide variety of other start dates have been proposed in the literature and others have questioned the need for a formalised unit. The AWG have considered these other conceptualisations of the Anthropocene, but this proposal refers to the original concept of a unit of the Geological Time Scale.

Section 3 – Characterisation of Anthropocene geological deposits and their stratigraphic value: The AWG's gathered evidence shows that there is a *chronostratigraphic* basis for the Anthropocene (e.g., Williams *et al.*, 2011, Waters *et al.*, 2014; Zalasiewicz *et al.* 2019), such that an Anthropocene series may be recognised in recent geological deposits, and that this complements an Anthropocene epoch of *geochronology* (i.e., Earth history and process). These may be distinguished from the Holocene Series of geological deposits that accumulated pre-mid-20th century and its corresponding Epoch. The AWG found abundant evidence of this distinction, summarised as follows and in Figure ES1:

Lithostratigraphic evidence: The Anthropocene has seen a steep increase in the diversity of new 'minerals' (novel, synthetic inorganic crystalline compounds) which now greatly exceeds natural mineral diversity (Hazen *et al.*, 2017). Some, including elemental aluminium and titanium, are largely confined to the Anthropocene and have been produced and dispersed in geologically significant quantities. Proxies of fossil-fuel burning are fly ash (including spheroidal carbonaceous particles; Figure ES1) and black carbon, stratigraphic patterns of which are global and help locate a Holocene–Anthropocene boundary in many sedimentary settings (e.g., Rose, 2015). Plastics, synthetic organic polymers, have also been disseminated by human action, wind and water to become near-ubiquitous in post-mid-20th century sediments, both non-marine and marine (Zalasiewicz *et al.*, 2016). The Anthropocene also includes novel 'rocks', most distinctively concrete with >500 Gt produced since 1950 and rare beforehand, and hence commonly an effective stratigraphic marker to distinguish Anthropocene from Holocene urban deposits (e.g., Terrington *et al.*, 2018). The rapid 'evolution' of synthetic materials affords a high-resolution stratigraphy based on the appearance and obsolescence of different materials (e.g., Waters *et al.*, 2018a). The Anthropocene too has seen striking changes in patterns of erosion and sedimentation stemming from intensified mineral exploitation, landscape modification (such as dam building), urbanization and agriculture, with anthropogenic sediment flux having increased 2000% since 1950 and now exceeding natural sediment flux >15-fold (Syvitski *et al.*, 2022). Anthropocene sedimentary mass is thus disproportionally large compared to its ~70-year timespan.

Chemostratigraphic evidence: Chemostratigraphic markers include those reflecting the perturbation of the Earth's major element cycles, such as those of carbon, nitrogen and phosphorus. Fossil fuel burning and habitat loss have led to sharp departure from the Earth's broadly stable Holocene levels of atmospheric CO_2 levels of ~280 ppm to reach now ~420 ppm, with ~110 ppm of this rise being since 1950 CE (Rubino *et al.*, 2013; Figure ES1). This rise is directly recorded in polar ice, and indirectly in biogenic materials through a stable carbon isotope anomaly of now ~2 per mil via the Suess effect with fossil fuels being isotopically light (Rubino *et al.*, 2013; Figure ES1). Methane levels show comparable, even larger rises (Ferretti *et al.*, 2005; Figure ES1). Both represent striking departures from Holocene stability, with major effects (already initiated) on climate (Summerhayes, 2019; Figure ES1), sea level and biosphere. Surface reactive nitrogen and phosphorus levels have approximately doubled since ~1950 CE, mainly via increased fertiliser use; the nitrogen perturbation has left a stratigraphic signal via N_2O and nitrate concentrations (Wolff, 2013) evident in glacial ice and more widely in stable nitrogen isotopes, even in sites distant from agriculture (Hastings et al., 2009; Holtgrieve *et al.*, 2011; Figure ES1); the dispersal of both have led to spreading 'dead zones' since the 20th century, visibly recorded in sediments such as those of the Baltic Sea via markers of low-oxygen/anoxic conditions (Kaiser *et al.*, 2023). Stratigraphic signals of metals such as lead and mercury from smelting, industry, vehicle use, etc. are complex, variably extending to Roman and earlier times, though commonly show a marked 'Great Acceleration' upturn (Gałuszka & Wagreich, 2019). A clearer signal is given by novel persistent organic pollutants, such as the pesticides DDT and toxaphene, residues of which help identify an Anthropocene interval in many sedimentary settings (e.g., Muir & Rose, 2007). The sharpest chemostratigraphic signal so far identified is from artificial radionuclides such as plutonium and isotopes of caesium, americium etc. (Waters *et al.*, 2015), which appeared on Earth as a result of the nuclear weapons testing programme, and dispersed (together with 'excess' radiocarbon) regionally by above-ground atomic bomb detonations from 1945, and from 1952 globally by the more powerful thermonuclear ('H-bomb') tests (Figure ES1). The relatively long-lived plutonium-239 isotope (detectable for ~100,000 years) is suggested as the primary marker for the Anthropocene.

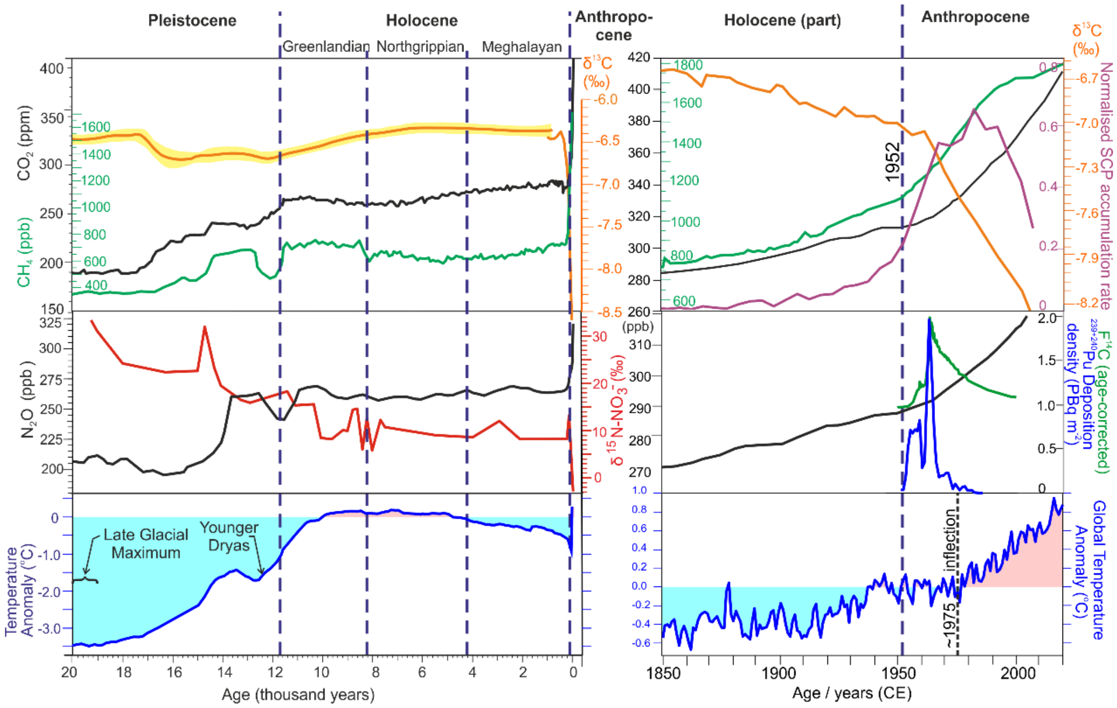

Figure ES1. Summary of significant stratigraphical markers of the Anthropocene series/epoch: (Left figure) compares the scale of change during the Holocene–Anthropocene transition compared with the Pleistocene–Holocene transition and component stages/ages (and sub-series/sub-epochs) of the Holocene; (Right figure) Details of some of the stratigraphic markers shown in the left figure and additional novel anthropogenic markers showing inflexions and inceptions focused on ~1950 CE. For sources, see respective figures in Part 1 Section 3 (for right figure) and Section 5 (for left figure). SCP – spheroidal carbonaceous particles.

Climate and sea level evidence: The warming of the Earth's surface has lagged the sharp upturn in CO_2, CH_4 and other greenhouse gas levels (see above) by ~30 years. The lag was partly caused by: (i) the increased abundance of aerosols resulting from greater industrial air pollution between 1945 and mid-1970s after which clean air legislations substantially cut aerosol emissions; and (ii) the inevitable delay between ocean warming leading to ice melt (especially the removal of Arctic sea ice and the associated loss of albedo). A further lag in sea level rise through: (iii) thermal expansion of the oceans, took time as heat from the surface gradually penetrated to deeper depths; and (iv) the inherent delay in the melting of land-based ice. These trends are now clear and sharply distinct from Holocene relative climate and sea-level stability, as would be expected given that the global temperature rise (of ~1°C from 1975 to 2020) was an order of magnitude faster than at the Pleistocene–Holocene transition (Figure ES1). Earth now has a marked energy imbalance (von Schuckmann *et al.*, 2023), ensuring that further warming and sea level rise are 'locked in' until sometime after atmospheric greenhouse gas concentrations have fallen to near-Holocene levels. The resultant stratigraphic signals are complex. Anthropogenic warming, though partly masked by decadal variations, has been detected in Antarctic ice ^{18}O (Casado *et al.*, 2023) and coral records (DeLong *et al.*, 2023) and is driving changes in species distribution, such as in planktonic foraminifera (see below). Global sea-level change (~30 cm since pre-industrial times, though now ~4.6 mm/yr: WMO, 2022) is beginning to produce a transgressive signal following ~3 kyr of stability to within ±0.1 m (Onac *et al*., 2022), especially in coastal regions affected by anthropogenic subsidence (Syvitski & Kettner, 2011).

Biostratigraphic evidence: Human impacts on terrestrial biota extend back ~50,000 years, notably via extinctions (initially of megafauna, later more general, e.g., Barnosky *et al*., 2011; Ceballos *et al*., 2015), translocations of numerous animal and plant species, and progressive domestication of many species. These changes have intensified sharply into the Anthropocene, in part a consequence of greatly increased trade, with the effect of homogenising biota on land and sea. Resulting biostratigraphic signals are complex and mostly regionally expressed but, via webs of correlation, can provide effective and precise identification of Anthropocene strata globally (Williams *et al*., 2022). Some biostratigraphic changes reflect other perturbations. Post-1950 CE changes in lake diatom assemblages in part reflect nitrogen enrichment (e.g., Wolfe *et al*., 2013*)* as well as phytoplankton responding to lake warming (Yan *et al*., 2023). The warming of the oceans in recent decades has led to novel planktonic foraminifer assemblages and northward shift in mid-latitude Northern Hemisphere Atlantic plankton and fish towards the Arctic. Although ~70 years is generally regarded as too brief for significant species evolution, in that time new, successful morphologically and genetically distinct species have originated and become widespread, e.g., the ‘marbled’ crayfish and the broiler chicken, the latter now making up some two-thirds of all bird biomass (Bennett *et al*., 2018). Another category that may be included here are technofossils – fossilisable technological artefacts (Zalasiewicz *et al*., 2014). Abundant, highly diverse and very rapidly ‘evolving’, these can provide high-precision age control to help recognise and correlate Anthropocene deposits, especially in urban settings (Wagreich *et al*., 2023) though more widely too, as in many marine deposits (e.g., Ramirez-Lodra *et al*, 2011).

Section 4 – Recognition of the Anthropocene in different sedimentary environments: The Anthropocene may be distinguished, through various combinations of the >100+ stratigraphic proxy signals recognised, across most of the Earth’s sedimentary environments, both non-marine and marine (Waters *et al*., 2018b, 2023). The highest resolution is available in environments where annual (or subannual) lamination is present, such as stratified lakes, estuaries and marine basins, biogenic strata such as tree rings and banded corals, and glacial ice. Speleothems can provide annual resolution, though the signals may be delayed if the speleothem-forming fluids pass through thick soil cover. Deposits such as peat and non-varved lake deposits lack such annual control, but may provide effective and high-resolution records nonetheless. Shelf marine deposits commonly include Anthropocene proxy signals, but resolution may be compromised by bioturbation or trawling disturbance, while deep marine deposits are commonly thin because of slow accumulation. Urban deposits (‘artificial ground’) commonly contain plentiful age indicators (especially technofossils) to allow distinction of Anthropocene from Holocene, while typically being geometrically complex, with many hiatuses.

Section 5 – Rank and duration of the Anthropocene as series/epoch: The use of the “-cene” suffix has been followed consistently during the Cenozoic to denote epoch/series rank, and this is considered to be the most appropriate level given that the Holocene Series/Epoch is no longer an adequate descriptor of the state of the Earth System. Though undoubtedly very short in a geological context, the Anthropocene is already geologically distinct from the Holocene with series/epoch rank being justified by: (1) the appearance of >200,000 synthetic (human-made) mineral-like compounds, unprecedented in the geological record; (2) atmospheric CO_2 and CH_4 concentrations, preserved in ice-sheet air bubbles, outside of the range of variability of the Holocene and probably the Quaternary too (Figure ES1); (3) a stable carbon isotope anomaly observable across numerous geological archives with significantly decreased values compared with the Holocene (Figure ES1); (4) nitrate and N_2O concentrations in polar ice exceeding that of the last 100 kyr and 800 kyr, respectively, and $\delta^{15}N$ values consistently lower at any time in the Holocene, appreciably lower than Pleistocene values (Figure ES1); (5) global mean surface temperatures now exceeding peak levels of the Holocene (Figure ES1) and set to rise even higher; and (6) tightly clustered biostratigraphic changes associated with vastly elevated rates of species extinctions and extirpations, displacement of non-native plant and animal species and dominance of domesticated species, permitting practical biostratigraphic distinction from the Holocene.

Although the case for the Anthropocene rests on the present stratigraphic record and not the future one, some critical changes will be geologically long-lasting, and preclude return to Holocene conditions. Physical changes, such as the presence of novel materials (e.g., plastics and concrete) and geomorphological features such as dams and cities, are likely the shortest-lasting, being subject to erosion and reworking, with stratigraphic burial and preservation of remaining debris. The climatic consequences will be longer, given the long lifetime of atmospheric CO_2, and of heat (and CO_2) stored in the ocean: just with existing greenhouse gas emissions, climate effects are projected to persist for ~0.5 myr, with glacial inception unlikely for 120,000 years (Talento & Ganopolski, 2021). Biological effects such as species extinctions and translocations of non-native species – of which there are many thousands, and showing an increasing trajectory (Seebens *et al.*, 2017) – are effectively permanent, changing the path of future biological evolution, and therefore for the nature of the future biostratigraphic record. The Anthropocene, already, has irreversibly set the Earth System on a new course.

Part 2

The proposed GSSP and three SABSs were selected following detailed analysis of 12 original candidate sections from a range of eight sedimentary environments across five continents. The remaining 8 sections constitute key reference sections. Given the lack of stratigraphic tradition of recognising and correlating Anthropocene deposits, this analysis (Waters & Turner, 2022; Waters *et al.*, 2023) played an important role in testing and validating this concept. The GSSP interval was recognised in all 12 sections, mostly with high precision (Figure ES2).

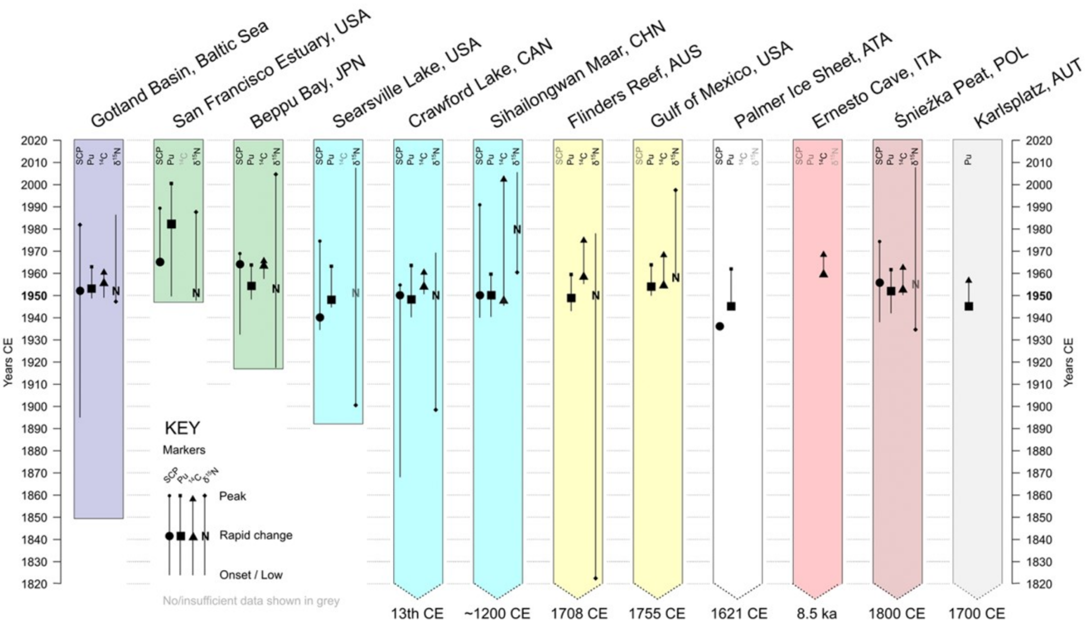

Figure ES2. Correlation of significant shifts in or appearances of stratigraphic markers between candidate GSSP, SABS and reference sites documented for this proposal. Colour of cores reflects environment of formation. From Waters et al. (2023).

Proposed Anthropocene GSSP – Crawford Lake, Canada: The proposal is detailed in McCarthy *et al*. (2023, in submission). Crawford Lake is a small meromictic lake occupying a sinkhole in Silurian dolomitic limestones near Milton, Ontario, Canada. Annual varves form below a chemocline, even though the bottom waters are oxygenated, comprising pale calcite crystals (summer) and dark organic matter (fall-winter). Barcode-like thickness variations allow precise correlation between cores. The succession has been studied over a ~1000-year interval, that records landscape/vegetation changes caused both by local indigenous communities and by later European settlers, and this provides context for the topmost ~70 year interval (17.0 cm thick) of the proposed Anthropocene. Crawford Lake is in a regional conservation area, and well protected but accessible. Scientific access is possible via agreement with the management body (Conservation Halton) and their Indigenous council. Cores (including the proposed GSSP) are stored at the National Biodiversity Cryobank of Canada; others are at the Royal Ontario Museum and Carleton University.

Within the latest Holocene to Anthropocene interval, age control is provided by a distinctive calcite-rich 'Dust Bowl' marker varve assigned to 1936 CE, and ^{137}Cs (Figure ES3) on individual varves.

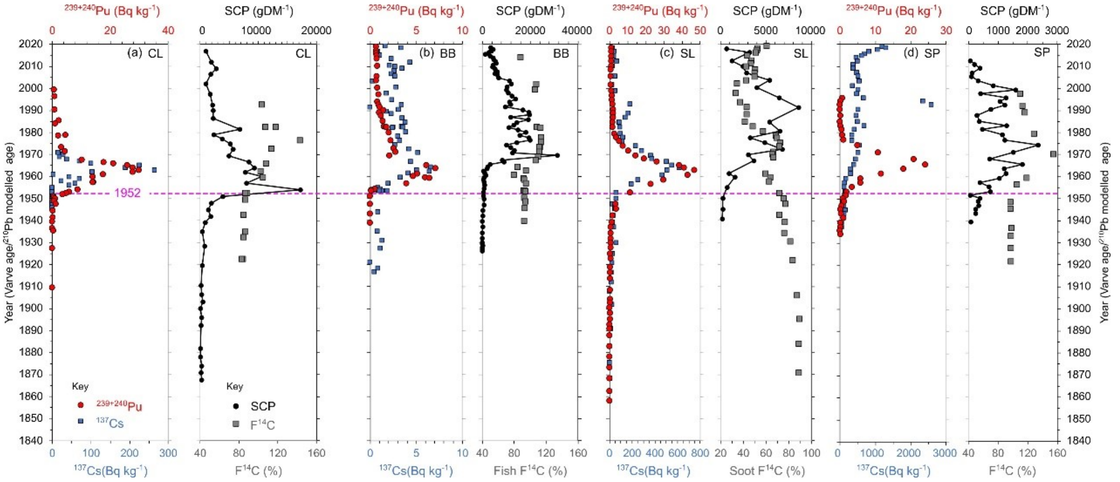

Figure ES3. Correlation of primary marker ($^{239+240}$Pu) and selected additional markers (spheroidal carbonaceous particles (SCPs), caesium (^{137}Cs) and radiocarbon (F^{14}C) between proposed Anthropocene GSSP at (a) Crawford Lake (CL) and the three SABSs of (b) Beppu Bay (BB), (c) Sihailongwan Maar Lake (SL) and (d) Śnieżka Peatland (SP) relative to the 1952 CE onset of the Anthropocene.

Proxy signals that identify the base of the Anthropocene are:

- the base of the initial rapid increase in the main Pu bomb spike at the 1952 CE varve, with the peak at 1962–1964 CE (Figure ES3), consistent with the pattern of global radionuclide yields
- the 'bomb' radiocarbon signal, although blurred because of the old carbon content of the lake, is detectable in samples ~1958–1990 CE (Figure ES3), with the base of the marker ~1.5 cm above the GSSP level
- the ^{137}Cs bomb spike, beginning 1955 CE, and peaking 1962–64 CE (Figure ES3)
- spheroidal carbonaceous fly ash particles from high-temperature fossil fuel burning, increasing sharply from 1953 CE (Figure ES3)
- increasing heavy metal concentrations from 1948 (Cu), 1950 (Pb), and 1952 CE (Zn) and also the elemental ratio Ti/Ca in 1952 CE, related to increased steel production nearby
- marked shifts in chrysophyte, diatom, and palynomorph assemblages reflecting catchment and water column changes from 1952 CE
- *Ulmus* (elm) regional decline (from the westward spread of Dutch elm disease) from the mid-1950s.

The GSSP for the Anthropocene series/epoch and Crawfordian age/stage is proposed at 17.0 cm in core CRA23-BC-1F-B at the base of the dark lamina in a varve deposited in 1952 CE, at the level where the primary marker shows a rapid increase in $^{239+240}$Pu concentrations.

Proposed Anthropocene SABS

1) Beppu Bay, Japan: The proposal is detailed in Kuwae *et al.* (2023). Beppu Bay is a small, deep depression located close to the coast of northeastern Kyushu. The deepest area of the bay, >60 m below sea level, has seasonally oxygen-deficient bottom water restricting bioturbation, resulting in varve formation. Each annual varve comprises a dark/low-density layer of organic matter and a pale/high-density detrital layer. Analysis of markers has recorded landscape, agriculture and industrial changes extending back 1300 years; the SABS core BMC21 S1-5 spans 1916 to 2021 CE, with the Anthropocene succession 64.8 cm thick. It and other cores are stored at the Center for Marine Environmental Studies (CMES), Ehime University, Matsuyama, Japan. The chronology of the proposed SABS core is determined through varve-counting supported by 16 age-known event layers, with a massive and thick flood event layer corresponding to a major flood event on 26th June 1953 providing reliable age control to locate the Anthropocene onset. These are validated by ^{210}Pb and ^{137}Cs analysis. The SABS core shows potential year-long minor gaps beneath some event layers and a slump layer within the succession. The GSSP interval is recognised within the 1952-dated varve at 64.8 cm depth.

Proxy signals which constrain the base of the Anthropocene in the SABS core are:

- the base of the plutonium bomb-spike associated with a rapid increase in $^{239+240}$Pu activities from 60.5 cm depth, corresponding to 1954 CE (Figure ES3)

Additional proxies from further cores from the same locality include:

- the base of the uranium bomb-spike associated with a rapid increase in the ^{236}U/^{238}U ratio in a varve corresponding to 1953 CE
- increase in artificial radiogenic iodine with higher values of ^{129}I/ ^{127}I ratios in the 1953 CE varve
- the base of the ^{14}C bomb-spike, with a percent modern ^{14}C (pM^{14}C) activity in anchovy fish scales in the 1957 CE varve (Figure ES3)
- the base of the caesium bomb-spike, with ^{137}Cs activity increasing above 59.5 cm depth, corresponding to 1953 CE (Figure ES3)
- abrupt increase in spheroidal carbonaceous particles (SCPs) in the 1964 CE varve (Figure ES3)
- lowest occurrence of microplastic particles in the 1954 CE varve
- lowest detection of total polychlorinated biphenyls (PCBs) in the 1953 CE varve
- abrupt increase in bulk heavy metal concentrations in the 1953 CE varve
- abrupt fall in δ^{13}C value in anchovy fish scales in the 1953 CE varve
- elevated δ^{15}N value in anchovy fish scales in the 1953 CE varve
- lowest detection of the red-tide-associated dinoflagellate species *Polykrikos kofoidii* in the 1953 CE varve
- initial major increase in algal pigments (fucoxanthin, chlorophyll-b and pheophytin-b, β-carotene) in the 1950 CE varve
- initial increase or lowest detection of persistent organic pollutants (POPs: DDT, DDE, α-HCH) and polycyclic aromatic hydrocarbons (PAHs) in the 1953 CE varve

2) Sihailongwan Maar Lake, China: The proposal is detailed in Han *et al.* (2023). Sihailongwan Lake is a small, deep thermally stratified maar lake with no river inlets or outlets, located in a remote area of Jilin Province in northeast China. Lowered dissolved oxygen concentrations over the past 70 years have led to a prominent change in colour from yellow laminated clays to the deposition of dark organic-rich laminae interlayered with pale detrital layers forming varves. The proposed SABS freeze core SHLW21-Fr-13 comprises varves that span from 1808 to 2020 CE. The chronology is determined through varve counting, cross-validated by ^{210}Pb, ^{137}Cs and ^{226}Ra analyses.

The site is within Jilin Longwan National Nature Reserve, accessible by paved road, with the proposed SABS and other cores from the locality stored in the Core Repository at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS) in Xi'an. The GSSP interval is recognised within the 1952-dated varve at 8.9 cm depth.

The primary marker which helps locate the base of the Anthropocene in the SABS core is:

- a rapid increase in $^{239+240}$Pu activities from 8.8 cm depth, corresponding to 1953 CE (Figure ES3)

Additional proxies from additional cores from the same locality:

- a marked increase in ^{129}I activities and ^{129}I/^{127}I ratios above the 1950 CE varve
- a marked increase in spheroidal carbonaceous particles (SCPs) above the 1950 CE varve (Figure ES3)
- a marked upturn in the fraction of black carbon soot component attributable to fossil fuel burning above the 1950 CE varve, while char decreases
- slightly increased heavy metal concentrations in the 1950 CE varve
- increase in polycyclic aromatic hydrocarbons (PAHs) in the 1950 CE varve
- rapid decrease in eDNA composition and Shannon index of phytoplankton above the 1950 CE varve

3) Śnieżka Peatland, Poland: The proposal is detailed in Fiałkiewicz-Kozieł *et al.* (2023). The Śnieżka Peatland is located in the Polish Sudetes mountains, in the Karkonoski National Park of the Krkonoše/Karkonosze Transboundary Biosphere Reserve. The chronological control of the proposed SABS core Sn0 is based on ^{210}Pb and F^{14}C, and validated with ^{137}Cs records. The base of the 50 cm-long core was dated to 1931 ± 8 CE, but with analyses in peats dated to 1571 CE at the base of another nearby core. The proposed SABS core and two nearby cores, are archived at the Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań. The GSSP interval is recognised at 39.5 cm depth in core Sn0.

Proxy signals which constrain the base of the Anthropocene in the SABS core are:

- the 1952 upturn in Pu activity, observed at 39.5 cm depth (Figure ES3)
- the lowest occurrence of spheroidal carbonaceous fly ash particles (SCPs; Figure ES3) and spheroidal aluminosilicates (SAPs) at 44–45 cm depth (~1939 ± 7 CE) with SCPs showing a pronounced upturn in early 1950s, and lowest occurrence of mullite at 40.5 cm depth (~1950 CE) followed by rapid increase in abundance
- elevated concentrations of Hg from ~1960 CE.

Additional proxies from a further core from the same locality:

- significant upturns in Al, Zn and Pb in the 1950s commencing with small peak in ~1950 CE
- lowest occurrence of pollen of the alien plant *Ambrosia artemisiifolia* (common ragweed) in 1956 ± 3 CE
- absence of testate amoebae mixotrophs (*Archerella flavum*) above 36.5 cm (1959 ± 3 CE)

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