Anthropocene 19 (2017) 55–60

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Viewpoint

The Working Group on the Anthropocene: Summary of evidence and interim recommendations

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ARTICLE INFO

Keywords:
Anthropocene
Chronostratigraphy
Geochronology

ABSTRACT

Since 2009, the Working Group on the 'Anthropocene' (or, commonly, AWG for Anthropocene Working Group), has been critically analysing the case for formalization of this proposed but still informal geological time unit. The study to date has mainly involved establishing the overall nature of the Anthropocene as a potential chronostratigraphic/geochronologic unit, and exploring the stratigraphic proxies, including several that are novel in geology, that might be applied to its characterization and definition. A preliminary summary of evidence and interim recommendations was presented by the Working Group at the 35th International Geological Congress in Cape Town, South Africa, in August 2016, together with results of voting by members of the AWG indicating the current balance of opinion on major questions surrounding the Anthropocene. The majority opinion within the AWG holds the Anthropocene to be stratigraphically real, and recommends formalization at epoch/series rank based on a mid-20th century boundary. Work is proceeding towards a formal proposal based upon selection of an appropriate Global boundary Stratotype Section and Point (GSSP), as well as auxiliary stratotypes. Among the array of proxies that might be used as a primary marker, anthropogenic radionuclides associated with nuclear arms testing are the most promising; potential secondary markers include plastic, carbon

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http://dx.doi.org/10.1016/j.ancene.2017.09.001
Received 27 January 2017; Received in revised form 28 August 2017; Accepted 2 September 2017
Available online 08 September 2017
2213-3054/

isotope patterns and industrial fly ash. All these proxies have excellent global or near-global correlation potential in a wide variety of sedimentary bodies, both marine and non-marine.

1. Background

In common usage, the Anthropocene refers to a time interval marked by rapid but profound and far-reaching change to the Earth's geology, currently driven by various forms of human impact. The term stems from Paul Crutzen's improvisation at a conference in Mexico in 2000, and subsequent publications the same year (with Eugene Stoermer, who had been using the term informally for some years previously) and 2002. Although the term arguably had significant antecedents (see Steffen et al., 2011; Hamilton and Grinevald, 2015), Crutzen's intervention marked the widespread adoption of the Anthropocene in the literature, at first among the Earth System science (ESS) community in which he is a central figure (e.g. Steffen et al., 2004), and subsequently more widely. Crutzen explicitly proposed the term as a geological time unit, with his use of the term 'epoch' and suggestion that the Holocene had effectively terminated (Crutzen, 2002), but it had not been subjected to any of the formal processes of the International Commission of Stratigraphy (ICS), which are required for inclusion within the International Chronostratigraphic Chart (= Geological Time Scale (GTS) of common usage). Indeed at that stage the stratigraphic community was not yet involved in the discussion.

Initial consideration within the stratigraphic community began in 2008, by the Stratigraphy Commission of the Geological Society of London, prompted by wider appearance of the Anthropocene in the scientific literature, often without the caveat that this was an entirely informal unit. Based on an overview of evidence, a large majority of members of this national body agreed that the term had sufficient 'stratigraphic merit' to be considered for potential formalization (Zalasiewicz et al., 2008). This led to an invitation from the Subcommission of Quaternary Stratigraphy (SQS), the relevant component body of the ICS, to establish a working group to examine the question formally. The working group, officially designated as Working Group on the'Anthropocene' (AWG) began activities in 2009 and included several of the members of the Stratigraphy Commission of the Geological Society of London who had contributed to the call for consideration of formalization (Zalasiewicz et al., 2008).

From the beginning, the AWG represented a broader community than is typical of ICS working groups, which for the most part consist mostly or entirely of stratigraphers and palaeontologists experienced in the rocks and fossils of the particular time unit under study. However, because the Anthropocene concept not only spans geological time but also involves an evaluation of human impact upon the Earth System through historical and instrumental records, it was considered appropriate to include representatives of the community working on the processes of contemporary global change including climate science, ecology, archaeology, human history and the history of science, oceanography, polar science and even international law (for which the Anthropocene had begun to be used as a framing concept: Vidas, 2011). Such breadth of expertise reflects both the potential utility of the term for a range of disciplines and communities, and, for such a recent time interval, the significant evidence from other Earth-related disciplines that can be considered in stratigraphic terms. Nonetheless, the fundamental tasks undertaken by the AWG were geological: to assess whether the Anthropocene could be considered a potential chronostratigraphic/geochronologic unit, and to determine whether it is sufficiently different from the Holocene Epoch of geological time (which began 11,700 years ago: Walker et al., 2009) to warrant establishment of a new geological epoch or indeed a unit of higher rank with global correlation potential.

The AWG follows standard stratigraphic procedures (e.g. Remane et al., 1996), rather than embracing any alternative interpretations of the Anthropocene that have emerged outside of the geological and ESS communities (e.g. Corlett, 2015; Lövbrand et al., 2015; Ruddick, 2015; Lidskog and Waterton, 2016; Bennett et al., 2016). While the AWG acknowledges keen and broad interest in the concept of an Anthropocene, as well as the significance of the term for addressing and connecting to societal questions, the role of the AWG, as constituted, is to evaluate the relevant stratigraphic evidence.

Consideration of the Anthropocene as a unit of geological time nevertheless required a wide initial approach, because the way it emerged may be said to have turned stratigraphy on its head (Barnosky, 2014). The great majority of chronostratigraphic units emerged in broad terms as a result of prolonged study of the rock record, dating back to the 19th century and even earlier, later followed by better understanding of their stratigraphic quality and more precise delineation using high-resolution biostratigraphy, technical advances in radiometric dating, cyclostratigraphy and stable isotope chemostratigraphy. By contrast, the Anthropocene of Crutzen and the ESS community (Seitzinger et al., 2015) emerged as a concept (or a mooted epoch) based on contemporary observations of Earth System processes compared to a Holocene baseline as discerned from paleoenvironmental studies, with little consideration of the recent stratal record. Hence, the early focus of AWG analysis included consideration of the range of evidence of recent global change, combined with particular emphasis on determining whether this change was associated with sufficient potential geological evidence to make the case for the Anthropocene as a new chronostratigraphic unit, and if so at what rank. There are several theoretical possibilities for rank, including that of substage/subage, series/epoch, and system/period. If the Anthropocene were considered distinct from the Holocene Series/Epoch, then it would be necessary to assess when the transition from Holocene to Anthropocene occurred. Ultimately this analysis involves establishing whether there is a stratal record that might provide chronostratigraphic support for the proposed epoch, and which stratigraphic entities might be used to characterize, correlate and define it.

The work of the group was mostly conducted via email and the sharing of manuscripts, as the basis for discussions concerning published evidence from various sources, to see if it would be possible to compile a range of lithostratigraphic, chemostratigraphic and biostratigraphic evidence in stratal archives that might represent a potential Anthropocene time interval. Four AWG meetings took place through the kind support of: the Geological Society of London (London, 2011), the Haus der Kulturen der Welt (Berlin, 2014), the MacDonald Archaeological Institute (Cambridge, UK, 2015), and the Fridtjof Nansen Institute (Oslo, 2016).

The group identified a number of changes to the Earth System that characterize the geological Anthropocene. These include: marked acceleration of rates of erosion and sedimentation; large-scale chemical perturbations to the cycles of carbon, nitrogen, phosphorus and other elements; the inception of significant change in global climate and sea level; and biotic changes including unprecedented levels of species invasions across the Earth. Many of these changes are geologically long-lasting, and some are effectively irreversible. A range of potential proxy signals emerged as potentially important during the analysis, for instance the spherical carbonaceous particles of fly ash (Rose, 2015; Swindles et al., 2015), plastics (Zalasiewicz et al., 2016), other 'technofossils' (Zalasiewicz et al., 2014a, 2016) and artificial radionuclides (Waters et al., 2015), changes to carbon and nitrogen isotope patterns (Waters et al., 2016) and a variety of fossilizable biological remains (Barnosky, 2014; Wilkinson et al., 2014). Many of these signals will leave a permanent record in the Earth's strata. The group's publications on these and related matters so far include two major volumes (Williams et al., 2011; Waters et al., 2014b), together with a range of other peer-reviewed papers (e.g. Edgeworth et al., 2015; Steffen et al., 2016; Waters et al., 2015, 2016; Williams et al., 2016; Zalasiewicz et al., 2015). The group has responded, too, to critiques of the Anthropocene as a potential formal chronostratigraphic unit (Zalasiewicz et al., 2017). A compilation of the stratigraphic evidence to date regarding the Anthropocene is detailed in a summary volume (Zalasiewicz et al., in press).

Initial analysis suggested that the Anthropocene might be best defined as starting somewhere near the beginning of the Industrial Revolution (Zalasiewicz et al., 2008), as suggested by Crutzen and Stoermer (2000) and Crutzen (2002) based on the initial upturn of ice-core CO_2 concentrations above Holocene baseline values. Subsequently a number of starting dates were suggested, ranging from early or midway within the Holocene (e.g. Smith and Zeder, 2013; Ruddiman, 2003, 2013; Wagreich and Draganits unpublished), through the early 17th century colonization of the Americas (Lewis and Maslin, 2015), to sometime in the future (Wolff, 2014). The group considered whether the Anthropocene needed to be a chronostratigraphic unit (with, by definition, a synchronous base) or whether it could alternatively be a time-transgressive unit with a diachronous base (like the 'archaeosphere' of Edgeworth et al., 2015).

For the Anthropocene to be a formal chronostratigraphic/geochronologic unit of geological time, a synchronous base is demanded. Having considered a range of possible starting dates, the AWG identified the 'Great Acceleration'—the approximately synchronous upward inflections in the mid-20th century in a number of proxies associated with population, the global economy, energy and resource use and industrialization (Steffen et al., 2007)—as likely to provide the most appropriate signals for identification of the base of this new unit of geological time (Waters et al., 2014a, 2014b; Zalasiewicz et al., 2014b, 2015a). Inception corresponding with the Great Acceleration was reinforced by the recognition of further potentially correlatable stratigraphic markers indicating significant environmental change at this level (e.g. Wolfe et al., 2013; Rose, 2015; Swindles et al., 2015; Waters et al., 2015, 2016), and by a revised and updated summary of the trends of the Great Acceleration (Steffen et al., 2015).

This mid-20th century level seems to serve best the prime requirement for a chronostratigraphic base of high-precision global synchroneity (Waters et al., 2016). It arguably coincides with the beginning of major and at least partly irreversible change to the Earth System, including major perturbations of the C, N and P cycles, of the Earth's biota in both terrestrial and marine realms, and the introduction of new materials. These changes have been sufficient to produce a new and distinctive unit of strata, reflecting new patterns within the Earth System that will be preserved, and are likely to be perpetuated, into the far future.

We conclude that human impact has now grown to the point that it has changed the course of Earth history by at least many millennia, in terms of the anticipated long-term climate effects (e.g. postponement of the next glacial maximum: see Ganopolski et al., 2016; Clark et al., 2016), and in terms of the extensive and ongoing transformation of the biota, including a geologically unprecedented phase of human-mediated species invasions, and by species extinctions which are accelerating (Williams et al., 2015, 2016).

It is important to note that the base of the proposed Anthropocene time unit is not defined by the beginning of significant human influence upon the Earth. Early humans began extinguishing megafauna in the Late Pleistocene (Koch and Barnosky, 2006) before going on to develop and spread agriculture and animal husbandry (Ruddiman, 2003, 2013; Ellis et al., 2013). But those changes were diachronous: extinction pulses were separated by tens of thousands of years depending on the continent, as were physical transformations of the landscape associated with agriculture (which may also have caused a mild rise in CO_2 and CH_4 from the mid-Holocene onward, Ruddiman, 2003, 2013). Human activities only came to have an effect that was both large and synchronous, and thus leave a clear (chrono-) stratigraphic signal, in the mid-20th century. A wide range of evidence from this time indicates the rapid increase in scale and extent of global human impact on the planetary environment, also clearly recognizable from a wide range of synchronous stratigraphic indicators (Steffen et al., 2016; Waters et al., 2016; Williams et al., 2016; Zalasiewicz et al., in press). This coincidence of marked inflections in Earth System trends with an array of stratigraphic indicators makes the Anthropocene stratigraphic boundary proposed for the mid-20th century more like the Cretaceous–Paleogene boundary, where the Earth System and stratigraphic changes essentially coincide. This is different from the Ordovician–Silurian (Zalasiewicz and Williams, 2013) and Devonian–Carboniferous (Becker et al., 2016) boundaries, which, as currently defined, do not precisely coincide with the Earth System changes that mediate the overall differences between the respective period/system units. Those boundaries have been chosen instead for optimal effectiveness of global boundary correlation – that is, to represent more or less synchronous and practically detectable time planes traceable within strata across the Earth – rather than to be 'best fits' to a major change in the structure or functioning of the Earth System.

2. What type of boundary is the Anthropocene?

A Global Standard Stratigraphic Age (GSSA) defines a boundary by its numerical age; in contrast, a Global boundary Stratotype Section and Point (GSSP) defines a physical reference point selected within a stratal section at a specified locality, in effect, a stratigraphic "golden spike." Although a GSSA has been suggested for the Anthropocene (Zalasiewicz et al., 2015a), based on the detonation of the first atomic bomb on July 16th 1945, at Alamogordo, New Mexico (USA), it has become clear that the geological community as a whole is more comfortable with a GSSP (see Finney and Edwards, 2016). Therefore, the AWG is currently working towards candidate GSSP selection (see below).

We have also considered the hierarchical rank of a potential formal Anthropocene time unit. The possibilities range from a Sub-Age or Age within the Holocene Epoch (in which the latter unit would therefore continue to the present day) to a Period or even Era level (meaning that the Quaternary, or even the Cenozoic, would be regarded as having terminated). The question is a complex one. Many changes associated with the Anthropocene already exceed both Holocene and Quaternary natural variability. These include changes to atmospheric CO_2, CH_4 and N_2O levels, and changes in carbon stable isotope ratios seen in both terrestrial (e.g. wood) and marine (e.g. annually banded corals) proxies. Other changes, such as the temperature and sea-level rises that have resulted to date from changes in the greenhouse gas composition of the atmosphere exceed Holocene but not Quaternary climate variability. Furthermore, the Earth System and its resultant stratigraphic patterns (some of which, like the global dispersion of plastics, are novel in Earth history) are still clearly evolving at a geologically very rapid rate. In that context, it should be borne in mind that the sea-level rise since the Late Pleistocene lagged considerably behind the temperature change of the time, and took some 11,000 years to come to completion (i.e. to reach equilibrium) due to the slow response of the great ice sheets and ocean thermal expansion to warming (Clark et al., 2016). Recent assessment of the range of stratigraphic evidence (Waters et al., 2016; Steffen et al., 2016) suggests that consideration of the Anthropocene as a potential epoch separate from the Holocene seems appropriate and conservative, given the range of stratigraphic signals that now fall outside the range of Holocene values (although see e.g. Bacon and Swindles, 2016 and Rull, 2016 for suggestions of higher hierarchical rank). This is generally consistent with the *de facto* hypothesis of Crutzen and Stoermer (2000) and Crutzen (2002) (see also, e.g. Steffen et al., 2015) that the Earth System now lies outside of Holocene conditions and continues to move rapidly away from them (Steffen et al., 2016).

3. Preliminary summary of evidence and recommendations

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 summarized in this paper). 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), outlining the work that still needs to be done. Votes on all of the main current questions on the Anthopocene were taken by email ballot immediately prior to the meeting. The votes are 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 this stage, they had equal weighting).

The majority opinion of the group, as reported at Cape Town, is 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.

There was virtually unanimous agreement that the Anthropocene concept, as articulated by Paul Crutzen and Eugene Stoermer in 2000, is geologically substantiated. A potential Anthropocene chronostratigraphic unit is locally thin and of short duration in geological terms, but the Earth System changes involved and the resultant stratigraphic signals are of sufficient scale, global extent, rapidity and irreversiblility to demonstrate that consideration of the Anthropocene as part of the GTS is reasonable.

- *Should the Anthropocene be formalized?* Voting result: in favour**, 30**; against, 3; abstain, 2.

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.

- *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.

Most of the AWG voted for assignation as an epoch/series. This option is preferred over either a lower rank (e.g. age/stage, or sub-age/sub-stage, i.e. as a subdivision of the Holocene) or a higher rank (period or era). In common with all other geological time units, the Anthropocene would comprise both a 'pure time' unit (an Anthropocene Epoch) and an equivalent unit of strata (an Anthropocene Series). If the Anthropocene is adopted as an epoch, this would mean that the Holocene Epoch has terminated, but that we remain within the Quaternary Period and Cenozoic Era (Fig. 1).

- *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.

Human impact has left discernable traces on the stratigraphic record for thousands of years—indeed, since before the beginning of the Holocene. However, substantial and approximately globally synchronous changes to the Earth System most clearly intensified in the 'Great Acceleration' of the mid-20th century. The mid-20th century also coincides with the clearest and most distinctive array of anthropogenic signals imprinted upon recently deposited strata. Hence, the mid-20th century represents the optimal beginning of a potential Anthropocene Epoch (and, simultaneously, the base of an Anthropocene Series). This does not deny the reality of prior anthropogenic changes, which may be seen as Anthropocene precursors, most of which are, in comparison to the Anthropocene proper, relatively small in impact (because the human population was small with smaller per capita energy use and consumption of resources), regional rather than global and/or diachronous in time (e.g. the spread of agriculture), and largely confined to the land, with relatively little impact on the oceans.

- *Should the Anthropocene be defined by GSSP or GSSA?* Voting result: **GSSP, 25.5**; GSSA, 1.5; uncertain, 8.

The onset of the Anthropocene might be defined by a Global Standard Stratigraphic Age (GSSA), i.e. a numerical age that can be expressed as a calendar date such as 1945. It could also be defined by a Global boundary Stratotype Section and Point (GSSP; the colloquial 'golden spike'), which is a physical reference point in strata at one carefully selected place. Majority opinion of the AWG is to seek and choose a candidate GSSP, as this is the most familiar and widely accepted method of defining formal geological time units.

- *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/δ^{15}N, 0; biostratigraphic extinction/assemblage change, 0; other (lead, persistent organic pollutants, technofossils), 3; uncertain, 2; abstain, 6.

This question provoked a wider range of responses than did the previous questions, reflecting the large array of stratigraphic proxy indicators recognised to be useful in identifying Anthropocene strata (Waters et al., 2016). In practice, when locating any chronostratigraphic boundary, the full range of evidence is used, and the primary marker itself is not always the most widely useable proxy. Consider for instance the change in hydrogen/deuterium ratios used as primary marker for the base/beginning of the Holocene (Walker et al., 2009). This signal is traceable in Greenland ice layers; for wider correlation of the boundary various other proxy signals are used. However, the primary marker is ideally correlatable widely. Perhaps for this reason, a clear majority chose radionuclide signals (plutonium, radiocarbon) associated with the 'bomb spike,' as these provide arguably the sharpest

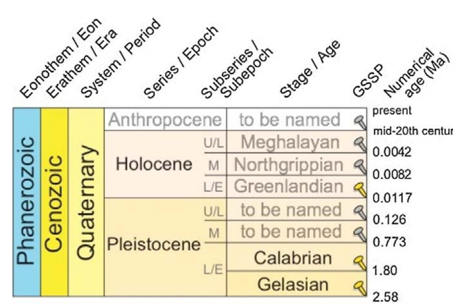

Fig. 1. The Quaternary time scale as currently preferred by the Anthropocene Working Group, with the Anthropocene shown at the rank of series/epoch. Black type indicates names officially approved and ratified by the International Commission on Stratigraphy (ICS)/Executive Committee of the International Union of Geological Sciences (IUGS EC). Names in grey type have yet to be officially sanctioned by ICS/IUGS EC, although stage names and subseries for the Holocene (Walker et al., 2016) have been approved by the Subcommission on Quaternary Stratigraphy. The rank of subseries is not presently recognised in the International Chronostratigraphic Chart, but is currently under consideration by the ICS (Head et al., 2017). Note that if the Anthropocene is proposed as depicted here, then one or more stages/ages corresponding to the Anthropocene should also be proposed for approval. Golden spikes = approved/ratified GSSPs; grey spikes = GSSPs awaiting submission or approval.

and most globally widespread signal.

4. Conclusions and future steps

The AWG has analyzed the concept of the Anthropocene in stratigraphic terms, and has collated and considered a sufficiently wide range of evidence to permit preliminary conclusions and recommendations to be drawn. The AWG concludes that the Anthropocene represents a distinct change of geological processes that are clearly reflected in stratal characteristics. Anthropocene deposits are significant and geologically 'real', and in a number of respects novel, on the scale of Earth history. These changes mark the proposed Anthropocene as being sufficiently different from the Holocene to constitute a new unit of geological time. The future trajectory of the Anthropocene remains to be seen and will depend on future changes to the Earth System. However, it seems likely that, as humans continue to operate collectively as a major geological agent, with modulation, and in some cases amplification, by feedback effects – such as that of albedo changes in polar regions – human impacts will become increasingly significant.

By clear majority, a decision has been taken to pursue a proposal to formalize the term Anthropocene, with the suggestion that this be at series/epoch level, by means of a GSSP with a base/beginning placed in the mid-20th century. This timing represents the first appearance of a clear synchronous signal of the transformative influence of humans on key physical, chemical, and biological processes at the planetary scale. As such, it stands in contrast to various local or diachronous inscriptions of human influences on the Holocene stratigraphic record.

The AWG has already begun the process of identifying potential GSSPs, by analysing the general environments in which the best combinations of stratigraphic signals are likely to be found (e.g. undisturbed lake or marine sediments, peat, annually banded coral skeletons, polar snow/ice layers, speleothems, tree rings and so on: Waters et al., in submission).

This analysis will lead to the selection of sites for sampling and further analysis, to provide full descriptions of relevant signals in the strata, a process that we hope will lead to the identification of one or more suitable candidate sites for a GSSP and auxiliary stratotypes. Whatever signal is chosen, the primary marker will need to be well expressed in the stratotype section so as to identify the best level for the GSSP. The GSSP itself, if approved, would define the base of the Anthropocene Series/Epoch. Secondary markers will also need to be identified within the candidate sections to assist in recognizing the primary event elsewhere, and widen the range of paleoenvironments available for correlation to the GSSP and auxiliary stratotypes. We hope to carry out this process over the next 2 or 3 years.

The findings will form the basis for the preparation of a formal proposal, to our immediate parent body, the SQS, on defining a formal Anthropocene unit. If the SQS endorses the proposal, it will be submitted to the SQS's parent body, the ICS, for further voting. A favourable vote by the ICS voting membership would then have to be ratified by the Executive Committee of the IUGS. If all of these conditions can be fulfilled, then the Anthropocene would become a formal part of the GTS.

There is no guarantee that such a proposal will be accepted, even if the AWG recommends such a course. The GTS needs to remain as stable as reasonably possible, so that geologists can communicate not just across the world but also between generations. The decision-making process associated with any potential changes to it is therefore both rigorous and conservative, with supermajority vote needed for acceptance at voting stages. Whichever way this particular process ends, it is clear that human beings are now operating as a major geological agent at the planetary scale, and that their activities have already changed the trajectory of many key Earth processes, some of them irreversibly, and in doing so have imprinted an indelible mark on the planet. This implies that the Holocene no longer serves to adequately constrain the rate and magnitude of Earth System variability.

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