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# A transparent framework for defining the Anthropocene Epoch

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## Abstract

Lewis and Maslin (2015) applied modern geological requirements to a systematic search for evidence of markers that could be used to define a new geological time unit, the Anthropocene Epoch. These must include (1) a near-permanent change to the Earth System that sets it on to a new trajectory and (2) global changes to the Earth System recorded in a number of stratigraphic deposits worldwide to provide a correlative boundary event or marker called a Global Stratotype Section & Point (GSSP) or 'golden spike'. Using this framework Lewis and Maslin conclude that just two time periods likely adhere to the criteria. These are the irreversible cross-ocean exchange of species alongside the globally synchronous coolest part of the 'Little Ice Age' in the 17th century, marked by the 1610 minima of $CO_2$ (Orbis Spike), or the accelerating atmospheric, oceanic and terrestrial changes in the second half of the 20th century, conveniently marked by the 1964 peak radionuclide fallout (Bomb Spike). Two recent responses by members of the Anthropocene Working Group (Zalasiewicz, 2015a, 2015b) to Lewis and Maslin (2015) do not dispute the GSSP framework, nor that these are the only two time periods that minimally fit the requirements for a new epoch. Instead they question our selection of two specific 1610 and 1964 GSSP primary markers. We respond to their misconceptions and misunderstandings about geological criteria and relevant evidence required to define a GSSP. Our primary goal, however, is to present a framework to assist the scientific community in objectively and transparently arriving at a robust selection of a GSSP and correlated markers to define the Anthropocene Epoch.

**Keywords**

Anthropocene, Colombian Exchange, Earth System, fossil pollen, global environmental change, golden spikes, Great Acceleration, nuclear, paradigm shift, phytolith

## Introduction

The concept and term 'Anthropocene' has been used with increasing frequency over the last decade. Since the year 2000 the most commonly used definition of the Anthropocene was that it began in the year 1800 (Crutzen, 2002; Crutzen and Stoermer, 2000; Steffen et al., 2011; Zalasiewicz et

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al., 2011a). This date, coincident with the early part of the Industrial Revolution, marks an important moment in human history with eventual global-scale environmental impacts, yet it is not consistent with the geological norms used to define a geological epoch (Gradstein et al., 2012; Smith et al., 2014). Epochs within the Phanerozoic, the last 541 million years, are today defined using a Global Stratotype Section & Point (GSSP), alongside correlated changes in stratigraphic deposits worldwide, to indicate a fundamental change to Earth's state in the time before compared with the time after the marker-event (Gradstein et al., 2012; Smith et al., 2014). That is, a dated globally correlated marker is selected within the long-term change of the Earth from one state to another. The temporal longevity of a typical epoch is on the order of millions of years, and the before-and-after differences may take tens or hundreds of thousand years to complete. Such globally distributed markers do not exist near 1800 (Lewis and Maslin, 2015; Zalasiewicz et al., 2015c). Thus, we reasoned that if a GSSP and correlated markers exist, then they should be chosen to define the Anthropocene Epoch, and therefore its inception.

In 2013 we could find no published comparison of potential GSSP markers with which to formally define an Anthopocene Epoch. At that time there seemed relatively little interest in GSSPs. So with the encouragement of colleagues we worked on a review and submitted it to *Nature* on 26 March 2014. After extensive reviews over almost 10 months, with four reviewers of whom at least one was a member of the Anthropocene Working Group (AWG[1]), the paper was accepted on 12 January 2015 (Lewis and Maslin, 2015). We concluded two dates did likely minimally adhere to the GSSP criteria to define the Anthropocene: 1610 and 1964. Unbeknown to us, on the same day, the majority of the members of the AWG also published a paper discussing how to define the Anthropocene (Zalasiewicz et al., 2015c). They recommended that the Anthropocene should not be defined using a GSSP, but instead by a date chosen by the AWG. However, instead of 1800 they chose 1945 (technically a Global Standard Stratigraphic Age, GSSA, usually reserved for geological time units >541 million years ago; see Gradstein et al., 2012; Smith et al., 2014). This was a landmark paper for the AWG, as it was the first peer-reviewed paper authored by the majority of the group, and garnered much publicity (e.g. Zalasiewicz and Williams, 2015).

An almost identical group of members of the AWG who published the paper recommending a 1945 GSSA (Zalasiewicz et al., 2015c) have then published two responses to Lewis and Maslin (2015), one in *Nature* (Zalasiewicz et al., 2015b), and one in this journal (Zalasiewicz et al., 2015a). We note that AWG members chose not to submit a comment to *Nature* which would have been peer-reviewed, but instead chose to write to the non-peer-reviewed correspondence section of *Nature* (Zalasiewicz et al., 2015b). The second response (Zalasiewicz et al., 2015a), submitted to the Perspectives and Controversies section of this journal, likewise avoided formal peer review.

In response to these three AWG papers (Zalasiewicz et al., 2015a, 2015b, 2015c), we emphasise the need for a transparent framework to objectively assess the existing evidence relevant to a geological definition of the Anthropocene, objective assessments of what further evidence should be sought, and transparent methods to prioritise differing evidence. After stating our framework and its logic we then deal with outstanding specific criticisms in Zalasiewicz et al. (2015a, 2015b).

In this paper we proceed in five parts. First, we discuss why scientists should define the Anthropocene, as understanding the reasons may help with the formal definition. Second, we describe how geologists divide time, which is via GSSP requirements, as this also assists in setting a framework for formally defining the Anthropocene Epoch. Third we describe a two-step process of defining the Anthropocene, for any body of evidence. Fourth, we address the errors and misunderstandings in the AWG responses to the two time periods (Orbis and Great Acceleration) and potential GSSPs ($CO_2$ in glacier ice and $^{14}C$ in tree rings) we highlighted in Lewis and Maslin (2015) as promising inception dates for the Anthropocene, alongside their genuine limitations as marker-events. Fifth, we briefly response to Zalasiewicz et al. (2015a) regarding human narratives and the Anthropocene. Taken together we hope this paper assists researchers in moving towards an objective, transparent assessment of the evidence from which to recommend a formal definition of the Anthropocene, including a start date.

## Why define the Anthropocene?

One key reason why it is desirable to agree a definition for the Anthropocene Epoch, whether formally ratified by the geological community or not, is because clear and precise definitions aid understanding. Surprisingly, a recent paper argued that scientists should deliberately leave the Anthropocene undefined (Ruddiman et al., 2015). Applied broadly, this route leads to obscurantism and confusion and should be avoided. However, we recognise that differing definitions may be relevant to differing disciplines, particularly outside the physical sciences (Maslin and Lewis, 2015).

Additionally, the likely key reason why geologists should set a formal definition of the Anthropocene Epoch is the integrity and internal consistency of the Geologic Time Scale (GTS). Geologists have uncovered the major events of Earth's 4.6 billion year history, dividing this history into a hierarchical series of ever-finer units, with stages nested with epochs, nested within periods, nested within eras, nested within eons (Gradstein et al., 2012). Divisions represent changes in the functioning of Earth as a system and the concomitant changes in the identity, abundance and composition of the resident life-forms. Larger differences result in classifications at higher unit-levels. The question, in terms of the GTS, is whether human activity has altered the Earth as a system, with permanent or extremely long-lived impacts, to such an extent that defining a unit of geological time is logically obvious. A strict adherence to the previously defined norms of defining epochs and other higher units is thus necessary to ensure that the categorisation of Earth's history is consistent across time. Furthermore, given the clearly contentious nature of the idea of the Anthropocene, strict adherence to the requirements generated *before* the modern usage of the Anthropocene term at the turn of this century, provides a relatively clear and objective geological test of the impact of the human activity on the Earth and its future trajectory. The alternative is to argue that the time closest to the present day within the GTS is somehow in need of exceptions to agreed norms. This would obviously present challenges to the process of defining the Anthropocene as any definition would be open to easy criticism that the process is biased and ideologically driven (see Maslin and Lewis, 2015, for this discussion).

## Epochs within the Phanerozoic are defined by GSSPs

Formally, geological time units are defined by their lower boundary, that is, their beginning. New geological time units are defined by multiple stratigraphic records to delimit before-and-after major changes to the Earth as a system (Smith et al., 2014). These divisions represent differences to the functioning of the Earth as a system and the integrated changes manifest in the resident life-forms. Boundaries are demarcated using a GSSP, or by an agreed date, termed a GSSA. Within the Phanerozoic Eon (meaning 'revealed life' that started 541 million years ago), epochs are defined by GSSPs and complemented by other correlated changes to the Earth System documented in other stratigraphic records (Gradstein et al., 2012; Smith et al., 2014). A recent review of GSSPs states as its first major conclusion: 'GSSPs are currently the internationally agreed method of fixing the definitions of stage [and therefore epoch] boundaries in rock sections'. It further notes, '[t]he ultimate aim of the GSSP project is to define a complete and globally correlatable set of lower boundaries for all stages of the Phanerozoic' (Smith et al., 2014).

The usual GSSP selection limitations are largely absent when considering the Anthropocene, as ice cores, marine sediments and other recent records will likely consist of adequate continuous sedimentation, be accurately dated, and several records spanning the globe are likely to exist (see limitations in Smith et al., 2014). Furthermore, GSSPs need not rely on biostratigraphic (fossil) evidence (Smith et al., 2014; the Holocene Epoch is defined without reference to fossils). Thus, there is no practical impediment to defining the Anthropocene the usual way any other epoch would be defined – by a GSSP and correlated stratigraphic markers. Specifically, a proposed GSSP must have (1) a principal correlation event (the marker), (2) other secondary markers (auxiliary stratotypes), (3) demonstrated regional and global correlation, (4) complete continuous sedimentation with adequate thickness above and below the marker, (5) an exact location – latitude, longitude and height/depth – because a GSSP can be located at only one place on Earth, (6) be accessible, and (7) have provisions for GSSP conservation and protection (Gradstein et al., 2012; but also see Smith et al., 2014 for further details).

One further practical argument against the use of a GSSA date chosen by committee is that any date may be challenged as being arbitrary and politically motivated (Lewis and Maslin, 2015; Maslin and Lewis, 2015). It is clear that the Industrial Revolution is a key event in human history. But which date should be chosen: 1760, 1800, 1850? Similarly for the Great Acceleration: 1945, 1950 or later? Furthermore, important events always have precursor events. When should the tracing of dates back from an actual geologically recorded environmental change stop? Watt's refinement of the steam engine? The first prototype working steam engine? Or the first use of coal for cooking or heating? The inevitable arbitrariness in a small group choosing a date is much less likely to be widely accepted compared with a well-justified and evidenced GSSP and correlated stratigraphic data. Data and weight of evidence should define the Anthropocene Epoch.

## A framework for defining the Anthropocene Epoch

Our framework is designed to assess all relevant evidence using a transparent and rational approach to assess the potential selection of a GSSP and correlated secondary markers to define the Anthropocene Epoch. It is in two parts: (1) screen the geological evidence against the geological requirements for defining an epoch to assess the evidence that we are in a new epoch, including support for different GSSPs and associated globally correlated markers; then (2) compare those time periods that minimally fit the requirements for a Anthropocene Epoch GSSP against a set of objective, specified, relevant and agreed-upon criteria to enable the selection of one time period and GSSP from the group of time periods that minimally fit the GSSP requirements. Lewis and Maslin (2015) undertook part one, but did not comment on part two stating only '[w]e hope that identifying a limited number of possible events and GSSP markers may assist in focusing research efforts to select a robust GSSP alongside a series of auxiliary stratotypes'. We can only begin the second part here, but suggest it is the role of the AWG to obtain consensus on the criteria.

We use the example of the Holocene Epoch, as it is instructive in terms of defining an Anthropocene Epoch. It was only recently ratified and so follows the newer understanding and recommendations of global correlation among multiple markers, and does not focus solely on biostratigraphic records (Smith et al., 2014; Walker et al., 2009). The transition from the glacial to interglacial was long, with surface air temperature rising for ~8000 years. Within this period of change one much shorter time period had to be chosen within which to place the boundary. An anomalous short-term abrupt change in temperature, which is superimposed on the long-term trend was chosen, because short-term abrupt changes to the Earth System provide the best global correlations in stratigraphic material. Thus, having documented the Earth System change (glacial to interglacial planetary conditions), the selected time period within that long change was at the beginning of a rapid near-global temperature rise following the end of an anomalously cool period. That is, a brief time period with high correlation potential was chosen. Finally, the GSSP was selected, an inflection of 2H excess (deuterium) in a Greenland ice core, because it is the most direct indicator of the abrupt change at that time (specifically sea surface temperature). Though Zalasiewicz et al. (2015b) claim that a GSSP should document changes larger than the variability of the prior epoch, this is not the case for the Holocene Epoch as the changes in 2H excess are well within the changes documented within the prior Pleistocene Epoch (cf. Walker et al., 2009; Solomon et al., 2007: figure 6.2). The Holocene ice-core GSSP is then complemented by changes in sediments from four lakes (Germany, Canada, Japan, Australia), mostly documenting changes in pollen counts, and one oceanic record (off Venezuela) mostly documenting chemical changes (Walker et al., 2009).

The ratified Holocene Epoch GSSP by Walker et al. (2009) provides an excellent template for defining the Anthropocene Epoch, with the key points being (1) a small but clear transition within a very long-term change is all that is required for the boundary placement, and (2) points of inflection in stratigraphic data where the Earth System undergoes a short-term rapid change can provide good markers within overall longer-term and larger trends marking the transition of Earth from one state to another, and (3) only a small number of stratigraphic records, showing consistent changes, are required (six for the Holocene). Although, it is worth noting that the Holocene GSSP occurs towards the end of the long increase in surface air temperature. By comparison the Anthropocene Epoch is not being discussed in the same way – the implicit argument of all work seeking to define the Anthropocene Epoch is that the boundary is placed at the beginning of the long-term change that humans are exerting on the Earth System and its trajectory.

## Defining the Anthropocene framework, part I: Screen data against GSSP requirements

The increasing variety and magnitude of impacts of human activity on the Earth System, some of which are schematically represented in Figure 1, require a boundary to be selected. To do this the first part of our framework compares the geological requirements for defining an epoch, moving forward through time to assess each time period, as presented in Lewis and Maslin (2015). Essentially, this is a systematic search for some near-permanent change to the Earth System (as epochs typically last millions of years) coupled with widespread correlated environmental changes that are documented in stratigraphic deposits that collectively indicate a change to the Earth System to provide a globally correlated boundary marker. We note no criticism of this approach in Zalasiewicz et al. (2015a, 2015b).

Lewis and Maslin (2015) concluded from this search that the impacts of the hunter-gatherers on Earth's Megafauna (>10,000 BP), the impacts of early farming (~11,000 BP), the impacts of widespread farming (~5000 BP) and the impacts of the early Industrial Revolution (~1800 CE) did not meet these requirements. Again, we note no criticism from the AWG members that we conclude that each of these time periods did not co-occur with near-permanent changes to the Earth System, *and* changes to the Earth System documented in several stratigraphic deposits worldwide. We further concluded that two time periods, (1) the time following the post-1492 collision of the Old and New Worlds leading to the irreversible exchange of species across continents and ocean basins *alongside* the globally synchronous coolest part of the 'Little Ice Age' in the 17th century captured

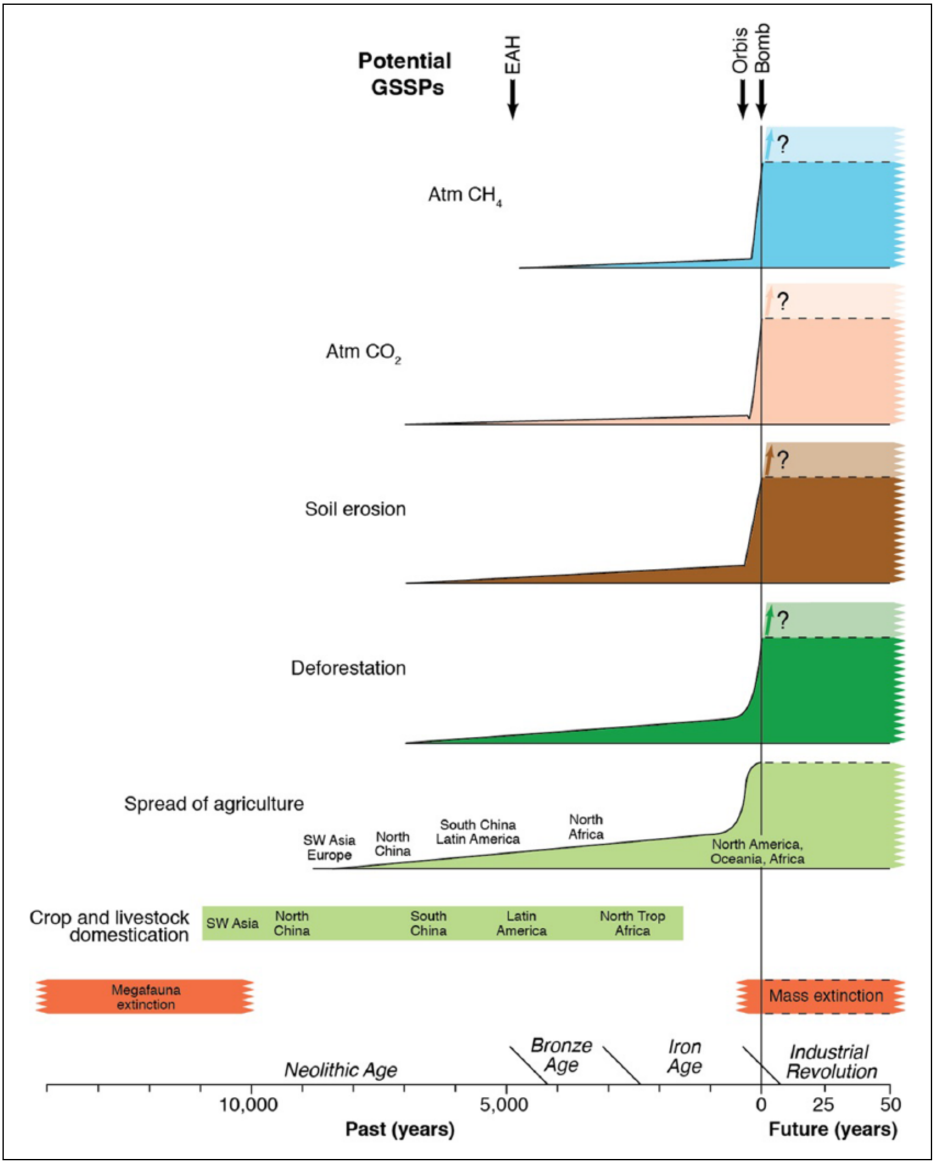


**Figure 1.** Schematic figure showing the varied and increasing impacts of human activity on the Earth System. Within this long-term change of Earth from one state to another a specific event or date is required to be selected to mark the beginning of the Anthropocene. In contrast to other geological time units the final state of Earth is not known. EAH = Early Anthropogenic Hypothesis.
*Source*: Adapted, expanded and scaled appropriately from Ruddiman et al. (2015), with three possible GSSP markers reported in Lewis and Maslin (2015).

in stratigraphic deposits worldwide (Orbis Hypothesis; ~1600 onwards), and (2) the accelerating global atmospheric, oceanic and terrestrial changes in the second half of the 20th century captured in stratigraphic deposits worldwide (Great Acceleration; ~1950 onwards) *both* likely adhere to the

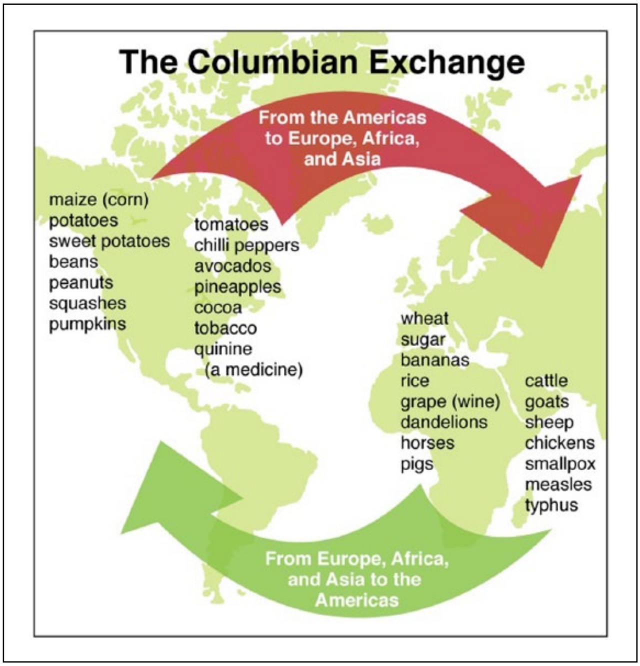


**Figure 2.** The Colombian Exchange describes the global transfer of crops, domesticated animals, diseases and human commensals between the Old and New Worlds following the arrival of Europeans in the Americas after 1492 and subsequently developed global circuits of trade. The transformation of human diets was a major change in human history.

requirements to define the Anthropocene Epoch using GSSP criteria. We also concluded a broader point, that if the requirements for defining the Anthropocene Epoch are a GSSP with global correlation *and* dated to within a few years or decades, then only those changes associated with well-mixed atmospheric gases can provide such globally correlated signals. Thus, overall, there is evidence that a strict assessment of the evidence compared with the GSSP requirements leads us to the conclusion that a formal definition of the Anthropocene is possible, beginning at one of two possible events/time periods.

Our selection of the 1610 GSSP followed the following logic. The long-term change to the Earth's trajectory is the irreversible cross-continental movement of species, and between disconnected oceans, for example, seen as maize fossil pollen at ~1600 in a European marine sediment (Mercuri et al., 2012). This Colombian Exchange is well known and provides much stratigraphic, archeological and modern material globally (Crosby, 2003; Diamond, 1997; Mann, 2011; Figure 2). However, newer GSSP requirements state that biostratigraphic markers should not be used as the primary GSSP marker, so we chose, identically to the Holocene Epoch GSSP, the parameter in a stratigraphic deposit that most closely allies to the phenomena that is changing the Earth System at that time. For the 17th century period, the likely cause, in part, is the major human population decrease due to the arrival of Europeans in the Americas which killed ~50 million people, mostly via the arrival of the smallpox virus as part of the Colombian Exchange, resulting in the recovery of abandoned farmland to its original vegetation thereby removing 7–14 Pg C from the atmosphere over a few decades, which is captured in a 7–10 ppm decrease in $CO_2$ measured in the highest-resolution Antarctic ice cores (Dull et al., 2010; Lewis and Maslin, 2015, and references therein; Nevle et al., 2011). Thus, we selected the minima of $CO_2$ at 1610, captured in the Law Dome ice core to mark a possible beginning of the Anthropocene (Figure 3). Other globally correlated changes, captured in stratigraphic deposits, flow from the change in radiative forcing caused by the change in $CO_2$ (e.g. $\delta^{18}O$ in speleothems in Chinese caves; Wang et al., 2005). Practically, a 1610 GSSP marks both the irreversible mixing of once-separate biotas setting Earth on a new trajectory and Earth's last globally synchronous cool period before the onset of the long-term warmth of the Anthropocene.

Despite many questions about the Orbis Hypothesis in Zalasiewicz et al. (2015a) the authors do not dispute that species crossed continents and ocean basins, in an essentially permanent change to Earth (see Zalasiewicz et al., 2015a: figure 2). Additionally, the authors also agree that the globally synchronous cool period between 1594 and 1677 was captured in a variety of geological deposits (Neukom et al., 2014). Zalasiewicz et al. (2015a, 2015b) instead note that the drop in atmospheric $CO_2$ with a minima at 1610 is 'not outside the range of natural Holocene variability', thereby excluding it as a marker. As discussed above, this criticism is easily dismissed as the Holocene Epoch GSSP is defined by and located at an inflection of 2H (deuterium) excess which that falls well within the range documented within the prior epoch, the Pleistocene (cf. Solomon et al., 2007; figure 6.3; Walker et al., 2009). We emphasise that GSSP primary markers selected to be boundaries of geological time units may be modest compared with the changes occurring to the Earth at that time or when compared with the changes before and after the boundary event, as noted by others, for example, see Zalasiewicz and Williams (2014). Thus, despite the criticism of Zalasiewicz et al. (2015a, 2015b), a 1610 boundary adheres to the GSSP criteria for defining an Anthropocene Epoch.

Objectively selecting a boundary for the Great Acceleration is challenging, as it has occurred via varied environmental changes associated with increasing land-use change, mostly in the tropics, increasing numbers of people utilising fossil fuels, directly and indirectly via increased consumption of material goods, and other changes, as shown in the data collation by Steffen et al., (2015; also shown here in Figure 4). In Lewis and Maslin (2015), like Zalasiewicz et al. (2015c), we selected a globally widespread marker, radionuclide fallout. This signal can be interpreted as the equivalent of a major human-created 'volcanic eruption' that merely coincides with the Great Acceleration, but probably gives the best global correlative potential because of the global fallout. For this signal we selected $^{14}C$ in tree rings from the temperate zone because annual rings give an unambiguous annually dated marker, and despite the $^{14}C$ half-life (5730 years) the marker can easily be used by many generations of scientists. We chose the peak in fallout based on generic considerations: (1) earliest detectable dates reflects detection technologies, which change over time and affect correlatability; (2) detecting small changes at the earliest detectable date are more likely influenced by natural geochemical background levels; (3) signal decay will affect earliest dates more than peak values (Lewis and Maslin, 2015). Zalasiewicz et al. (2015a, 2015b) do not disagree that the Great Acceleration is a possible beginning of the Anthropocene, but that the first detection of the radionuclide marker ought to be used. We respond that misunderstanding of the GSSP evidence in section '1964 CE Bomb Spike GSSP proposal' below. Regardless of that debate, there is no dispute that the Great Acceleration, including radionuclide fallout, adheres to GSSP criteria to mark the inception of the Anthropocene.

Other choices are certainly possible for the primary marker within each of the two time periods, switching the 1610 $CO_2$ drop in an Antarctic ice-core, or the 1964 $^{14}C$ peak in European tree rings, to become secondary markers, but such choices must be evidence-based following a clear logic outlined for the selection of primary GSSP markers.

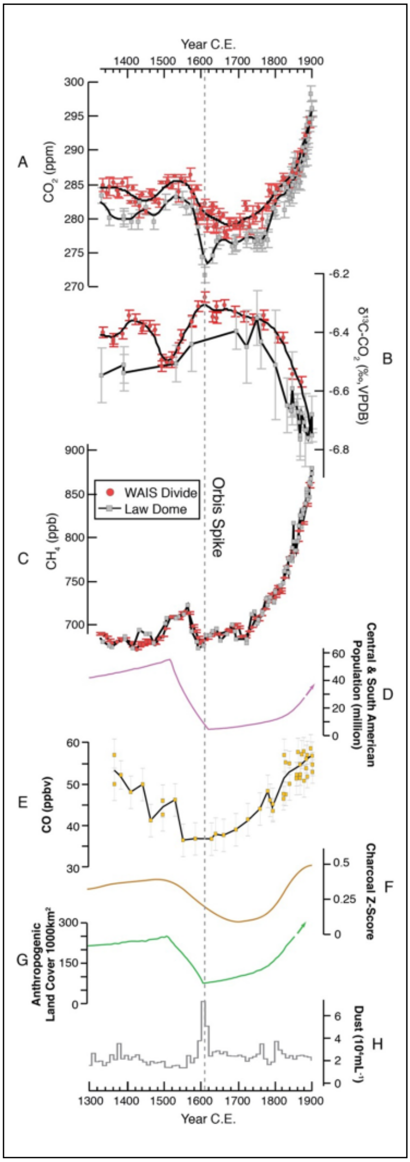


**Figure 3.** Earth System changes in the 16th and 17th centuries, temporally coincident changes in the population of the Americas, proxies of fire numbers and intensity, estimated anthropogenic land-cover change, and the impacts of the coincident Huaynaputina volcanic eruption that in combination with the irreversible exchange of species via the Colombian Exchange at this time suggest a possible 1610 GSSP to begin the Anthropocene. (A) Atmospheric carbon dioxide concentration from Law Dome and WAIS Antarctica ice cores (Ahn et al., 2012). (B) $\delta^{13}C–CO_2$ from the Law Dome and WAIS core, indicating strong land uptake of $CO_2$ in the 16th century in the well-sampled WAIS core (Bauska et al., 2015). (C) Methane concentration from Law Dome and WAIS Antarctica ice cores (Ahn et al., 2012). (D) Estimated human population in Central and South America (Krumhardt, 2011). (E) Carbon monoxide from a South Pole ice core, a proxy of Southern Hemisphere biomass burning (Wang et al., 2010). (F) Charcoal composite, indicating biomass burning, using 100-year smoothed Z-score anomalies (Power et al., 2013). (G) Estimated anthropogenic land cover in Central and South America (Kaplan et al., 2011). (H) Dust in a Peruvian ice core from the 1600 Huaynaputina eruption (Thompson et al., 2013).

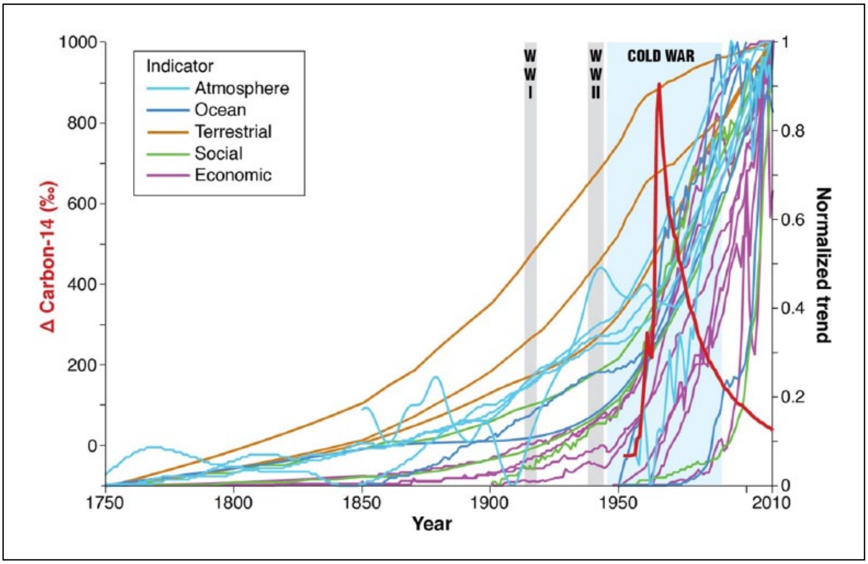


**Figure 4.** Data representing the Great Acceleration plus superimposed 1964 peak in radionuclide fallout.
*Source*: All data from Steffen et al. (2015) were normalised, right axis. Radiocarbon from nuclear weapons testing, relative to an international standard, from Rakowski et al. (2013), left axis.

## Defining the Anthropocene framework, part II: Select a specific time period/event

Lewis and Maslin (2015) highlighted that it is difficult to objectively select between the Orbis or Great Acceleration GSSP proposals without further research. More generally, some process is required to select between any two or more time periods/events that fit GSSP requirements. What is required is a second part of a framework for defining the Anthropocene: transparent and objective criteria with which to compare events/time periods and relevant markers to assess which, if any, may be considered clearly preferable. In Zalasiewicz et al. (2015c) the AWG members suggest that the Great Acceleration is 'optimal' stratigraphically, yet unfortunately nowhere do they define 'optimal'. We suggest it ought to be a task of the AWG to establish the criteria from which to transparently and objectively compare differing evidence. Here we begin that process.

To fully comply with GSSP requirements more research than that presented in Lewis and Maslin (2015) is required. We propose four possible criteria to potentially distinguish the Orbis Hypothesis, Great Acceleration, and any others that we may have missed in our evidence review.

1. Are there at least six stratigraphic deposits spanning the low-, mid- and high-latitudes, Northern and Southern Hemispheres, and from terrestrial, marine and polar environments, showing globally correlated changes? (Following the example of the Holocene Epoch GSSP ratified proposal, Walker et al., 2009.)
2. Are each of these six or more stratigraphic deposits stratigraphically complete, that is with adequate thickness before and after the event, and show no obvious hiatuses across the boundary? (Following the most important criticism of utilising GSSPs for boundaries: incompleteness of records, see Smith et al., 2014.)

3. Are each of these six stratigraphic deposits preserved and accessible to researchers? (Following a second criticism of some past GSSP decisions; Smith et al., 2014.)
4. Select the boundary that includes the clearest long-term change that is near-permanent on the scale of millions of years (to identify changes on geological timescales relevant to epochs).

While the Earth System changes in the 17th century are obviously smaller than those in the late 20th century we suspect both the Orbis and Great Acceleration time periods will likely pass all of these criteria. One possible exception to this is the correlation in marine environments, as sediments take time to settle, so these may not have adequate thickness after the mid- to late-20th century. This may then exclude the Great Acceleration as a possible beginning of the Anthropocene Epoch, as global correlation would be lacking. This requires more investigation. We suspect the only long-term changes that are near-permanent on the scale of millions of years are species extinctions (not usually used as GSSP markers) and the cross-continental and cross-ocean basin movement of species (analogous to new species) and resulting new hybrid species (Thomas, 2013; often used as GSSP markers, see Smith et al., 2014).

One way of choosing between any two or more qualifying and very close, in geological time, time periods is to return to the question of what the ‘signal’ a boundary such as the beginning of the Anthropocene Epoch is attempting to illustrate. If the view is that human activity represents a force of nature, similar to other forces of nature, such as meteorite strikes, plate tectonic changes or abrupt climate change via sustained volcanic eruptions, and it is this that is driving Earth to a new state, then the signal is the impact of human activity on the Earth System once it reaches a global level. Thus the first time period/event that adheres to GSSP requirements should be used as this captures the *complete* human signal from an Earth System perspective. We therefore strongly believe that the first change that fits the criteria of a GSSP definition of a geological time unit should be chosen.

Another approach is to choose the appropriate time period on ‘practicality’, a rarely defined term, but often meaning better correlation potential. If this is the case – choosing amongst events with global correlation – then all potential time periods should be appraised on an identical basis to assess which has the better correlation potential. However, while correlation is essential in deep-time to match markers, for the near past an emphasis on practicality is itself of limited practical use. Given today’s high-resolution dating techniques and the nearness in the past of both the 17th and 20th centuries such correlative exercises are rarely needed. Scientists will date their stratigraphic record, or use the scientific literature to correlate against local or regional events. They are unlikely to use a GSSP marker for correlation. The desire to improve the dating of sediment over the last decades or few hundred years is not itself an important reason to define the Anthropocene.

Other additional criteria to those we outline could be used, for example, selecting a boundary that fits the GSSP requirements but best fits a profound historical turning point in human history. Whichever criteria are used to distinguish events/time periods that each meet the global correlation and long-term change requirements must, in our view, be specified and published for community discussion.

## 1610 CE Orbis Spike proposed GSSP

The 1610 Orbis proposal is based on a long-term change to the Earth, due to the irreversible exchange of species across continents and ocean basins following the arrival of Europeans in the Americas and subsequent globalisation of trade (Crosby, 2003; Mann, 2011; Pomeranz, 2000). The key change is the two-way transfer of crop and domesticated animal species and later the establishment of naturalised and new hybrid species (Figure 2). This is geologically unprecedented, and the evolutionary legacy of these species movements unambiguously sets the Earth on a new trajectory. The evolutionary consequences of these changes will be one of the few clearly visible changes to Earth over the typical timescale of an epoch of millions of years that can be recorded today.

However, Zalasiewicz et al. (2015b) suggest that the 'global biostratigraphic signal from the colonizing of the Americas remains incompletely documented', and we agree that more research is needed to document the first occurrence of fossil pollen and/or phytoliths or other long-lived fossilised plant remains on a new continent. Yet, we consider that this holds great potential, in the same way that new species have been used to recognise other transitions from one epoch to another. These crop movements are human-caused, near-permanent and geologically unprecedented. For example, after ~1600 maize pollen is found in at least 70 marine and lake sediments in Europe (from the European Pollen database, see Lewis and Maslin, 2015). Similarly, the arrival of cassava/manioc in Africa and banana in the Americas, both likely indicated by the presence of phytoliths, should provide further stratigraphic evidence, as does the later arrival of wheat in North America. Following modern advice we do not suggest maize arrival in Europe as the primary GSSP because, like all biostratigraphic markers, the near-global appearance of a new species is always diachronous (Gradstein et al., 2012; Smith et al., 2014). Lewis and Maslin (2015) proposed a new approach to investigating and documenting one of only a few identified human-induced changes to the Earth System that places it onto a permanently new trajectory. More research will be required to fulfil its potential.

Zalasiewicz et al. (2015b) suggest the global atmospheric $CO_2$ decline does not match the Americas' population decline, as some of the population loss continues until 1650, therefore the decline in $CO_2$ should continue until at least then, 'which is not seen in the ice core data'. Both the Law Dome and WAIS ice cores in fact show a $CO_2$ decline from ~1550 to beyond 1650 (Figure 3A). The difference between the two is the superimposed 'extra' 3 ppm on the Law Dome core (hence reports of 7–10 ppm declines; Ahn et al., 2012). Zalasiewicz et al. (2015b) also note that as atmospheric $CO_2$ integrates global changes in population and land cover, the $CO_2$ minima would occur after 1610. Considering the data in Figure 3(A), the WAIS data conform to a later minima, as does the Law Dome data, aside from the superimposed 'extra' 3 ppm drop centred on 1610. Zalasiewicz et al. (2015b) also suggest the decline may be caused by ocean circulation changes. However, changes in $\delta^{13}C–CO_2$ in the high-resolution Antarctic WAIS ice-core indicate that the land and not the oceans are the main driver of atmospheric $CO_2$ over the period 755–1850, as do other $\delta_{13}C–CO_2$ records (Bauska et al., 2015). This land carbon uptake pattern is in line with global population and the carbon impacts from the resultant land-use change over the period 1500–1650 (Bauska et al., 2015; Kaplan et al., 2011). In Figure 3 we add relevant data showing the coincident Americas population reduction, decline in fire frequency and/or intensity, modelled land-cover change, increase in land carbon storage and resulting decline in atmospheric $CO_2$ (i.e. each step from population reduction to $CO_2$ decline). It is therefore difficult to construct an alternative plausible scenario to explain the $CO_2$ drop without, at least in part, invoking human activity.

Finally, Zalasiewicz et al. (2015b) suggest that the global temperature change at the coolest part of the 'Little Ice Age' may not provide stratigraphic markers, but Lewis and Maslin (2015) listed 11 different candidate stratigraphic records. A number of correlated changes can be seen in Figure 3, alongside the coincident Huaynaputina eruption, itself recorded globally, showing this concern is unfounded (space precludes showing more in this paper such as speleothem $\delta^{18}O$ in China, e.g. Wang et al., 2005; and see references in Lewis and Maslin, 2015).

While the case for human activity being at least a contributory factor in the 7–10 ppm decline in $CO_2$ is fairly clear, a better primary GSSP marker may now be available from more recent research. The record of $\delta^{13}C$–$CO_2$ from the WAIS Antarctic ice-core becomes less negative, implying a steep increase in land carbon uptake beginning at ~1500 and ending at ~1610 CE (Bauska et al., 2015). This may improve upon $CO_2$ as the primary GSSP marker as it is more directly related to the uptake of carbon on land. An additional reason for favouring the $\delta^{13}C$–$CO_2$ record is the currently unexplained difference between the two high-resolution Antarctic ice core $CO_2$ records (Figure 3A). It was previously considered that the Law Dome record was of higher resolution, hence explaining the discrepancy between the Law Dome and WAIS cores, as noted in Ahn et al. (2012); this motivated our choice of GSSP. However, newer results suggest that both ice cores have similar resolution (Mitchell et al., 2015). Thus while both show an abrupt decrease of ~7 ppm beginning after 1550, the Law Dome presents a further superimposed 3 ppm $CO_2$ drop at 1610, whereas the WAIS core shows a continuing decline but lacks this feature (Figure 3A). Additional measurements are currently required to ascertain why this 3 ppm difference occurs in one core, and not the other, at that time (S Marcott, L Mitchell and T Bauska, personal communication, May 2015).

To summarise, given the major changes to the Earth System after 1610, including near-permanent changes following the Colombian Exchange, and all the changes associated with the Industrial Revolution, and that no clearly discernable permanent global change to the Earth System is clearly documented prior to this date, 1610 is a reasonable potential GSSP boundary for the Anthropocene. Concerns that the signal is small compared with the entire change from Holocene to Anthropocene are based on a misunderstanding of GSSP boundary markers, while concerns that human activity may not have been at least a partial driver are unfounded (and a surprising argument given Zalasiewicz et al., 2011a state that the cause of any change, in their view, is irrelevant to its use as a marker of change), and queries about the number of other correlated markers are misplaced. However, much more work is clearly required to fully document the stratigraphic legacy of the Colombian Exchange and the homogenisation of Earth's biota.

## 1964 CE Bomb Spike proposed GSSP

The conditions of the atmosphere, oceans and land-surface in the latter half of the 20th century suggest a likely departure from the bounds of variability within the current interglacial (e.g. Stocker et al., 2013). Some of these conditions represent very long-lived changes of geological import, including accelerated species movement among continents, the delay of the next glacial inception, and the legacy of nuclear explosions. Lewis and Maslin (2015) selected as a potential primary GSSP marker the 1964 peak in radionuclide fallout, specifically $^{14}C$ in temperate tree rings, as this event has global correlation, can be dated to an unambiguously annual resolution, and provides the best correlation potential with other radionuclide species.

First, Zalasiewicz et al. (2015a, 2015b) disagree with the suggestion that the peak radionuclide can be used as a GSSP marker stating, 'it is more conventional, and usually more practical in terms of worldwide correlation, to place a boundary based on chemical or isotopic excursion at the beginning, rather than at the peak, of such a major geochemical change in strata'. Hence they argue that a GSSP defined boundary should be placed at the beginning of the excursion, which defines the 'golden spike', instead of the suggested peak in radionuclide fallout. However, this is an incorrect interpretation of the two deep-time examples they give, and is false when considering more recent 'non-deep time' GSSP ratifications.

The first example they give is the base of the Cenozoic Era, Paleogene Period, Paleocene Epoch and Danian Stage which is defined at the reddish layer at the base of the ~50 cm thick, dark boundary clay in a tributary of the Oued Djerfane, west of El Kef, Tunisia, where it coincides with the Iridium Anomaly fallout from a major asteroid impact (http://www.stratigraphy.org/GSSP/Danian.html). The boundary is defined by the red clay layer which contains the iridium peak, *not* the start of the rise in iridium as Zalasiewicz et al. (2015a, 2015b, 2015c) claim. Their second example is the base of the Eocene Epoch and Ypresian Stage, which is defined in the Dababiya Section, near Luxor, Egypt, at the base of a lithostratigraphic unit where the initiation of the Carbon Isotope Excursion is recorded (http://www.stratigraphy.org/GSSP/Ypresian.html). In fact it is the base of the lithostratigraphic unit that contains the carbon isotope excursion, *not* the start of the excursion itself that defines the epoch, as Zalasiewicz et al. (2015a, 2015b) claim.

If we then move to the definition of the Quaternary Period, Pleistocene Epoch and Gelasian Stage then this boundary is defined as the *top* of a sapropel called MPRS 250 (http://www.stratigraphy.org/GSSP/Gelasian.html) which is found in the Monte San Nicola Section located on the southern coast of Sicily (Italy). A sapropel is a dark organic-rich layer found in marine sediments, due to a reduction in the oxygen content of the bottom waters. Sapropels are common within Mediterranean marine sediments. The Monte San Nicola sapropel MPRS 250 GSSP is dated at 2.588 Ma and occurs close to the end of a prolonged cooling interval which led to the onset of Northern Hemisphere glaciation (Maslin et al., 1998). The fact that this GSSP occurs in a warm stage (MIS103) has little overall consequence for the widely agreed concept of the Quaternary, namely the onset of major glaciation in the Plio–Pleistocene (Gibbard and Head, 2010). Again, the boundary is not marked by the beginning of an excursion.

The Holocene Epoch GSSP, which is probably the best analogy to any Anthropocene GSSP, is defined as an inflection point, which shows the clearest signal of climatic warming in the North Atlantic region at the end of the Younger Dryas. Overall, the Zalasiewicz et al. (2015b) justification that the boundary of the Anthropocene is located at the start of the Bomb Spike radio-carbon excursion is an incorrect interpretation of how GSSPs have been defined. There is no simple ‘convention’ in placing GSSP boundaries at the first sign of geochemical change in a stratigraphic deposit. Alternatively, if the Bomb Spike is viewed essentially as a human-induced ‘volcanic eruption’ the use of peak fallout has obvious precedent.

The real justification for Zalasiewicz et al. (2015b) not agreeing with using the 1964 peak radionuclide fallout as a marker is because ‘the year 1964 is later than the near-synchronous upward inflections of many physical and socio-economic trends and their respective stratigraphic signals, which date to around 1950’, which for evidence they cite Zalasiewicz et al. (2015c) and Steffen et al. (2015). In Figure 4 we plot the normalised changes for all the physical, biological and socio-economic trends reported in Steffen et al. (2015). It is unclear visually, in the absence of the Bomb Spike, exactly where a data-driven choice of Great Acceleration boundary should be placed. Regarding only those data-sources that derive from stratigraphic records (the five atmospheric records plus ocean acidification), it becomes even less clear, particularly as $CO_2$ has been rising for ~200 years, global air temperature did not increase in the 1950s and 1960s, and global temperature changes are often key drivers of other changes in stratigraphic deposits. Some clear stratigraphic data-driven procedure for defining the beginning of the Great Acceleration is likely necessary. Alternatively, as we state in Lewis and Maslin (2015), the radionuclide signal is not an Earth-changing event, so either the beginning of the signal in the 1950s or the peak in 1964 is merely a coincidence. In our view the radionuclide fallout ought to be seen akin to a volcanic eruption, a short-term, global and therefore useful marker coincident with the Great Acceleration – but it should be clearly noted that it lacks a causal relationship to the acceleration of changes to the Earth System in the second half of the 20th century.

Additionally, Zalasiewicz et al. (2015b) noted that: ‘living wood may not be universally accepted’ as a stratigraphic material. Crucially, the samples are composed of dead material. Trees in Europe exist from before 1945 so there is no difficulty in sampling them prior to the first nuclear explosion. They can be preserved for thousands of years suggesting they would be accepted just as glacier ice or ocean cores are now used (e.g. see Smith et al., 2014). Next Zalasiewicz et al. (2015b) state that the ‘excess radiocarbon signal is diachronous and inconsistent’, because the fallout in the Northern Hemisphere is generally in 1963–1964 and in the Southern Hemisphere in 1964–1965. This view contradicts the statements in Zalasiewicz et al. (2015c): ‘Some of these signals (e.g. the radionuclides) are in effect globally synchronous’. Furthermore, in the same paper they state, ‘we propose that the beginning of the nuclear age, that led to dispersal of artificial radionuclides world-wide, may be adopted as an effective stratigraphic boundary in Earth history. These radioisotopes appear in ice at both poles and on all continents’. The ‘inconsistency’ noted in Zalasiewicz et al. (2015b), but not in Zalasiewicz et al. (2015c), is related to the possible lack of accurate correlation in extremely young marine sediments. We agree that if there is a lack of any correlation for 70% of the Earth’s surface this would likely mean that a Great Acceleration GSSP proposal could not be completed. However, other radionuclide species such as 239-Plutonium likely persist in marine sediments (Ketterer et al., 2004).

Surprisingly, Zalasiewicz et al. (2015b) state that marine sedimentary deposits are ‘the typical setting within which most, though not all, GSSPs are defined’. This statement is flatly false: almost all ratified primary GSSP markers are on ‘rocky outcrops’ (Smith et al., 2014: figures 2, 3 and 4). Finally, Zalasiewicz et al. (2015b) then suggest that other radionuclide species may be a better choice, based on a longer half-life. Lewis and Maslin (2015) suggested selecting these as secondary markers as they are likely to be less precisely dated than $^{14}C$ in tree-rings (Fehn et al., 1986; Ketterer et al., 2004). To summarise, we see no compelling reason why the 1964 peak in radionuclide fallout as $^{14}C$ in annual tree-rings should be discounted as a possible primary marker of a formal definition of an Anthropocene Epoch.

## Human narratives

In a section at the end of Lewis and Maslin (2015) termed ‘The wider importance’, we discussed how the choice of either 1610 or 1964 may affect ‘the perception of human actions on the environment’. We did this only *after* completing a review of ‘anthropogenic signatures in the geological record against the formal requirements for the recognition of a new epoch’ as the abstract stated. Zalasiewicz et al. (2015b) assert that the social or political ‘arguments regarding nuclear weapons testing, and the related international treaties’ were a ‘key factor’ in our choice of the peak of $^{14}C$ in temperate tree-rings as the beginning of the Anthropocene. We reject this. The reasoning behind our choice is clearly stated in Lewis and Maslin (2015) and repeated again, above. Moreover in Maslin and Lewis (2015) we restate the warning given by Lewis and Maslin (2015) that political and other societal considerations ideally should not be part of the decision-making process of defining any formal Anthropocene Epoch, or should be made explicit. Indeed, we noted that such considerations have been deeply problematic in the past, leading to the anomaly that the Holocene Epoch was ratified even though it does not differ in important ways from other Pleistocene interglacials (until the impacts of human activity become apparent).

We are concerned that the AWG publications of Zalasiewicz et al. (2015a, 2015b, 2015c) including the majority of the AWG members marks a change of approach from a facilitator role

**Table 1.** Results from poll of AWG members when asked when they considered the Anthropocene began conducted in early 2015 (Waters C, AWG secretary, personal communication, 21 April 2015).

| | No response | Diachronous boundary | Synchronous: unspecified | Synchronous: Palae-oanthropocene | Synchronous: Industrial Revolution | Synchronous: mid-20th century | 1945 age | 1945 or mid-century |
|---|---|---|---|---|---|---|---|---|
| No. votes | 13 | 2 | 1 | 1 | 1 | 7* | 2 | 4 |

*Note*: *additionally two members stated mid-20th century with a question mark.

encouraging the publication of Anthropocene-relevant material, to an advocacy group publicising certain ideas and attempting hasty dismissal of other ideas. We view this as perplexing and dangerous. Prior to Zalasiewicz et al. (2015c) the AWG had organised the publication of a special issue of *Philosophical Transactions of the Royal Society A* (Zalasiewicz et al., 2011b), and a *Geological Society of London Special Publication* (Waters et al., 2014). They contained 30 papers, some by AWG authors, some not, and no papers had more than four AWG members as authors. None of these publications could be viewed as the 'voice' of the AWG, unlike Zalasiewicz et al. (2015c) where the view of the AWG was made publically explicit (e.g. Zalasiewicz and Williams, 2015). The AWG was convened by the International Commission on Stratigraphy (ICS), like other boundary working groups, to openly and without bias consider all the data and arguments and produce a view within a specified time period. The recent papers by members of the AGW would appear to have strayed away from this remit.

Downsides to a formal grouping of scientists adopting collective advocacy positions are well-known and are described and explained by Realistic Group Conflict Theory, where out-groups are judged to differing criteria compared with the in-group (Baumeister and Vohs, 2007; Whitley and Kite, 2010). The rapid-fire responses (Zalasiewicz et al., 2015a, 2015b) to Lewis and Maslin (2015) appear in line with theoretical expectations from social psychology. Surprisingly, the in-group collective opinion of the AWG, as presented by Zalasiewicz et al. (2015c), of a 1945 GSSA to begin the Anthropocene Epoch is actually far from the collective view of the AWG. Zalasiewicz and Williams (2015) stated: '26 of the 38 members on the panel agreed that July 16, 1945, the date of the world's first nuclear test, is a "practical and effective" choice' to begin the Anthropocene. By contrast, a poll of the AGW *after* the publication of Zalasiewicz et al. (2015c) but *before* Lewis and Maslin (2015), asked the question of when the Anthropocene began: only two members selected 1945, see Table 1. The publication of conclusions that only a small minority of the AWG appear to agree upon ought to be deeply concerning. This is evidence that the recent AWG publications are being judged to differing standards to others' papers, in line with Realistic Group Conflict Theory.

To avoid these types of problems in the future we suggest the AWG return to operating along similar lines to other International Commission on Stratigraphy Boundary working groups and major scientific committees such as the Royal Society or National Academy of Sciences working groups, or the Intergovernmental Panel on Climate Change (IPCC). These collate the scientific evidence and publish definitive reports; they do not publish a commentary every time a group of scientists publish a paper that is not in line with their favoured hypothesis.

## Conclusion

Scientists are in general agreement that we live in the Anthropocene, a human-dominated geological time unit. One key question, as the Earth has been altered from a state of being unaffected by human activity towards a different future state, is where to place a boundary maker to separate the old geological time and the new (Figure 1). In many ways this is no different from any other Phanerozoic boundary definition, with rules (GSSPs), scientific evidence, debates and a committee (the AWG) to sift the evidence and arrive at a view.

Zalasiewicz et al. (2015c) state, ‘As members of the Anthropocene Working Group, we contend that the proposed new geological epoch should reflect a unique stratigraphic unit that is characterized by unambiguous, widespread and essentially permanent anthropogenic signatures …’. We agree: our two-step framework operationalises that sentiment. Step one is to screen the available evidence against current GSSP requirements (Gradstein et al., 2012; Smith et al., 2014) to identify time periods that likely comply with geological GSSP boundary markers in a similar way to recently ratified GSSP boundaries such as the Holocene Epoch (Walker et al., 2009). In our view this includes the identification of required research to improve the evidence base for potential candidate time periods. Step two is then to generate and agree on objective criteria with which select a single GSSP time period to become the GSSP boundary of the Anthropocene.

Our review in Lewis and Maslin (2015) noted that the Colombian Exchange – the irreversible cross-ocean movement of species – is one of the very few human-induced changes that is likely captured today in stratigraphic records and is a near-permanent change to Earth (Figure 2). The evolutionary repercussions will be obviously visible for the millions of years, as the Earth System is now on a new trajectory. We consider this and the associated drop in $CO_2$, less negative $\delta^{13}C$–$CO_2$, and stratigraphic impacts of the Huaynaputina eruption all near 1610 CE are worthy of further investigation as a possible GSSP boundary (Figure 3). Zalasiewicz et al. (2015a, 2015b) state their primary concern that the drop in $CO_2$ is ‘not outside the range of natural Holocene variability’. This concern is easily dismissed: the Holocene Epoch is defined by 2H (deuterium) excess, in which neither the value or absolute range change across the inflection is outside the range of 2H values in the prior epoch, the Pleistocene.

We also noted that the second half of the 20th century, with the great number, scale and variety of long-lived changes to the Earth System, likely fits the GSSP requirements, with the 1964 peak in radionuclide fallout from weapons testing being a useful marker (Figure 4). Surprisingly, Zalasiewicz et al. (2015a, 2015b) state their primary concern with this marker is that the beginning rather than peak fallout should be utilised as a marker, based on an assertion of geological convention. However, this is based on a misreading of the GSSP literature: there is no such convention.

Overall, there is no evidential reason why both the 1610 and 1964 proposals should not be further developed. As the AWG is mandated to review all the evidence that may contribute to a formal proposal for an Anthropocene Epoch in a critical, open and transparent way, we hope the AGW will fulfil this role.

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## Note

1. The AWG was initiated by the International Commission on Stratigraphy to collate, assess and evaluate the evidence for recommending (or not) the formal definition of the term 'Anthropocene' for possible incorporation into the Geologic Time Scale.

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