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FCT Fundação para a Ciência e a Tecnologia

HoST - Journal of History of Science and Technology
Vol. 19, no. 1, June 2025, pp. 173-183
10.2478/host-2025-0008

DISTINGUISHED LECTURE

Humans and the Great Lakes—Anthropogenic Impact and the Search for the "Anthropocene Golden Spike"

Francine M. G. McCarthy

Earth Sciences, Brock University, Canada

fmccarthy@brocku.ca

Abstract: Since Paul Crutzen introduced the term Anthropocene twenty-five years ago, it has become conflated with the concept of anthropogenic impact, which is globally diachronous. Crutzen introduced the term as a geological epoch to reflect the altered state of the Earth System, however, signifying an end to the Holocene Epoch whose relative stability fostered the evolution of human culture. The culmination of a fifteen-year effort to formally define the Anthropocene as an epoch was the proposal of a "golden spike" in sediments from a small Canadian lake in a conservation area near Toronto. Several episodes of anthropogenic impact are recorded in its annually laminated sediments in addition to the signature of the Great Acceleration of the mid-twentieth century. Evidence of the rapid increase in fossil fuel consumption, industrial production and human population can be precisely dated in the varved sediment of this unique lake, and the sharp increase in radionuclides with the introduction of the H-bomb allows the use of the anthropogenic isotope plutonium-239 as a globally synchronous marker of the base of the proposed Anthropocene epoch. The International Union of Geological Sciences rejected adding the Anthropocene to the Geological Time Scale, rejecting the idea that human activities have shifted the planetary system away from Holocene norms. Arguably, ignoring evidence that *Anthropos* has altered how the atmosphere, biosphere, and other components of the Earth System interact is at least as political as adding the Anthropocene to the Geologic Time Scale, impeding scientific communication efforts to deal with the climate crisis.

Keywords: chronostratigraphic Anthropocene, Crawford Lake, GSSP, Geological Time Scale, geomythology

The toll exerted by humans on our planet has increased with technological advancements beginning with the development of tools and controlled use of fire millions of years ago. With the development of agriculture, population grew from an estimated 5-10 million people around 10,000 years ago to 1 billion around 200 years ago against a background of relatively stable climatic conditions characterizing the Holocene Epoch.[1] Enhanced soil erosion and eutrophication of water bodies near fixed agricultural settlements are recorded by physical, chemical and biological markers in the sedimentary record of nearby water bodies.

As a geoscientist who specializes in the study of pollen and the remains of other organisms in pollen slides as proxies of environmental conditions, I have focused on assessing prehistoric changes in lake ecosystems resulting from both natural/climatic and anthropogenic stressors. One of these is Crawford Lake, in the Great Lakes region of Canada, where the impact of agricultural settlement between the thirteenth and early sixteenth century and since colonial settlement since the early nineteenth century has been documented.[2] The unique characteristics of this small, very deep lake allow sediments to accumulate undisturbed, and alternating light- and dark-coloured sediments mark the warm and cold seasons each year, allowing precise dating of these 'varved' sediments, much like tree rings. Environmental reconstructions from the sediment record can then be compared to the instrumental record since the late nineteenth century and to earlier historic and archaeological records.

The precise sub-annual resolution was the main factor leading to the selection of a core from Crawford Lake as the proposed 'golden spike' (evoking the final spikes driven into railways connecting eastern and western North America) to formally define the Anthropocene epoch. This was the culmination of the efforts of the Anthropocene Working Group (AWG) of the International Commission on Stratigraphy's Subcommission on Quaternary Stratigraphy. The working group was established in 2009 to assess whether there was stratigraphic reality to Nobel laureate Paul Crutzen's claim that that "the Earth System has recently moved well outside the range of natural variability exhibited over at least the last half million years" suggesting "the term 'anthropocene' for the current geological epoch".[3] By 2016, when the AWG's decision to work toward formalization of the Anthropocene as an epoch/series of the Cenozoic Era (suffix '-cene') with a mid-twentieth century boundary was ratified at the 35th International Geological Congress in Cape Town, the term Anthropocene had been

[1] "How Has World Population Growth Changed Over Time?", Max Roser and Hannah Ritchie, 1 June 2023, Our World in Data, https://ourworldindata.org/population-growth-over-time

[2] Erik J. Ekdahl et al., "Prehistorical Record of Cultural Eutrophication from Crawford Lake, Canada," *Geology* 32, no. 9 (2004): 745-748.

[3] Paul J. Crutzen and Will Steffen, "How Long Have We Been in the Anthropocene Era?," *Climatic Change* 61, no. 3 (2003): 251-257.

cited in over 3000 papers, used in a variety of contexts to illustrate the impact of humans on our planet.

Technically called Global boundary Stratotype Sections and Points (GSSPs), golden spikes are designated points in the sedimentary record that serve as reference datums that define each official interval of the Geological Time Scale, distinct from any preceding it. The search for a geologic/ chronostratigraphic section that defines the characteristics of the Anthropocene, distinct from the Holocene Epoch, began in 2018, with financial support from the Haus der Kulturen der Welt and KBB. Twelve sites were investigated for "Anthropocene markers" —evidence in the geologic record of the Great Acceleration and of nuclear fallout, which serves as a globally synchronous marker of the Cold War. Although Crutzen initially favoured the Industrial Revolution as the tipping point (specifically citing improvements made to the steam engine by James Watt in the late eighteenth century), it is seldom reported that he came to agree to the mid-twentieth century as a better boundary between the stable Holocene and rapidly changing Anthropocene.[4]

Several other factors led to the selection of this small lake in the drainage basin of Lake Ontario, in the heavily populated region between Canada's largest city, Toronto, and the industrial city of Hamilton as the proposed GSSP; these include its readily accessible location within 1-hour drive of three international airports, and the interpretive facilities at the conservation area that has been protected by the Halton Region Conservation Authority since 1969. From a conceptual perspective, the clear evidence of several episodes of anthropogenic impact on the lake preceding the mid-twentieth century recorded in a 1m-long core was a very important attribute—it clearly illustrates the distinction between 1) an Earth System shift defining the beginning of a distinct epoch and 2) the record of human impact recorded in the geologic record. The latter usage of the term, championed by proponents of an "Anthropocene Event", ignores the basic contention that planetary conditions are already well beyond the climatic stability that had characterized the previous 10,000 years, i.e., that we are no longer living in a Holocene world.[5]

The Great Lakes drainage basin was carved by ice sheets from ancient river valleys, explaining why the Great Lakes-St. Lawrence Seaway carries so much freight through this heavily industrialized part of North America—and why the health of the world's largest freshwater resource has been negatively impacted for centuries. On the Canadian side of the Great Lakes, early European explorers and fur traders encountered the Wendat ('Huron') who

[4] Will Steffen et al., "Stratigraphic and Earth System Approaches to Defining the Anthropocene," *Earth's Future* 4, no. 8 (2016): 324-345.

[5] Paul J. Crutzen and Eugene F. Stoermer, "The Anthropocene," *IGBP Global Change Newsletter* 41 (2000): 17–18.

practiced Three Sisters Agriculture—exploiting the symbiotic relationship between maize, whose stalks supported tendrils of legumes whose roots fixed precious nitrogen from the atmosphere, and cucurbits (squash, pumpkin) whose broad leaves covered the soil, cutting down on evaporation and weeds. The land had been occupied for millennia by Indigenous hunter gatherers, such as the Anishnaabe, who relied on the bounty of the lakes and the tributaries that flow into them, including wild rice (*Manoomin*) and remnant megafauna.[6]

Indigenous oral traditions record deep awareness of the relationship between the Earth's subsystems and myths that appear to preserve ancestral memories of geological events.[7] These are consistent with paleoenvironmental reconstructions from microfossils and other indicators preserved in the sediment record, suggesting a long human history in the Great Lakes region. In the tale of *Nanabush and the Giant Beave*r (a species that became extinct thousands of years ago),[8] Nanabush destroyed a giant beaver dam holding water back at the narrows between what we know as Lake Superior and Lake Huron. This shows several clear parallels with geologic evidence of catastrophic destruction of the Nadoway–Gros Cap Barrier that had held back glacial meltwater in the Superior basin, flooding into the dry channels that existed during the arid Early Holocene in what is now the North Channel of Lake Huron.[9]

Another myth recounts how Lake Huron's water used to be salty from the tears that Nanabush shed upon hearing of the reckless death of his favourite nephew. This oral tradition was the decisive piece of evidence that convinced my colleagues at the Geological Survey of Canada-Atlantic that our microfossil evidence indicating the presence of brackish water during a prolonged drought around 10,000 – 8000 years ago was credible.[10] My colleagues were clearly among those who "place an emphasis on the validity of myths as representing the product of actual observed historical natural events" more than they relied on microfossil data![11] Since then, drought-driven low-stands with naturally impacted water

[6] Catherine H. Yansa and Kristin M. Adams, "Mastodons and Mammoths in the Great Lakes Region, USA and Canada: New Insights Into Their Diets As They Neared Extinction," *Geography Compass* 6, no. 4 (2012): 175-188.

[7] Lenore Keeshig. *The Geomythology of Georgian Bay- Parallels Between Anishnaabe Stories and Geologic Research*. Paper dated December 2013.

[8] Nanabush and the giant beaver, The Ojibwe Legends – A blog by Noble in General *https://mlpforums.com/blogs/entry/6665-nanabush-and-the-giant-beaver/*, August 28, 2013, last accessed 14 May, 2025.

[9] Henry M. Loope et al., "Early Holocene Dune Activity Linked with Final Destruction of Glacial Lake Minong, Eastern Upper Michigan, USA," *Quaternary Research* 74, no. 1 (2010): 73-81.

[10] M. Brian Calvert and Francine M. G. McCarthy, "When Nanabush Wept: Paleodrought-forced Early Holocene Lowstands, And Implications Under Projected Climatic Scenarios," Abstract, *IAGLR 2010*, Toronto, ON, May 17-21, 2010.

[11] Bruce W. Masse et al., "Exploring the Nature of Myth and its Role in Science." *Geological Society, London, Special Publications* 273, no. 1 (2007): 9-28.

quality have been identified throughout eastern North America. Divers have discovered hunting blinds associated with bones of woodland caribou on a ridge across the Lake Huron basin, and hunters may have taken advantage of saline water during the highly evaporative Early Holocene to preserve game hunted as woodland caribou migrated seasonally across a narrow isthmus that joined the eastern (Canadian) and western (American) shores of Lake Huron.[12] Warmer, wetter conditions since the Middle Holocene drowned the isthmus and filled the Great Lakes basins, making them the largest potable surface water body on our planet.

However, humans have had a huge impact on water quality, particularly in the mid-twentieth century when unregulated effluent from heavy industry and large cities, together with agricultural runoff, led to Lake Erie being referred to as dead. This bleak diagnosis, and the fire that burned for days on one of Lake Erie's tributary rivers, convinced governments to intervene. In 1972, United States Congress passed the Clean Water Act, and the US and Canada signed the Great Lakes Water Quality Agreement. The environmental movement that was essentially initiated by Rachel Carson's seminal book *Silent Spring* and the photograph of our fragile planet taken during the Apollo 8 mission on Christmas Eve 1968 finally began to impact policy.[13]

Despite establishment and enforcement of stringent restrictions on effluent and emissions, harmful algal blooms (HABs) continue to adversely impact ecosystem and human health. The economic cost of HABs was illustrated for several days in early August of 2014, when the water treatment plant in Toledo, Ohio was unable to produce potable water from the lake, as it was too contaminated from toxins secreted by the *Microcystis* algae. An even more troubling and persistent consequence of algal blooms resulting from ongoing excess nutrient influx is the development of a "dead zone" in the deep central basin of Lake Erie, covering several thousand square kilometres of lake bottom.[14]

Anthropogenic activities in the first half of the last millennium had a beneficial impact, however, as agricultural settlement altered the water chemistry of Crawford Lake, allowing seasonally laminated (varved) sediments to accumulate in its deep basin beginning in the thirteenth century. The chronological precision possible in sediments of this small lake in a

[12] Francine M. G. McCarthy, John H. McAndrews and Ellis Papangelakis, "Paleoenvironmental Context for Early Holocene Caribou Migration on the Alpena-Amberley Ridge," in Elizabeth Sonnenburg, Ashley K. Lemke and John O'Shea, eds. *Caribou Hunting in the Upper Great Lakes: Archaeological, Ethnographic, and Paleoenvironmental Perspectives*. Memoirs of the Museum of Anthropology, University of Michigan. Memoir 57, 13-29 (Ann Arbor, MI: University of Michigan Press, 2015).

[13] Rachel L. Carson, *Silent Spring* (Houghton Mifflin Harcourt, 1962).

[14] Hanna S. Anderson et al. "Continuous In Situ Nutrient Analyzers Pinpoint the Onset And Rate of Internal P Loading Under Anoxia in Lake Erie's Central Basin," *ACS ES&T Water* 1, no. 4 (2021): 774-781.

conservation area along the northern coast of Lake Ontario made it a logical site to examine as a candidate for the Anthropocene 'golden spike'. There is archaeological evidence of several intervals of settlement, and radiocarbon ages of charred remains of maize and beans in excavated hearths date to the mid-fourteenth and fifteenth centuries,[15] consistent with peaks in pollen of cultigens and spores of their pathogens during those intervals. Varving resulted from the increased primary productivity associated with the flow of nutrients from hundreds of humans practicing Three Sisters agriculture—cultural eutrophication. Canada geese, whose droppings are especially rich in the remains of cultigens and their fungal pathogens, were particularly efficient drivers of eutrophication,[16] and the Crawford Lake ecosystem was permanently altered by the increased nutrients. Enhanced photosynthesis tied up CO^2 in the tissues of algae, altering the pH in surface waters sufficiently to allow calcite crystals to form in the more basic/alkaline surface water and sink to the lakebed during each warm season. These crystals form light-coloured lamina that cap dark organic matter, mainly the microscopic remains of algae and their microscopic consumers in this naturally fishless lake after they die during the fall, producing seasonal couplets.[17] The seasonal layers are undisturbed by wind or animals at the bottom of this small, deep, permanently stratified meromictic lake that fills a sinkhole in calcareous rocks of the Niagara Escarpment (the same 430-million-year-old formation over which Niagara Falls flows 100 km to the south). The sediment archive holds biological and physicochemical records that can be read at sub-annual resolution, much like tree rings – in fact, there is good correlation between the environmental interpretations of pollen and other microfossils in the lake sediments and the thousand-year tree ring record of white cedars, which are rooted in cracks in the calcareous bedrock.[18] Especially wide tree rings in the first decade of the sixteenth century corroborate the hypothesis from the sedimentary archive that a great flood contributed to abandonment of the longhouse village at Crawford Lake.

The presumed descendants of the people who built the longhouses and farmed the land in the northwestern part of the Crawford Lake drainage basin recently met to decide on a name in the Wendat ("Huron") language for the village site. The name chosen by Wendat

[15] Joshua M. Moraal, "An Investigation of Hydrologic Changes in the Monimolimnion of Crawford Lake, Ontario, Canada, and Possible Linkages with Indigenous Settlement" (MA Thesis, Brock University, St. Catharines, 2025).

[16] John H McAndrews and Charles L. Turton, "Fungal Spores Record Iroquoian and Canadian Agriculture in 2nd Millennium A. D. Sediment of Crawford Lake, Ontario, Canada," *Vegetation History and Archaeobotany* 19 (2010): 495-501.

[17] Francine M. G. et al., "High-Resolution Analysis of the Varved Succession at Crawford Lake Across the Base of the Proposed Crawfordian Stage and Anthropocene Series," *The Anthropocene Review* (2025): 20530196251315454. Online first.

[18] Brendan M. Buckley et al., "Inferred Summer Precipitation for Southern Ontario Back to AD 610, As Reconstructed From Ring Widths of Thuja Occidentalis," *Canadian Journal of Forest Research* 34, no. 12 (2004): 2541-2553.

and Wyandot Chiefs and Faithkeepers and Citizens of the Wendat Confederacy Nations, who were members of the Wendat/Wyandot Women's Advisory Council working on the *Daughters of Aataentsic* book project, is *kionywarihwaen*—"where we have a story to tell," but more literally "where our matter/affair is lying down."[19] Crawford Lake has many stories to tell, and there are many ways to tell them. The people who settled there almost 800 years ago could not have imagined that one of those stories would receive global attention, and that their impact on the lake would produce the conditions needed for the global impact of the Great Acceleration and the Cold War to be preserved so well.

Human impact on Crawford Lake peaked in the latter half of the nineteenth century when British immigrant George Crawford operated a sawmill on its south shore. Selective logging of tall pines and oaks is evident in pollen records and increased runoff from the surrounding slopes and the effluent from the sawmill into the lake allowed algae and their consumers to thrive, and hyper eutrophication and rapid sedimentation and burial allowed rarely fossilised cellulosic remains of dinoflagellates to preserve.[20] The sawmill and lumbering operations were abandoned in 1900, and subsequent human impact was limited to recreational use of the lake by the Crawford family until 1969, when George Crawford's grandsons sold the lake and surrounding land to the Halton Region Conservation Authority. After graduate student Maria Boyko discovered the pollen of maize and other cultigens in varved sediments long predating the rise in weed pollen that marks European land clearing, the part of a farm that extended onto the site of the Indigenous village was purchased and added to the Crawford Lake Conservation Area. Three longhouses were subsequently erected on the footprint uncovered during archaeological excavations, a visitor's centre and a few other park buildings were erected, and an interpreted boardwalk was built around the lake.

The limited local impact on Crawford Lake through the twentieth century made it sensitive to regional and global impacts associated with the Great Acceleration. At an International Geosphere-Biosphere Programme meeting in February 2000, decades of research as an atmospheric chemist led Paul Crutzen to suggest that we had entered a new epoch (denoted in the Cenozoic by the suffix -cene) in which humans (*Anthropos* in Greek) were the dominant geologic agent driving the Earth System away from Holocene norms.[21] The question addressed by the AWG was NOT whether a long (and diachronous) history of human impact could be traced in the geologic record, which is indisputable. Rather, it was to assess

[19] Kathryn Magee Labelle, *Daughters of Aataentsic Life Stories from Seven Generations* (Montreal, QC: McGill-Queens University Press, 2021), as recounted by Wyandot Elder/artist Catherine Tammaro.
[20] Andrea M. Krueger and Francine M. G. McCarthy, "Great Canadian Lagerstätten 5. Crawford lake–A Canadian Holocene Lacustrine Konservat-lagerstätte with Two-century-old Viable Dinoflagellate Cysts," *Geoscience Canada* 43, no. 2 (2016): 123-132.
[21] Crutzen and Stoermer, "The Anthropocene," 17–18.

whether, at some point, the Earth System had been altered sufficiently to make "Holocene" an inadequate descriptor of modern geologic conditions.

The possibility of adding the Anthropocene to the Geologic Time Scale received more attention from non-scientists than any other stratigraphic concept, and the Haus der Kulturen der Welt in Berlin coordinated high-resolution analysis of multiple proxies of the "Great Acceleration" at 12 sites around the world;[22] these represent a variety of geologic archives, ranging from growth rings in living corals to annual layers in ice from the Antarctic Ice Sheet. A rapid increase in fly ash (spheroidal carbonaceous particles/SCPs) and isotopic evidence of altered atmospheric composition resulting primarily from increased fossil fuel combustion was identified globally in records of the mid-twentieth century. Plutonium-239, almost undetectable until development of atomic and thermonuclear weapons, was chosen as the key chronostratigraphic marker ("time-keeper" in the sediment record) of the mid-twentieth century, since radioactive fallout is a globally synchronous signal. Due to its location downwind from the southeastern United States, even fallout from atomic bomb testing is recorded in varved sediments of Crawford Lake, as predicted by scientists modelling the fallout of these early tests, greatly underestimated and downplayed by the US government.[23] The sharp global increase in the organic layer deposited in the autumn of 1952 through winter of 1953 records the detonation of the first H-Bomb (*Ivy Mike*) at 7:15 AM on November 1, 1952 in the Pacific Proving Grounds, marking the nominal moment of the beginning of the proposed Anthropocene epoch. The brief moratorium from November 1958 to September 1961 is also clearly recorded in the sediment archive from Crawford Lake, as is the subsequent rapid increase at the peak of the Cold War until ratification of the Limited Test Ban Treaty in 1964 that is recorded worldwide.

On March 5, 2024, an article on the front page of the *New York Times* reported that "a panel of experts voted down a proposal to officially declare the start of a new interval of geologic time, one defined by humanity's changes to the planet". The vote on whether an Anthropocene epoch should be added to the timescale did not consider the evidence of Earth System change in the nearly 200-page proposal documented in the stratigraphic record of Crawford Lake and the other sites studied by the AWG. No formal response has yet to be received to explain rationale for rejection of the proposal– instead, members of the AWG heard the news via the *NYT* reporter, and not adding an epoch recognizing the impact of humans on the Earth system was described as a means to protect "the sanctity of the field

[22] John Robert McNeill and Peter Engelke, *The Great Acceleration: An Environmental History of the Anthropocene Since 1945* (Cambridge, MA: Harvard University Press, 2016).

[23] Will Steffen et al., "The Trajectory of the Anthropocene: The Great Acceleration," *The Anthropocene Review* 2, no. 1 (2015): 81-98.

of geology. . . from initiatives that some see as political."[24] Nor did the ballot include the associated proposal of establishing a Crawfordian age (a lower rank of geologic time within epochs), potentially as a fourth age of the Holocene Epoch to succeed the Meghalayan Age that "is not remarkable in the context of Holocene climate variability"[25] and defined using far fewer markers in a much thinner section in a speleothem (cave deposit).[26] Instead, after quickly ratifying the contested vote, the parent body of the Subcommission on Quaternary Stratigraphy, the International Union of Geological Sciences, promoted an alternative view—that of a protracted "event" with no clear point of Earth System change attributable to human activity—in the official statement published on their website. This alternative view, maintaining that the planet is still "operating by Holocene rules," was not formally presented to the committee, however. The AWG continues to await formal review of its proposal for a GSSP to define a Crawfordian age.

One common criticism is that formalizing an interval of geologic time beginning so recently includes the present and anticipates the future—but the present and the future are identical, whether we are still in the Meghalayan Age of the Holocene or the Anthropocene epoch and/ or Crawfordian age are defined. It is precisely because the Earth system has become so markedly different from Holocene norms in just over seventy years that defining the Anthropocene epoch matters.[27] It is demonstrable that the extraordinary outburst of consumption and productivity that defines the Great Acceleration forced abrupt physical, chemical, climatic and biological changes to the Earth System, and model predictions are increasingly looking to the distant geologic past for analogues to predict the consequences as tipping points in the climate system are reached. We do not have the luxury of waiting centuries—or even decades—to address the existential issues that face us. It is geologists who enabled our dependence on fossil fuels, but it is the geologic record that can help us adapt to the rapidly changing conditions. The challenge for earth scientists is to communicate our evidence to help effect the necessary changes despite the insistence of influential members of the stratigraphic community that we are still living in a stable Holocene world… *status quo*. At a time when fact-based decisions are crucial, infighting among geologists will hopefully not cause the public, and particularly decision-makers, to doubt the evidence that

[24] Geological Society of America, 2024. https://community. geosociety.org/gsa2024/program/technical/special-sessions

[25] Nicholas P. McKay et al. "The 4.2ka Event Is Not Remarkable in the Context of Holocene Climate Variability," *Nature Communications*, 15, 6555 (2024).

[26] Michael Walker et al., "Subdividing the Holocene Series/Epoch: Formalization of Stages/Ages and Subseries/Subepochs, and Designation of GSSPs and Auxiliary Stratotypes," *Journal of Quaternary Science* 34 (2019): 173–186.

[27] Naomi Oreskes, "Does the Anthropocene Matter?: The Definition of This New Geological Epoch Conveys the All-encompassing Nature of the Challenge we Face", *Scientific American* 330, no. 1 (2024): 89.

we shifted away from the stability that allowed the development of human civilization, with a tipping point in the mid-twentieth century.

Does the decision not to recognize *Anthropos* as the dominant geologic agent really matter? Arguably, the ongoing dispute among stratigraphers has brought even more attention to stratigraphy and Earth systems science than adding a geologic unit to the timescale would have. As one reporter put it: The Anthropocene is dead. Long live the Anthropocene."[28] However, a disturbing consequence of the "scientifisticuffs"[29] over the Anthropocene is the framing of efforts by the AWG as "a way for geologists to make a political statement," as Stanley Finney was quoted in the New York Times on 17 December 2022.[30] At a time of unprecedented climate warming, with associated impacts on our planet and on human well-being and socioeconomic and political stability, scientific information should be guiding decision makers.

Acknowledgements

This paper is an expanded version of a presentation at the CIUHCT Workshop "One Health and Geo-Anthropology in the Age of the Anthropocene", 13 December, 2024, to which I was invited by Prof. Davide Scarso. I appreciate the assistance of Chief Editor Bárbara Direito and executive editors Hugo Almeida and Clara Florensa, in converting the thoughts of an earth scientist into this essay. The ideas owe much to interactions with members of the Anthropocene Working Group and to the efforts of the many members of "Team Crawford" and colleagues at the Geological Survey of Canada who spearheaded much of the geoarchaeological research discussed.

Competing interests

No competing interests.

[28] Paul Voosen, "The Anthropocene is dead. Long live the Anthropocene," *Science, Scienceinsider/ Scientific Community*, 5 Mar, 2024.

[29] *First Dog on the Moon*, "SCIENTIFIC KERFUFFLE ALERT! When Did the Anthropocene Begin and What is a Golden Spike?!", *The Guardian*, July 14, 2023.

[30] Raymond Zhong, "For Planet Earth, This Might Be the Start of a New Age", *The New York Times*, 17 December, 2022.

Funding

This research was funded by Social Sciences and Humanities Research Council of Canada grant SSHRC 435-2023-0441 "Bomb Pulse: Cultural and Philosophical Readings of Time Signatures in the Anthropocene" and earlier funding for the Anthropocene GSSP research was provided by the Haus der Kulturen der Welt/KBB, the Natural Sciences and Engineering Research Council (NSERC), and Brock University.