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Stratigraphic and Earth System approaches to defining the Anthropocene

Will Steffen[1,2], Reinhold Leinfelder[3], Jan Zalasiewicz[4], Colin N. Waters[5], Mark Williams[4], Colin Summerhayes[6], Anthony D. Barnosky[7], Alejandro Cearreta[8], Paul Crutzen[9], Matt Edgeworth[10], Erle C. Ellis[11], Ian J. Fairchild[12], Agnieszka Galuszka[13], Jacques Grinevald[14], Alan Haywood[15], Juliana Ivar do Sul[16], Catherine Jeandel[17], J.R. McNeill[18], Eric Odada[19], Naomi Oreskes[20], Andrew Revkin[21], Daniel deB. Richter[22], James Syvitski[23], Davor Vidas[24], Michael Wagreich[25], Scott L. Wing[26], Alexander P. Wolfe[27], and H.J. Schellnhuber[28]

[1]Fenner School of Environment and Society, The Australian National University, Acton, Australia, [2]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden, [3]Department of Geological Sciences, Freie Universität Berlin, Berlin, Germany, [4]Department of Geology, University of Leicester, Leicester, UK, [5]British Geological Survey, Nottingham, UK, [6]Scott Polar Research Institute, Cambridge University, Cambridge, UK, [7]Jasper Ridge Biological Preserve, Stanford University, Stanford, California, USA, [8]Departamento de Estratigrafía y Paleontología, Facultad de Ciencia y Tecnología, Universidad del País Vasco UPV/EHU, Bilbao, Spain, [9]Department of Atmospheric Chemistry, Max-Planck-Institute for Chemistry, Mainz, Germany, [10]School of Archaeology and Ancient History, University of Leicester, Leicester, UK, [11]Department of Geography and Environmental Systems, University of Maryland–Baltimore County, Baltimore, Maryland, USA, [12]School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, UK, [13]Geochemistry and the Environment Division, Institute of Chemistry, Jan Kochanowski University, Kielce, Poland, [14]Institut de Hautes Études Internationales et du Développement, Geneva, Switzerland, [15]School of Earth and Environment, University of Leeds, Leeds, UK, [16]Institute of Oceanography, Federal University of Rio Grande, Rio Grande, Brazil, [17]Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (CNRS, Centre National d'Études Spatiales, Institut de Recherche pour le Développement, Toulouse, France, [18]History Department, Georgetown University, Washington, District of Columbia, USA, [19]Department of Geology, University of Nairobi, Nairobi, Kenya, [20]Department of the History of Science, Harvard University, Cambridge, Massachusetts, USA, [21]Dyson College Institute for Sustainability and the Environment, Pace University, Pleasantville, New York, USA, [22]Nicholas School of the Environment, Duke University, Durham, North Carolina, USA, [23]Department of Geological Sciences, University of Colorado–Boulder, Boulder, Colorado, USA, [24]Marine Affairs and Law of the Sea Programme, The Fridtjof Nansen Institute, Lysaker, Norway, [25]Department of Geodynamics and Sedimentology, University of Vienna, Vienna, Austria, [26]Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, District of Columbia, USA, [27]Department of Biological Sciences, University of Alberta, Edmonton, Canada, [28]Potsdam Institute of Climate Impact Research, Potsdam, Germany

Key Points:

- Stratigraphy and Earth System science have built a multidisciplinary approach for understanding Earth evolution, including the advent of the Anthropocene.
- Both approaches provide strong evidence that human activities have pushed the Earth into the Anthropocene, starting from the mid-20th century.
- Potential scenarios for the future Anthropocene range from more intense interglacial conditions to a greenhouse state with much less polar ice.

Corresponding author:
W. Steffen, will.steffen@anu.edu.au

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Abstract Stratigraphy provides insights into the evolution and dynamics of the Earth System over its long history. With recent developments in Earth System science, changes in Earth System dynamics can now be observed directly and projected into the near future. An integration of the two approaches provides powerful insights into the nature and significance of contemporary changes to Earth. From both perspectives, the Earth has been pushed out of the Holocene Epoch by human activities, with the mid-20th century a strong candidate for the start date of the Anthropocene, the proposed new epoch in Earth history. Here we explore two contrasting scenarios for the future of the Anthropocene, recognizing that the Earth System has already undergone a substantial transition away from the Holocene state. A rapid shift of societies toward the UN Sustainable Development Goals could stabilize the Earth System in a state with more intense interglacial conditions than in the late Quaternary climate regime and with little further biospheric change. In contrast, a continuation of the present Anthropocene trajectory of growing human pressures will likely lead to biotic impoverishment and a much warmer climate with a significant loss of polar ice.

1. Introduction

The Anthropocene, the proposed new geological epoch in Earth history [*Crutzen and Stoermer,* 2000; *Crutzen,* 2002; *Zalasiewicz et al.,* 2008], is challenging many areas of research in a variety of ways. The term and concept have been discussed within diverse disciplines in the natural sciences [e.g., *Ellis et al.,* 2012; *Gillings and Paulsen,* 2014; *Capinha et al.,* 2015; *Corlett,* 2015; *Williams et al.,* 2015] and in the environmental humanities and social sciences [e.g., *Chakrabarty,* 2009; *Vidas,* 2011; *Malm and Hornborg,* 2014; *Fischer-Kowalski et al.,* 2014; *Bai et al.,* 2015; *Latour,* 2015; *Vidas et al.,* 2015; *Bonneuil and Fressoz,* 2016], with more interdisciplinary approaches also appearing [*Braje,* 2015; *Latour,* 2015; *Maslin and Lewis,* 2015].

Although the proposal was initiated in the Earth System science community [*Crutzen and Stoermer,* 2000; *Steffen,* 2013; see *Revkin,* 1992 for an earlier proposed "Anthrocene"], recognition of the Anthropocene as an epoch following the Holocene necessitates that the proposal be grounded in the Geologic Time Scale, one of the cornerstones of geology. Subsequently, much work [*Zalasiewicz et al.,* 2015; *Waters et al.,* 2016 and references therein] has focused on testing whether the stratigraphic record of the Anthropocene is adequate for the formal definition of a new epoch following the protocols of the International Commission on Stratigraphy and its parent body, the International Union of Geological Sciences.

The result of this work has been a convergence of evidence and information obtained from Earth System science and from stratigraphy. Here we examine this convergence of approaches to define the Anthropocene, highlighting their changing relationship through time and the insights that each brings to examine the dynamics of the Earth System.

2. Historical Relationship Between Stratigraphy and Earth System Science

Earth System science is a highly interdisciplinary enterprise that aims to build a holistic understanding of our evolving planet [*Lenton,* 2015]. It arrived on the research landscape very recently (primarily since the 1980s), and some scholars have suggested that it represents an emerging paradigm [*Malone and Roederer,* 1985; *ICSU,* 1986; *Grinevald,* 1987; *Hamilton and Grinevald,* 2015]. Earth System science builds on the long history of advances in the geosciences [*Oldroyd,* 1996; *Bard,* 2004; *Galvez and Gaillardet,* 2012] and on more recent system-level thinking applied to the climate and the biosphere [*Budyko,* 1986; *Clark and Munn,* 1986; *NASA,* 1988; *Rambler et al.,* 1989].

An early pioneer of this holistic approach, following Alexander von Humboldt, was the Russian mineralogist and naturalist Vladimir I. Vernadsky, one of the founders of geochemistry and the creator of biogeochemistry [*Vernadsky,* 1924; 1929; 1998]. Vernadsky's research on biogeochemistry was central to the rise of Earth System science, and to the scientific study of Earth's biosphere in general [*Grinevald,* 1987; *Polunin and Grinevald,* 1988; *Smil,* 2002; *Jørgensen,* 2010], including humanity as a new geological agent [*Vernadsky,* 1924; 1945; 1998]. Vernadsky's pioneering work largely languished for several decades, but global biogeochemical cycles reappeared prominently in the 1970s when James Lovelock, the father of the Gaia hypothesis, provided a complementary conceptual framework for the Earth as a system [*Lovelock and Margulis,* 1974; *Lovelock,* 1979; 1988]. Contemporary Earth System science draws on a wide range of new tools and disciplinary expertise for directly observing and modeling the dynamics of the Earth System (cf. section 4), emphasizing the conceptual framework of complex-systems science, hence the emphasis on *System* in its name.

The Earth System is usually defined as a single, planetary-level complex system, with a multitude of interacting biotic and abiotic components, evolved over 4.54 billion years and which has existed in well-defined, planetary-level states with transitions between them [*Schellnhuber,* 1998; 1999]. A state is a distinct mode of operation persisting for tens of thousands to millions of years within some envelope of intrinsic variability. The Earth System is driven primarily by solar radiation and is influenced by other extrinsic factors, including changes in orbital parameters and occasional bolide strikes, as well as by its own internal dynamics in which the biosphere is a critical component.

Earth's mean temperature is determined primarily by its energy balance [*Feulner,* 2012], including the key variables of solar insolation (increasing during Earth history), greenhouse gas forcing (broadly decreasing during Earth history) and albedo. The distribution of heat at the Earth's surface is modified by orbital variations and paleogeographic patterns driven by tectonics, which in turn can drive feedbacks that lead to whole-Earth changes in albedo or greenhouse gas forcing. Thus, over multi-million year timescales, Earth's climate shifts in response to gradual changes in continental configuration, the opening or closing of ocean gateways, and the plate tectonic or Wilson cycle, which, together, drive long-term changes to the carbon cycle and the biosphere. These long, slow changes modify the effects of solar forcing, not least by changing the balance between sources of CO_2 (from volcanic activity) and its sinks (starting with chemical weathering and progressing through sequestration in sediments), as documented for example by *Berner* [1999a, 1999b, 2003], *Franks et al.* [2014] or *Summerhayes* [2015]. Short-term abrupt changes are imposed by sudden aperiodic volcanic activity that may be as brief as a single volcanic eruption or as long as the life of a Large Igneous Province of the kind that gave rise to the Siberian Traps and the end-Permian extinction. These are aside from natural fluctuations of minor amplitude driven by orbital change or internal oscillations within the ocean–atmosphere system, such as El Niño events or the Pacific Decadal Oscillation.

Contemporary Earth System science has benefited greatly from evidence generated by the geosciences, particularly stratigraphy, the primary geoscience that has developed the "book of records" of the Earth through time. The relationship between stratigraphy and Earth System science has been symbiotic and well defined: stratigraphy has been the generator of new knowledge about Earth history while Earth System science has interpreted that knowledge in a complex-systems framework that sometimes challenges geological interpretations of the stratigraphic record [e.g., Snowball Earth theory; *Budyko,* 1969; *Hoffman et al.,* 1998].

In terms of Earth history, this relationship was recently portrayed in *Zalasiewicz et al.* [2015]:

> An effective geochronological and chronostratigraphical boundary often reflects a substantial change in the Earth system, so that the physical and chemical nature of the deposits, and their fossil contents, are recognizably different above and below the boundary .... To take (an) example, the boundary between the Ordovician and Silurian periods reflects a brief, intense glacial phase that triggered one of the 'Big Five' mass extinction events, and hence profoundly altered the biota (and fossil record) of the Earth.

Thus, the relationship is most useful to Earth System science when a stratigraphic boundary marks a substantial change in the planetary mode of operation. Such boundaries should mark a transition from one fundamental state of the Earth System to another, or, in other words, mark a regime shift [*Scheffer and Carpenter,* 2003], although for the definition of many stratigraphic time boundaries this is not a prerequisite (see below). Some geological time units lower in the stratigraphic hierarchy may be defined by, for example, some distinctive paleontological change that is not associated with any substantial Earth System change, as in the definition of the Aeronian Age of the Silurian Period discussed below.

Zalasiewicz et al. [2015] went on to note:

> A stratigraphic time boundary, however arbitrary, needs as far as possible to be singular, globally synchronous and commonly understood.

Stratigraphy is valuable for Earth System science because it is also highly interdisciplinary, drawing information and insights from sedimentology, paleontology, geochemistry, geochronology, archeology, pedostratigraphy, paleomagnetism, paleoclimatology, and other fields. The unifying thread that brings this wide array of relevant disciplines together is the stratigraphic handbook of the International Commission on Stratigraphy [*Salvador,* 1994; *Remane et al.,* 1996], which sets out the following definitions to guide stratigraphic research:

Lithostratigraphic unit. A body of rock established as a distinct entity based on its lithological characteristics. The boundaries of lithostratigraphic units may be effectively synchronous (as for instance with units comprising, or bounded by, volcanic ash layers) or they may be markedly time-transgressive (as in, for instance, a unit comprising a succession of beach deposits that follow a migrating coastline as sea-level changes.).

Chronostratigraphic classification. The organization of rocks into units on the basis of their age or time of origin. The purpose of chronostratigraphic classification is to organize systematically the rocks forming the Earth's crust into named units (chronostratigraphic units) corresponding to intervals of geologic time (geochronologic units) to serve as a basis for time-correlation and a reference system for recording events of geologic history.

Chronostratigraphic unit. A body of rocks that includes all rocks formed during a specific interval of geologic time, and only those rocks formed during that time span. Chronostratigraphic units are bounded by synchronous horizons. They are generally made up of stratified rocks, while the equivalent geochronological units (of Earth time) are inferred from them and may also be recognized within units of nonstratified rock such as polyphase metamorphic units [*Zalasiewicz et al.,* 2013].

The following features of all chronostratigraphic unit definitions are important for the utility of chronostratigraphy for Earth System science.

1. A chronostratigraphic unit is typically represented by different types of sedimentary deposits that accumulate in environments ranging from land to deep sea, and which may be independently classified based on their physical characteristics into a hierarchy of lithostratigraphic or biostratigraphic units, the boundaries of which are commonly diachronous to various degrees (i.e., they cut across time planes). Such units are seldom entirely concordant with chronostratigraphic boundaries. Different kinds of time proxy evidence, such as guide fossils, geochemical patterns, and magnetic properties, may be used as approximations to time planes to help establish the boundaries of chronostratigraphic units.
2. A GSSP (Global boundary Stratotype Section and Point) or GSSA (Global Standard Stratigraphic Age; *Gradstein et al.,* 2012) is used to define a synchronous horizon within strata around the globe, based on the boundary of a chronostratigraphic unit. In practice, there are always uncertainties in tracing this boundary worldwide, but the error bars narrow as dating precision improves. These boundaries help constrain the pattern in time and space of changes in the behavior of the Earth System. For application to Earth System science, especially in identifying changes in the state of the system, having a globally synchronous boundary horizon is desirable, particularly for rapid or abrupt transitions. A central challenge, but also a remarkable advantage, to stratigraphers in the context of the Holocene–Anthropocene boundary is that the highly resolved timescale of human history (ca. 10,000 years) reveals diachroneity, sometimes on as fine a time scale as decades or even years, in the physical, chemical, and biological indicators of the transition. Such fine-scale diachroneity is ordinarily not detectable for older boundaries because time resolution is coarser.
3. In many cases a chronostratigraphic boundary and its associated lithostratigraphic (and/or biostratigraphic) unit(s) are broadly associated with a global shift in the state of the Earth System, commonly shown by marked changes in fossil assemblages and/or by changes in proxies for critical climate parameters. Although not all chronostratigraphic boundaries reflect a shift in the state of the Earth System, changes in the state of the Earth System should, in principle, result in a recognizable chronostratigraphic boundary. Examples of boundaries associated with an Earth System state shift are the transition from the Mesozoic to the Cenozoic (triggered largely by an asteroid impact that likely drove mass extinctions and reshaped the biosphere [*Molina et al.,* 2006]) and the onset of the Pleistocene ice ages (triggered by a coincidence of the Milankovitch orbital parameters with a paleogeography that attained requisite elevational and ocean-circulation patterns [*Lunt et al.,* 2012]). The latter is an event that, while representing significant Earth System change reflected in new stratigraphic patterns [*Pillans and Naish,* 2004; *Gibbard et al.,* 2005], is protracted and complex; hence, the base-Pleistocene boundary is placed with reference to the Gauss–Matuyama paleomagnetic boundary, not a major driver of Earth process *per se*, but a widely traceable horizon in strata within this key interval.

Over the last few centuries, geologists have assembled records of rocks and their various characteristics, for example their embedded fossils, and, more recently, their chemical, magnetic, and other properties. From this, they worked out time-based (i.e., chronostratigraphic) rock divisions based on clearly observable differences between a stratigraphic unit and the units above and below it, and used those to define geologic time (geochronologic) units. They then correlated the chronostratigraphic (rock) units globally to refine and modify the Geologic Time Scale in tandem with improving knowledge of stratal successions. The heuristic rule for linking chronostratigraphy to Earth System dynamics is this: If the differences in attributes between units are large and evident across many areas of the Earth, or if at least the difference from the underlying strata to the overlying boundary layer is large, then the likelihood of a change in the state of the Earth System is high. Otherwise, only gradual or local changes might have taken place, but they happened to have created a detectable, near-synchronous horizon.

Simple heuristic rules have their limits. For example, some selected boundary-defining biostratigraphic events may not be associated with fundamental systemic changes, but nevertheless form good boundary-defining markers, as in the emergence of the distinctive triangulate monograptid graptolites used to recognize the beginning of the Aeronian Age of the Llandovery Epoch of the Silurian Period [*Melchin et al.,* 2012]. This evolutionary event appears not to correlate with wider changes in biota or Earth System functioning. On the other hand, chronostratigraphically useful changes that are individually trivial as regards Earth System dynamics (as with the signal used to define the Ordovician–Silurian boundary: *Zalasiewicz and Williams,* 2014) may nevertheless prove to be useful for Earth System science by their association with a wider array of signals that reflect more fundamental change. While the Ordovician–Silurian boundary itself is based on a small change in paleoplankton composition that may not be important from an Earth System perspective, the boundary was preceded by changes driven by the onset and collapse of a particularly intense phase of a longer-lasting glaciation, in which the associated stratigraphic signals are regarded as having less precise power for correlation [*Page et al.,* 2007; *Hammarlund et al.,* 2012; *Melchin et al.,* 2012]. This large event likely represents a change in the state of the Earth System, even though it is not precisely coincident with a boundary in the Geologic Time Scale.

In summary, chronostratigraphy reveals the pattern of changes in Earth history, and leads to inferences about changes in the state of the Earth System. However, building a deeper understanding of the processes that drive the state changes requires theoretical as well as empirical investigations of the interacting components of the Earth System.

3. Unraveling Earth System Evolution From the Chronostratigraphic Record

3.1. Evolution of the Biosphere

The evolution of the biosphere can be divided into two fundamental stages. Between ~4 to 0.8 Ga (Ga = billion years ago), the biosphere comprised mostly of unicellular organisms occurring either individually or in colonies. This initial stage featured several important developments in biospheric functioning, such as the appearance of sulfur-reducing bacteria [*Grassineau et al.,* 2006; *Wacey et al.,* 2011; *Bell et al.,* 2015] and the development of photosynthetic metabolic pathways [*Grassineau et al.,* 2002; *Payne et al.,* 2008; *Allwood et al.,* 2009]. From ~0.8 Ga molecular (genetic), fossil, trace fossil, and biomarker evidence supports the evolution of a biosphere with metazoans (animals). This led to the Cambrian adaptive radiation (or Cambrian explosion), in which skeletonized organisms become preserved in rock successions worldwide [*Erwin et al.,* 2011]. The rich fossil record of the past 600 million years provides additional evidence of major innovations in the Earth's biota and their interaction with the abiotic components of the Earth System. For example, Neoproterozoic and Cambrian sedimentary strata provide the first evidence of motile bilaterian organisms [e.g., *Jensen,* 2003; *Hou et al.,* 2004] as part of an evolutionary continuum that produced the complex trophic structures of the marine ecosystems of the Phanerozoic [*Butterfield,* 2011].

The Ordovician to Devonian stratigraphic records show the rise of a complex terrestrial biosphere, first with nonvascular plants [*Edwards et al.,* 1992; *Wellman and Gray,* 2000; *Wellman et al.,* 2003] and later with vascular plants that produced only spores [*Hotton et al.,* 2001; *Stein et al.,* 2007], followed by the rise of seed plants along with more complex seedless vascular plants and the growth of extensive forests [*DiMichele et al.,* 1992; *Stewart and Rothwell,* 1993; *Greb et al.,* 2006]. Regime shifts in the Earth's biosphere are reflected by mass extinction events [*Barnosky et al.,* 2011] (arrows, Figure 1), after which major alterations in the trajectory of evolution occurred, and in the relatively rapid transitions between the three "evolutionary faunas" recognized by paleontologists as the Cambrian Fauna, the Paleozoic Fauna, and the Modern Fauna (Figure 1). For more detail on the evolution of the biosphere, see *Behrensmeyer et al*. [1992], *Stanley* [1993], *Nisbet and Fowler* [2014] and *Williams et al.* [2016].

3.2. Evolution of the Climate System

The stratigraphic record, based on a wide variety of geological, paleontological, and geochemical proxies [*Masson-Delmotte et al.,* 2013; *Bradley,* 2015; *Zalasiewicz and Williams,* 2016], also provides the evidence needed to infer changes in the climate (Figure 2). From the Archean to the present, homeostatic processes have forced Earth's climate to remain within rather narrow temperature limits, unlike those of its neighbors Venus and Mars. That constraint has allowed the three phases of water—liquid, vapor, and solid—to coexist on the surface of the planet, providing a key precondition for the appearance and evolution of life.

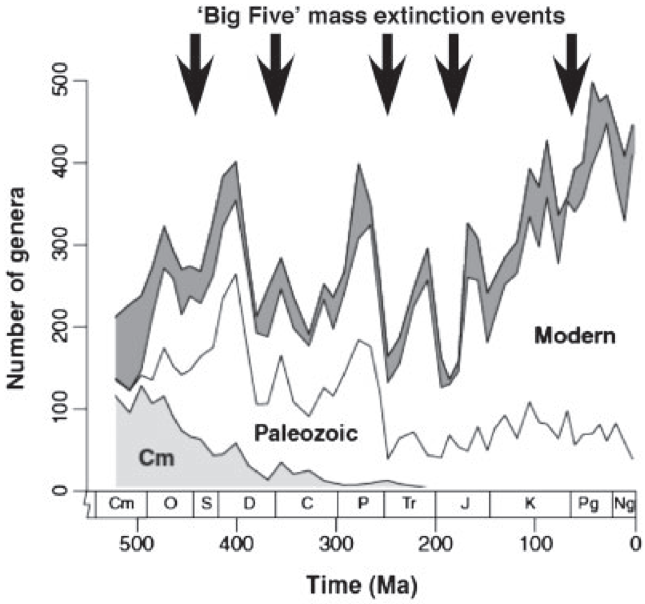

Figure 1. Sampling-standardized Phanerozoic marine diversity curve [*Alroy,* 2010], expressed as summed curves for constituent groups. Regime shifts in the Earth System are reflected in the transition from typical Cambrian (Cm) to Paleozoic to Modern marine faunas, and at mass extinction events (arrows). In this context "Cambrian," "Paleozoic," and "Modern" do not refer to the respective time periods of the same name, but instead to evolutionary stages of the biota. Major alteration in the trajectory of evolution occurred at each of the mass extinctions, recognizable by the estimated loss of at least 75% of commonly fossilized marine species, after which previously uncommon clades became dominant [*Barnosky et al.,* 2011]. The dark gray area at top represents genera not assigned to one of the three evolutionary faunas. Ma = million years ago.

The evolution of the climate system shows its highly systemic nature. This includes (i) the alternation between so-called greenhouse states (warm times when the poles were ice-free) and icehouse states (cold times with permanent polar and lower latitude sea ice and/or glacier ice), evident from late Archean times onward (Figure 2); (ii) the evolution of the global carbon cycle that provides a critical link between the physical climate and the biosphere [*Berner et al.,* 1983; *Berner,* 1990; 1999a, 1999ab]; and (iii) the Earth System's intrinsic negative feedback processes, coupled with lithosphere evolution (e.g., CO_2 release from within the Earth), that enable it to absorb and recover over the long term from marked temperature changes that cause severe glaciation [e.g., in the early and late Proterozoic—see *Fairchild and Kennedy,* 2007].

The stratigraphic record provides important clues to key positive and negative feedback mechanisms, such as the influence of ice cover on albedo or changes in atmospheric greenhouse gas composition (principally CO_2, methane (CH_4), and water vapor). These feedbacks can, under appropriate conditions, either amplify or dampen external forcing, such as orbital variation and solar insolation, to drive or suppress transitions between states of the climate [*Lunt et al.,* 2012].

Beerling and Royer [2011] compiled data from a variety of proxies to document the history of CO_2 through the Cenozoic. CO_2 rose from the end Cretaceous into the Eocene, peaked ~50 Ma (Ma = million years ago), then fell toward the end of the Eocene, following which values stayed rather low. This pattern is the same as that of global mean surface temperature, which rose to a peak ~50 Ma then fell to the point where the first Antarctic ice sheet formed ~34 Ma [see also *Anagnostou et al.,* 2016]. The ultimate driver for changing global CO_2 in this time frame was volcanic activity driven by plate tectonics, with changes in greenhouse gas forcing changing atmospheric and oceanic temperatures [e.g., see *Kent and Muttoni,* 2008]. However, as we discuss below, this pattern was disrupted briefly by a short-lived carbon injection event that caused a temporary warming at the Paleocene–Eocene boundary 56.0 Ma.

CO_2 and temperature both fell between Pliocene and Pleistocene times, probably in response to changing oceanic gateways (the rising of the Central American isthmus in Pliocene times, and the closing of the Indian Ocean–Mediterranean connection). During the Pleistocene, CO_2, at its lowest levels since glacial Carboniferous times, oscillated between 180 ppm in glacial cold times and 280 ppm in interglacial warm times, in response to periodic changes in temperature driven by orbital change. For more detail on the evolution of the climate, see *Summerhayes* [2015] and *Zalasiewicz and Williams* [2012; 2016].

In addition to providing essential knowledge on the evolution of the Earth System in the past, the stratigraphic record, coupled with mechanistic insights derived from Earth System science, can also provide insights into how the system might evolve in the future. The suggestion to use the past to inform the future was made as early as 1795, when James Hutton wrote " … from what has actually been, we have data for concluding with regard to that which is to happen hereafter" [*Hutton,* 1795].

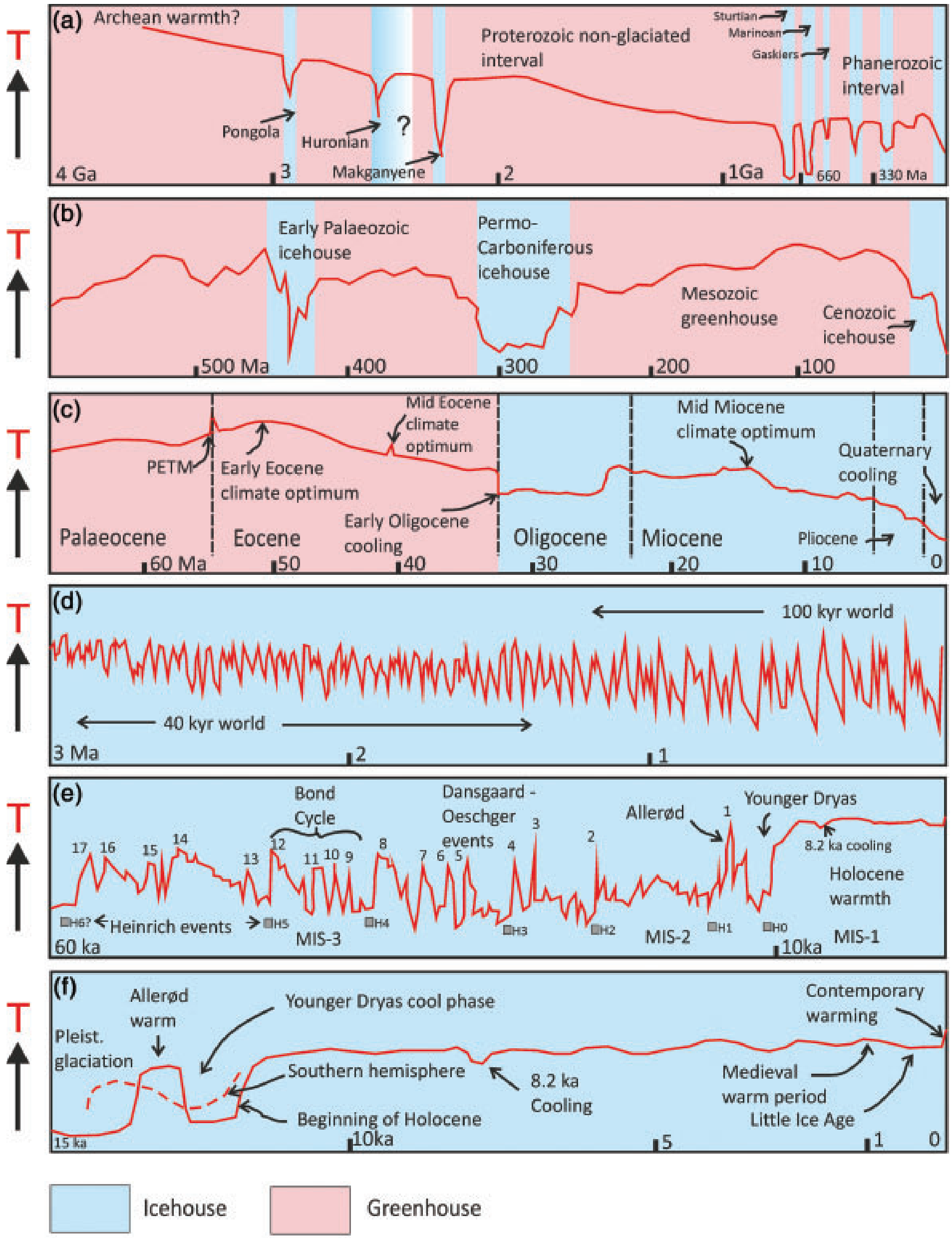

Figure 2. Global climate variation at six different timescales [modified from *Zalasiewicz and Williams,* 2016 and references therein]. On the left side of the figure, the letter "T" denotes relative temperature, which can be taken as mean surface temperature for panels a, b, and f, while panels c–e are predicted on a reading of "T" derived from the $\delta^{18}O$ of benthic marine foraminifera for different time frames of the Cenozoic, which for the intervals with permanent polar ice (within the Oligocene and younger) will record a combination of ice volume and ocean-floor temperature change. The hyperthermals of the Mesozoic (e.g., the Turonian) are not plotted. Ga = billion years ago; Ma = million years ago; ka = thousand years ago.

Building on Hutton's logic, we explore insights into the Anthropocene through the analyses of three earlier intervals in Earth history: the Paleocene–Eocene Thermal Maximum (PETM), the Mid-Piacenzian Warm Period (mPWP) in the Pliocene, and the Quaternary glacial–interglacial cycles.

3.3. Paleocene–Eocene Thermal Maximum

A major perturbation occurred at the epoch boundary between the Paleocene and the Eocene 56.0 Ma (Figure 2c; note that here we adopt 56.0 Ma for the timing of the PETM, consistent with the Geological Time Scale (*Gradstein et al.,* 2012)), which produced a sharp increase of 4–8°C in global mean surface temperature within a few thousand years. The elevated temperature persisted for 0.1–0.2 million years and led to the extinction of 35–50% of the deep marine benthic foraminifera, and to continent-scale changes in the distributions of terrestrial plants and animals [*Sluijs et al.,* 2007; *McInerney and Wing,* 2011; *Haywood et al.,* 2011; *Winguth et al.,* 2012]. The leading hypothesis to explain the PETM temperature spike is the geologically rapid (over a few thousand years) release of 3000–7000 Pg of carbon from methane hydrates in the sea floor, a release triggered by initial warming from other causes [*Dickens et al.,* 1995; *Dickens,* 2011; *Bowen et al.,* 2015]. As a result, oceans increased in acidity, the depth for calcium carbonate compensation became shallower [*Zachos et al.,* 2008], and sea-level rose up to 15 m [*Sluijs et al.,* 2008]. The PETM has some parallels with the present anthropogenic increase of atmospheric CO_2 but the human impact is proceeding at a rate likely to be ten times higher [*Cui et al.,* 2011; *Haywood et al.,* 2011; *Bowen et al*. 2015; *Zeebe et al.,* 2016]. According to *Zeebe et al.* [2016], carbon release from anthropogenic sources reached ca. 10 PgC/yr in 2014, which is an order of magnitude faster than the maximum sustained release of carbon in the PETM, which was <1.1 PgC/yr. That makes the present anthropogenic release rate unprecedented in the past 66 million years, and puts the climate system in a "no-analog" state that "represents a fundamental challenge in constraining future climate projections." In addition, *Zeebe et al.* [2016] point out that "future ecosystem disruptions are likely to exceed the relatively limited extinctions observed at the PETM."

As with the PETM, there is concern that an initial surface temperature rise caused by anthropogenic greenhouse gas emissions could trigger the release of significant amounts of carbon from methane hydrates, driving the temperature even higher [*Lenton,* 2011; see *White et al.,* 2013 for an alternative view].

3.4. Pliocene Epoch

A second interval of paleoclimate that informs some scenarios for the late 21st century climate is the Mid-Piacenzian Warm Period, mPWP (3.264–3.025 Ma; see *Dowsett et al.,* 2013 for an overview) within the Pliocene Epoch, (5.33–2.58 Ma). Various proxies for warm (interglacial) intervals of the Pliocene suggest that atmospheric CO_2 concentration may have peaked around or slightly above 400 ppm [*Pagani et al.,* 2005; *Haywood et al.,* 2011 and references therein], similar to the current atmospheric concentration of CO_2, although *Beerling and Royer* [2011] provide some evidence for CO_2 concentrations having reached close to 450 ppm in the mPWP. During these warm intervals, global mean surface temperature was 2–3°C higher than pre-industrial Holocene levels, and sea level is estimated to have been 10–20 m higher than today [*Miller et al.,* 2012; *Naish and Zwartz,* 2012]. The warm intervals of the Pliocene, especially the mPWP, are viewed as important possible scenarios for late 21st century climate [*Haywood et al.,* 2009 and references therein]. In particular, contemporary warming may also lead to sea-level rises of 10 m or more, with a delay of several hundred years at least while the ocean warms to its full depth and ice caps equilibrate to raise temperatures [*Clark et al.,* 2016].

3.5. The Quaternary Period: Complex-System Behavior of the Climate

More recent stratigraphic records provide convincing evidence for the complex-system behavior of Earth's climate. In particular, two Antarctic ice cores [*Petit et al.,* 1999; *EPICA,* 2004] display many striking features of Earth's climate that are characteristic of a single complex system (see *Scheffer,* 2009 for more details on the complex-system behavior of the Earth System). Records from these ice cores and from deep-sea cores provide evidence of:

i. Two reasonably well-defined states of the system—ice ages (glacial states) and brief warm periods (interglacials);
ii. Regular quasi-periodic transitions between the states (ca. 100,000-year modulations in the last 1.2 million years, ca. 40,000-year modulations earlier in the Quaternary; Figure 2d), which is characteristic of phase locking of key internal system dynamics under relatively weak external forcing. In this case, the forcing was provided by minor astronomical modulation of incoming solar radiation patterns via variations in Earth's orbital eccentricity and precession, along with axial tilt;
iii. Tight coupling between temperature and greenhouse gas concentrations, typical of critical feedback processes within a system that lead to tipping points when feedbacks switch from negative (self-limiting) to positive (self-reinforcing) [*Parrenin et al.,* 2013]; and
iv. Limit-cycle behavior that defines clear upper and lower limits for the fluctuations in temperature, CO_2, and CH_4.

Despite the abrupt climate oscillations of the Quaternary (Figure 2d), the biosphere showed no marked long-term change through this time. In fact, there was little elevation in extinction rates until the megafaunal extinctions of the latest Pleistocene and early Holocene [*Koch and Barnosky,* 2006; *Barnosky et al.,* 2011]. These extinctions appear to have resulted from interactions due to the coincidence of end-Pleistocene climate change with the trans-continental migration of rapidly increasing numbers of *Homo sapiens* into ecosystems that had never encountered them before [*Brook and Barnosky,* 2012].

3.6. Biosphere-Climate Interaction — The Earth System

The climate and the biosphere are two highly intertwined, aggregate components of the whole-Earth System — a single complex system — even though the evolution of those two components can be inferred somewhat independently from each other. The stratigraphic record provides the means by which a systematic integration of climate and biosphere evolution can be attempted — the evolution of the Earth as a system [*Stanley,* 1993; *Lenton et al.,* 2004; *Lenton and Watson,* 2011; *Stanley and Luciaz,* 2014; *Lenton,* 2015]. Complex-systems approaches have been applied by ecologists to track coevolution of the biosphere and geosphere as a series of states and transitions, especially through the metazoan stage [*Hughes et al.,* 2013]. Figure 3 presents a visualization of Earth System evolution [*Lenton et al.,* 2004], emphasizing the coevolution of the geosphere and biosphere.

4. The Contemporary Period — A Changing Relationship

Many traditional stratigraphic techniques remain important to our understanding of the Earth System. Ice cores extracted from polar ice sheets and tropical mountain glaciers have illuminated climatic changes during the late Quaternary. The Deep Sea Drilling Project and its successors have provided archives of long sediment columns from the deep ocean that underpin studies of stratigraphic and climatic change extending back to the Jurassic. Many other natural archives — marine, coastal, and lacustrine sediments, tree rings, charcoal deposits, long-lived corals, microfossils, paleontological, and archeological remains, ice cores, cave deposits, and historical records have been used to reconstruct environmental changes in the past. Multiproxy and interdisciplinary approaches have been used to reconstruct long-term records of environmental change, an excellent example of which is the PAGES (Past Global Changes) 2000-year reconstruction of global land surface temperature [*PAGES 2 k Consortium,* 2013]. Paleo-temperature reconstructions have been crucial in providing the Holocene baseline against which the Anthropocene can be evaluated from an Earth System perspective [*Bradley,* 2015; *Summerhayes,* 2015].

These techniques are now supported by an array of novel observational tools, particularly remote sensing technologies, which enable scientists to observe many important characteristics of the Earth System from space routinely and consistently. Scientists can now monitor, *inter alia*, the composition of the atmosphere; land-cover change; sea surface height, temperature, salinity, and biological productivity of the oceans; the temperature of the lower atmosphere; the standing biomass of forests; disturbances such as fire; and a wealth of human activities, including the night-time illumination of the planet and the rapid expansion of urban areas.

In situ measurements of Earth System processes have also increased dramatically in the last few decades. For example, the uptake of CO_2 by terrestrial ecosystems is directly measured by eddy covariance techniques. The climate is monitored in real time by a global network of stations that observe temperature, precipitation, solar radiation, wind speed, and other parameters. Through systems such as the Argo buoy network, oceanographers routinely measure the temperature, salinity, and chemical state of the ocean from the surface down to 2000 m. The flow of sediments, nitrogen, phosphorus, and other elements down river systems and into the coastal zone can be measured directly, as well as the subsidence of many of the world's large delta areas. Growing databases coupled with satellite observations show how humans have changed the terrestrial hydrological system by engineering the landscape [*Syvitski and Kettner,* 2011], especially by building millions of small impoundments and thousands of large dams [*ICOLD,* 2016].

More controversially, scientists also undertake manipulative experiments on critical processes of the Earth System. For example, large amounts of iron have been deposited onto nutrient-poor regions of the ocean to stimulate CO_2 uptake by phytoplankton [*Boyd et al.,* 2007]; *in situ* terrestrial ecosystems have been treated with excess CO_2 over many years [e.g., *Ainsworth and Long,* 2005]; soils have been warmed to observe changes in microbial activity [e.g., *Knorr et al.,* 2005]; and the species richness of grassland ecosystems has been altered to explore the effect on ecosystem functioning [e.g., *Tilman et al.,* 2006].

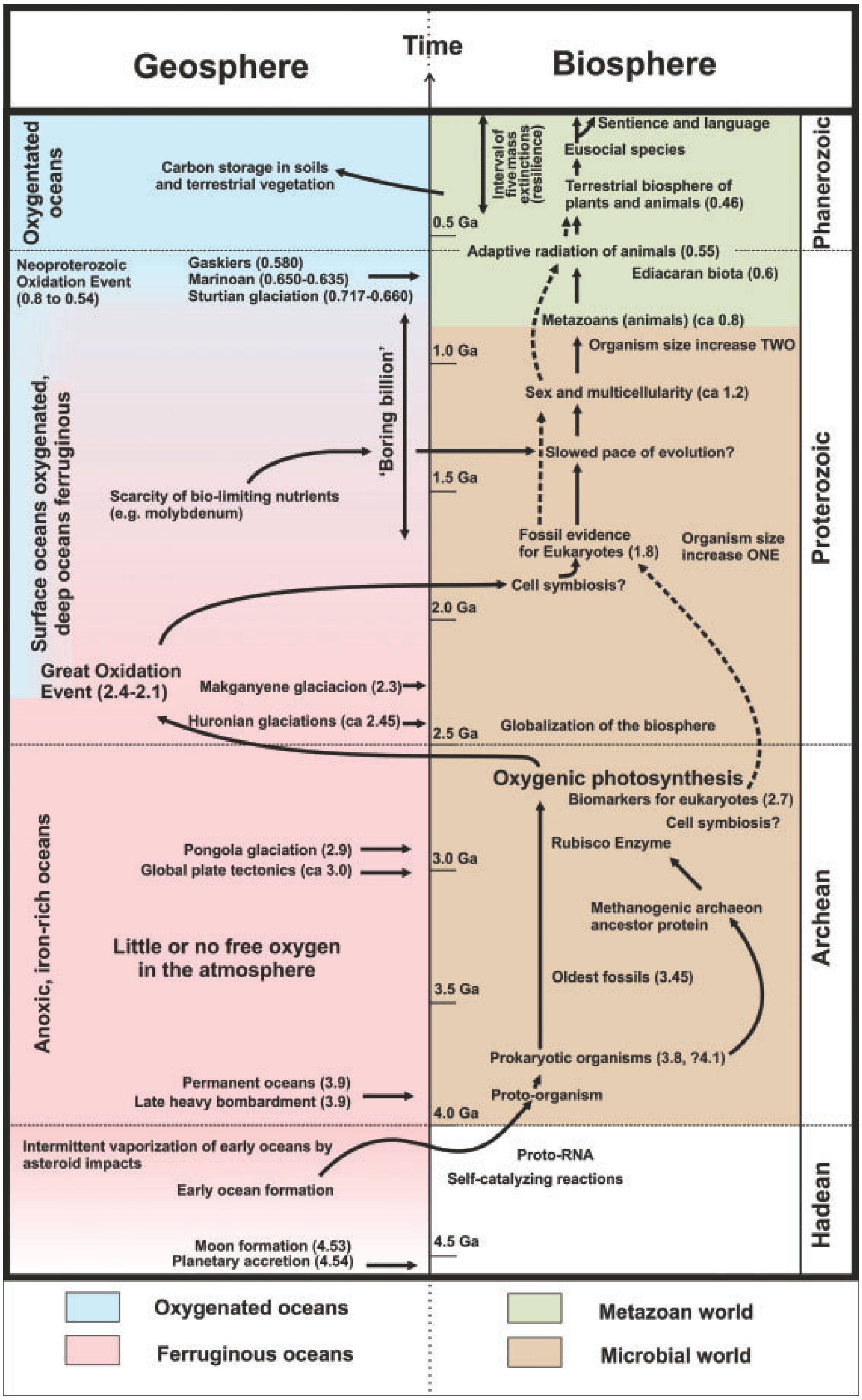

Figure 3. Time line of geosphere–biosphere coevolution on Earth. Here the geosphere is defined as the atmosphere, hydrosphere, cryosphere, and upper part of the lithosphere. The biosphere is defined as the sum of all biota living at any one time and their interactions, including interactions and feedbacks with the geosphere. The time line runs from the bottom to top, starting with the accretion of planet Earth and ending at the present. Numbers indicate ages in billions of years ago (Ga). The major geological eons are indicated in the scale on the right. Left of the time line are major features of and changes in the state of the geosphere, including some perturbations from outside the system. Right of the time line is the major transitions in the evolution of the biosphere, plus some other significant appearances. The major transitions in evolution are given abbreviated descriptions. The arrows crossing the two spheres depict patterns of coevolution and the fact that they are a single system. Eusocial behavior has evolved in several organism groups including arthropods and mammals, perhaps first in the Mesozoic, but possibly much earlier. Based on a concept from *Lenton et al.* [2004].

The dynamics of the Earth System can also be simulated using a spectrum of computational modeling approaches. These include simulating climate system dynamics using General Circulation Models (GCMs); this approach forms the basis for the IPCC (Intergovernmental Panel on Climate Change) projections of possible future changes of the climate system [*Flato et al.,* 2013]. GCMs are now being tested by their application to modeling past climate change, with some success [e.g., *Valdes,* 2011; *Lunt et al.,* 2012], and are increasingly incorporating more detailed dynamics of the biosphere. Coupling of GCMs with (mostly economic) models of human systems creates Integrated Assessment Models (IAMs). Other approaches include Earth system Models of Intermediate Complexity (EMICs) and simple conceptual or other models of reduced complexity [*Claussen et al.,* 2002]. EMICs and conceptual models are useful for exploring nonlinear systems behavior (i.e., tipping points and abrupt shifts) and for simulating Earth System dynamics over very long timeframes. Projections on geological timescales are underpinned by analyses of changes in insolation received by Earth [*Berger and Loutre,* 2002; *Laskar et al.,* 2010].

Earth System science has benefited from the formation of large international research networks, such as the World Climate Research Programme (WCRP), the International Geosphere–Biosphere Programme [IGBP: *Seitzinger et al.,* 2015], the International Human Dimensions Programme on Global Environment Change (IHDP), Diversitas, a global program on biodiversity change, the International Polar Year (2007–2009), and the global Earth's Critical Zone Network. Several of these have recently evolved into Future Earth (www.futureearth.org), a single, interdisciplinary research program on the Earth System, fully incorporating the human dimensions of the system.

It is no accident that the proposal for the Anthropocene Epoch [*Crutzen and Stoermer,* 2000; *Crutzen,* 2002] arose out of the Earth System science community, in particular out of the synthesis project of the IGBP. That project assembled a wealth of observations on recent changes to the Earth System and set them against the paleoenvironmental record of the Holocene, concluding that the Earth System was now operating in a "no analogue state" [*Steffen et al.,* 2004]. For the first time, a major shift in the state of the Earth System was proposed on the basis of direct observations of changes in the Earth System, without specific reference to evidence in the stratigraphic record.

Simultaneously, stratigraphy was experiencing a revolutionary increase in the types of materials and proxies that could be observed in the records of the very recent past, leading to essentially real-time stratigraphy. These include both the many artifacts of human activities over millennia in archeological strata [*Edgeworth et al.,* 2015; *Zalasiewicz et al.,* 2015; *Williams et al.,* 2016], and the rapidly developing stratigraphic record emerging from the technosphere [*Haff,* 2014] that will form archeological strata of the future. The latter include unique markers such as radionuclides, new forms of metals (e.g., aluminum), spheroidal carbonaceous particles from the combustion of fossil fuels, concrete, and plastics [*Zalasiewicz et al.,* 2016] and synthetic fibers [*Waters et al.,* 2016]. There has also been an increasing number of studies on high-resolution bio- and chemo-stratigraphic records of the last few centuries and decades [e.g., *Wolfe et al.,* 2013]. This high resolution, data-rich condition has, in part, triggered a growing array of options for defining the Anthropocene and its start date [e.g., *Crutzen,* 2002; *Ruddiman,* 2013; *Lewis and Maslin,* 2015; *Zalasiewicz et al.,* 2015; *Waters et al.,* 2016].

In summary, the relationship between stratigraphy and Earth System science is now much closer and more effective than it was just a few decades ago. Earth System science has a wealth of contemporary data to assess changes in the Earth System and to test predictions arising from theoretical grounds. It is this wealth of direct Earth System data that has led to the proposal for the Anthropocene Epoch. The challenge is to turn this rapidly expanding body of data in stratigraphy and Earth System science into a productive partnership that can define a significant change to the state of the planet consistent with both the Geologic Time Scale and Earth System science.

5. Defining the Anthropocene by Integrating Stratigraphic and Earth System Approaches

5.1. Stratigraphic Anthropocene

The stratigraphic approach to defining the Anthropocene is clear [*Waters et al.,* 2016]:

> Have humans changed the Earth system to such an extent that recent and currently forming geological deposits include a signature that is distinct from those of the Holocene and earlier

> epochs, which will remain in the geological record? If so, when did this stratigraphic signal (not necessarily the first detectable anthropogenic change) become recognizable worldwide?

A new time interval in Earth history can be defined only when globally synchronous stratigraphic signals related to the structure and functioning of the Earth System are clearly outside the Holocene norm, a new time interval in Earth history can be defined. There is an overwhelming amount of stratigraphic evidence that the Earth System is indeed now structurally and functionally outside the Holocene norm. This evidence includes novel materials such as elemental aluminum, concrete, plastics, and geochemicals; carbonaceous particles from fossil fuel combustion; widespread human-driven changes to sediment deposits; artificial radionuclides; marked rises in greenhouse gas concentrations in ice cores; and trans-global alteration of biological species assemblages [*Waters et al.,* 2016 and references therein].

Determination of a start date for the stratigraphic Anthropocene requires an examination of how the magnitude and rate of contemporary Earth System change, driven largely by human impact, may be best represented by optimal selection of a stratigraphic marker or markers to allow tracing of a synchronous boundary globally. Human environmental impacts began almost as soon as *Homo sapiens* appeared on the Earth. A rich array of stratigraphically relevant materials record these impacts, starting with the megafaunal extinctions of the latest Pleistocene, continuing through early agricultural activities that changed landscapes and emitted CO_2 and CH_4 to the atmosphere [*Ellis et al.,* 2012; *Edgeworth et al.,* 2015; *Ruddiman et al.,* 2015], and increasing significantly with the advent of the late 1700s industrial revolution [*Steffen et al.,* 2007]. Globally recognizable, geosynchronous change clearly began in the mid-20th century at the beginning of the Great Acceleration [*Hibbard et al.,* 2006; *Steffen et al.,* 2015a; *McNeill and Engelke,* 2016], which marks a step change in human activity.

There are precedents for utilizing not only the type but also the degree of change in the stratigraphic record to determine chronostratigraphic boundaries. For example, in the late 1820s, the Italian geologist Giambattista Brocchi used percentages of living molluscan forms in fossil assemblages to subdivide the strata of the Apennines. British geologist Charles Lyell followed Brocchi, extending his work across Europe. As noted in *Summerhayes* [2015]:

> By 1828, following Brocchi, he (Lyell) had used the percentages of modern molluscs in each epoch, and the relations of strata to one another, to subdivide the Tertiary Period into several geological Epochs . . . .. In the “Principles of Geology (1830–33)” [Lyell] named the four periods of the Tertiary as Eocene (“dawn of the recent”, with 3.5% modern species), Miocene (with 17% modern species), Early Pliocene (with 35-50% modern species) and Late Pliocene (with 90-95% modern species).

Choosing the boundary between the Holocene and the Anthropocene at the mid-20th century is consistent with Lyell’s approach in defining subdivisions within the Tertiary based on percentage or degree of change rather than simply on presence or absence of change.

Moreover, the observed differences between strata often indicate enhanced *rates* of change across the boundary. This is most clearly illustrated in the mass extinction events that coincide with some geologic boundaries (Figure 1), when extinction rates rise to at least tens of times above background rates [*Barnosky et al.,* 2011]. Contemporary rates of change in both the biosphere and the climate are particularly striking. At present, extinction rates are at least tens (and possibly hundreds) of times above background rates [*Miller et al.,* 1999; *Barnosky et al.,* 2012; *Pimm et al.,* 2014; *Ceballos et al.,* 2015]. The rate of species translocations around the globe, resulting in homogenization of the world’s biota and in new ecosystems, has risen sharply above the norm prior to extensive intercontinental shipping and air travel [*McNeeley,* 2001; *Williams et al.,* 2015]. Climate-triggered species movement, causing marked shifting of biogeographic ranges, rivals or exceeds the changes evident at both the beginning and end of the Pleistocene, and in the near future such changes may be an order-of-magnitude faster than any at the last glacial-interglacial transition [*Diffenbaugh and Field,* 2013].

The carbon cycle, a critical link between the biosphere and the climate, is now changing at rates 200 times above long-term background levels [*Berner,* 2003; *DePaolo et al.,* 2008; *Archer et al.,* 2009]. Atmospheric CO_2

concentration has risen over the past two decades about 100 times faster than the most rapid rate during the last glacial termination [*Wolff,* 2011], and about 10 times faster than the maximum rate of carbon outgassing during the PETM about 56.0 Ma [*Zeebe et al.,* 2016]. In terms of climate, the rate of increase in global average temperature since 1970 is about 170 times the Holocene baseline rate over the past 7000 years, and in the opposite direction [*Marcott et al.,* 2013; *NOAA,* 2016]. These accelerated rates are evident in stratigraphic signals, suggesting that human forcings since the mid-20th century are triggering as big a change to the Earth System as the transitions from the Pliocene into the Pleistocene, and then into the Holocene [*Barnosky et al.,* 2012], though not (yet) as big as those which coincided with the ends of the Permian, Cretaceous, and Eocene [*Summerhayes,* 2015].

5.2. Earth System Anthropocene

A simple ball-and-cup depiction of complex-system dynamics, which captures the concepts of an envelope of natural variability, a basin of attraction, and a regime shift (Figure 4), is useful in conceptualizing the Earth System approach to defining the Anthropocene.

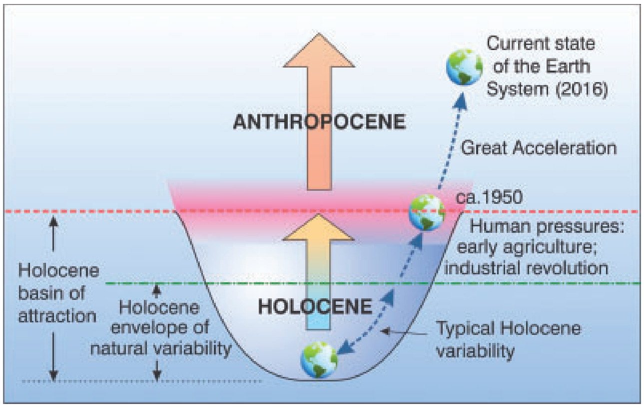

Figure 4. A ball-and-cup depiction of the Earth System definition of the Anthropocene, showing the Holocene envelope of natural variability and basin of attraction. The basin of attraction is more difficult to define than the envelope of variability and so its position is represented here with a higher degree of uncertainty.

Determining the start date for the Anthropocene from an Earth System science perspective requires a consideration of both the Holocene envelope of natural variability and the Holocene basin of attraction. The former represents the limit of natural variability of the Earth System (e.g., climatic and intrinsic biosphere variability that occurs in the absence of major human perturbations), shown in Figure 4 as the horizontal broken green line. Perturbations of the Earth System, such as those driven by more intensive human activity of agriculture and then the industrial revolution, can, up to a point, push the Earth beyond the limits of natural variability while remaining within the Holocene basin of attraction, that is, within a state of the Earth System that is still recognizable structurally and functionally as being the Holocene and within which negative feedbacks are still dominant [*Schellnhuber,* 2009].

In Figure 4, these emerging human pressures are positioned between the Holocene envelope of variability and the top of the Holocene basin of attraction, indicating a transition period of growing human activity that moves the Earth System toward the Anthropocene, but not yet into it. However, the beginning of the Great Acceleration marks a sharp step change in the nature, magnitude, and rate of human pressures on the Earth System, driving impacts that push the system beyond the Holocene basin of attraction [*Steffen et al.,* 2015a]. We base this judgment on (i) the fact that the current atmospheric concentration of CO_2 of 400 ppm is far higher than at any other time during the last 800,000 years at least [*PAGES,* 2016] and (ii) the rates of change of the climate system, described in detail above, which show that the system is in a strongly transient phase with significantly higher temperature and sea level virtually certain when equilibrium is finally re-established [e.g., *Clark et al.,* 2016]. That is, human forcing is now overwhelming the negative feedbacks that would keep the Earth System within the Holocene basin of attraction. As discussed above, the emerging stratigraphic evidence is consistent with this Earth System analysis and suggests that a mid-20th century start date for the Anthropocene is optimal [*Zalasiewicz et al.,* 2015; *Waters et al.,* 2016, and references therein].

In summary, the stratigraphic definition of the Anthropocene is virtually identical to the Earth System definition. In Figure 4 the stratigraphic Holocene Epoch (and Series) is represented by the area below the broken red line; the stratigraphic Anthropocene Epoch (and Series) by the area above the broken red line. The Earth

System Anthropocene in Figure 4 is shown not as a stable state but as a trajectory away from the Holocene; the ultimate nature of the Anthropocene when a new stable state is achieved cannot yet be determined; see section 6 below for further discussion.

The transition of the Holocene into the Anthropocene can be depicted by a dynamic version of the ball-and-cup metaphor (Figure 5). To undergo a regime shift and move to another stable state, the Earth System must be tipped out of the basin of attraction of its current state, the Holocene (horizontal broken red line in Figure 4). Alternatively (or concurrently), the existing basin of attraction (the cup in Figure 4) is substantially reconfigured by anthropogenic forcings so that there is no possibility of returning to the Holocene. This is depicted as a progressive flattening of the cup in Figure 5.

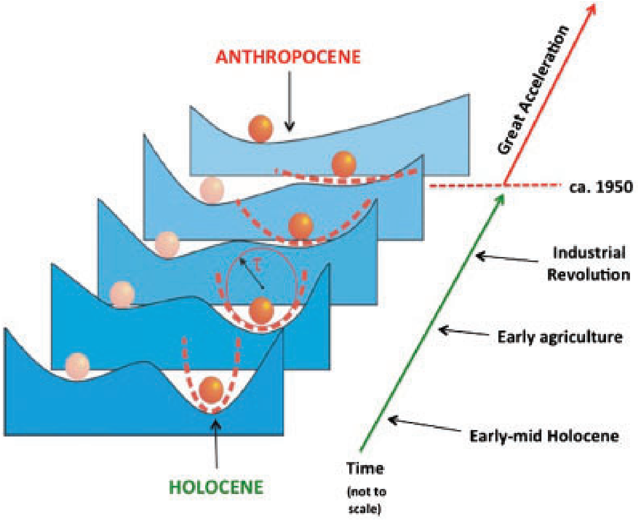

Figure 5. A ball-and-cup depiction of a regime shift. The cup on the right represents a stable basin of attraction (the Holocene) and the orange ball, the state of the Earth System. The cup on the left and the pink ball represent a potential state (the Anthropocene) of the Earth System. Under gradual anthropogenic forcing, the cup becomes shallower and finally disappears (a threshold, ca. 1950), causing the ball to roll to the left (the regime shift) into the trajectory of the Anthropocene toward a potential future basin of attraction. The symbol τ represents the response time of the system to small perturbations. Adapted from *Lenton et al.* [2008].

In the early to mid-Holocene, the basin of attraction is deep, but as human perturbations of the Earth System increase by development of agriculture and later by the industrial revolution, the Holocene basin of attraction becomes increasingly shallow. The step change in the structure and functioning of the Earth System with the beginning of the Great Acceleration in the mid-20th century, clearly evident in the stratigraphic record [*Zalasiewicz et al.,* 2015; *Waters et al.,* 2016] and in direct observations of Earth System change [*Steffen et al.,* 2015a], is represented by the final flattening and disappearance of the Holocene cup. This represents the crossing of a threshold into the trajectory of the Anthropocene toward a potential future basin of attraction.

The irrevocable nature of the regime shift away from the Holocene is clear. The Earth's biosphere may be approaching a third fundamental stage of evolution [*Williams et al.,* 2015; the first two, as noted above, being a microbial stage from ~4 to 0.8 Ga and thereafter a metazoan stage], and the climate is in an interval of rapid, and possibly, irreversible change. With the amount of CO_2 currently in the atmosphere, the planet will continue to warm, driving a long-term rise in sea level even if emissions of CO_2 ceased immediately [*Masson-Delmotte et al.,* 2013; *Clark et al.,* 2016]. Past rises in sea level have taken considerably longer to reach equilibrium than the rise in surface air temperature. For example, warming due to orbital influences ended around 11,700 ka, but sea level continued to rise, by an additional 45 m, for a further 5000 years as ice sheets continued to melt [*Clark et al.,* 2016].

It is clear from both chronostratigraphic and Earth System perspectives that the Earth has entered the Anthropocene, and the mid-20th century is the most convincing start date [*Waters et al.,* 2016]. Moreover, the Earth System is still in a phase of rapid change and the outcome is not yet clear; there is no sign that the system is anywhere near a stable or quasi-stable state. In the next section, we explore two possible trajectories and states of the Earth System in the Anthropocene.

6. The Future Trajectory of the Anthropocene

The ability of Earth System science to project changes into the future offers some interesting insights into the trajectory of the Anthropocene. Clearly, this trajectory is influenced strongly by human agency in addition to natural processes and feedbacks inherent in the Earth System, and so cannot be predicted

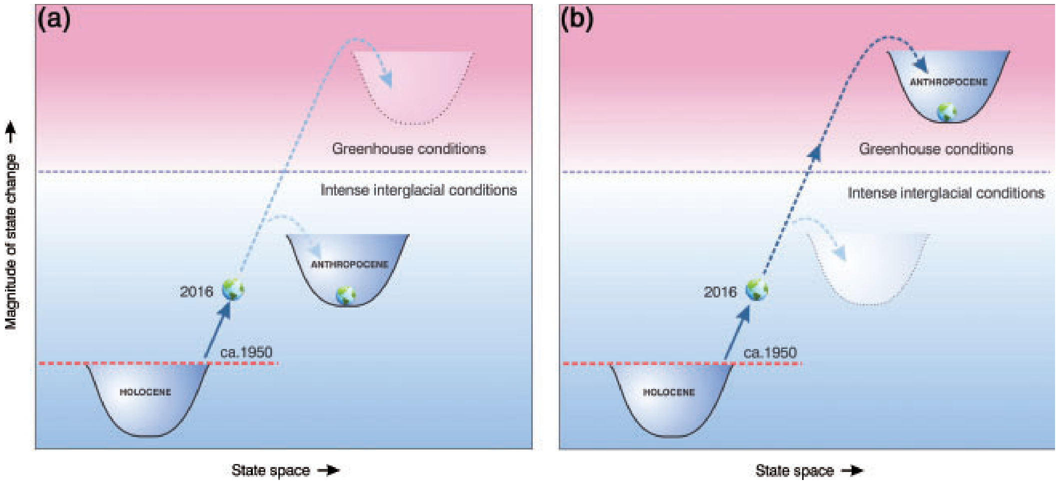

Figure 6. Two of the many possible scenarios for the Anthropocene, relative to the Holocene.

BOX 1. TWO CONTRASTING TRAJECTORIES FOR THE ANTHROPOCENE

Figure 6 uses the ball-and-cup metaphor of Figure 4, with the vertical axis representing the magnitude of change in the Earth System as estimated by both climate and biosphere indicators and the horizontal axis representing the state space of the system. The position of the Anthropocene state indicates relative difference from the Holocene state. The putative states of the Anthropocene (the cups) represent distinct modes of operation of the Earth System that emerge after the system's strongly transient phase ends and more stable conditions develop. We assume that these more stable conditions would persist for many millennia within some envelope of intrinsic variability.

The scenario in Figure 6a is broadly consistent with the Sustainable Development Goals [*UN,* 2015] and the 2015 Paris climate targets [2015*UNFCCC*, n.d.], and is based on rapid and deep reductions in greenhouse gas emissions and a radical turnaround in human exploitation of the biosphere. In this scenario, we assume that the climate is significantly warmer than that of the Holocene, but remains in more intense interglacial conditions with most of the Antarctic ice sheet intact; here the intensity of an interglacial is defined by a range of indicators representing different aspects of the Earth System (e.g., proxies for insolation, astronomical parameters, maximum CO_2 and CH_4 concentrations, global average surface temperature anomaly; see [*PAGES,* 2016]; Figure 9 and accompanying text). In this putative state of the Earth System, biodiversity does not decline much with respect to current conditions.

Figure 6b is an unmitigated Anthropocene scenario that assumes an ongoing increase in human pressures on the climate and the biosphere. Several tipping points in the Earth System are crossed, producing a possibly irreversible transition out of the late Quaternary regime of glacial-interglacial cycles and toward the Earth's sixth great extinction event. This leads to a climate that is much warmer than anything resembling an interglacial state [*PAGES,* 2016], with smaller polar ice sheets, a much higher sea level and a vastly changed biosphere. With an ongoing source of CO_2, this state of the Earth System could persist for millions of years, as similarly warm states have in the past (Figure 2).

with any confidence. Furthermore, it is not clear whether a scenario characterized by a transition from one well-defined state of the Earth System, the Holocene, to another well-defined state is plausible, given that the geological climate record shows a broad range of dynamics, such as transitions, aberrations, perturbations, singular events, and a great deal of variability overall. For example, following cessation of CO_2 emissions at the PETM, 56.0 Ma, the system reverted eventually to its former baseline over a period of around 100,000 years. Nevertheless, two contrasting state-and-transition scenarios, focusing on the climate and the biosphere, may provide insights into the spectrum of potential futures (Box 1; Figure 6).

Realizing the Sustainable Development scenario in Box 1 (Figure 6a) requires a significant and rapid shift in the nature and magnitude of human perturbations to the climate and the biosphere [*Rockström et al.,* 2009; *Griggs et al.,* 2013; *Steffen et al.,* 2015b]; it aims to keep the planet in a state in which human societies can continue to develop and thrive much as they did throughout most of the Holocene. This scenario is, in essence, an Earth System interpretation of the policy goal to avoid "dangerous interference with the climate system" [e.g., *WBGU,* 2011]. This underpins the policy target of limiting mean global surface temperature rise to less than 2°C above the pre-industrial level [*UNFCCC,* 2010], and the more aspirational 1.5°C target specified at the recent COP21 meeting in Paris [*UNFCCC,* 2015; *Schellnhuber et al.,* 2016].

Currently stated national commitments for greenhouse gas emission reductions fall considerably short of what is required to have a reasonable probability of meeting the 2°C target, let alone the 1.5°C target [*Meinshausen et al.,* 2009; *IPCC,* 2013; *Climate Interactive and MIT,* 2015]. However, if global society is able to achieve the required deep decarbonization, the temperature rise would likely peak late this century and decline very slowly over many millennia [*Solomon et al.,* 2009]. In that scenario, the climate would be beyond the orbital control of the late Quaternary, in the sense that warming would be more intense than that of any of the interglacial intervals of the late Quaternary (Figure 6a). The IPCC has concluded that "It is virtually certain that orbital forcing will be unable to trigger widespread glaciation during the next 1000 years. Paleoclimate records indicate that, for orbital configurations close to the present one, glacial inceptions only occurred for atmospheric CO_2 concentrations significantly lower than pre-industrial levels. Climate models simulate no glacial inception during the next 50,000 years if CO_2 concentrations remain above 300 ppm" [*Masson-Delmotte et al.,* 2013].

Consistent with the IPCC assessment, the recent model results of *Ganopolski et al.* [2016] suggest that anthropogenic atmospheric CO_2 from fossil fuel combustion may have already shifted the Earth System enough to postpone the next glacial inception for at least another 100,000 years. Furthermore, *Clark et al*. [2016] suggest that even with rapid decarbonization, a significant, long-term rise of sea level is still very likely. Last, if fossil fuel emissions continue on a business-as-usual trajectory for several more decades, deep-ocean acidification is likely irreversible on a millennial scale. Even "negative emissions"—massive implementation of anthropogenic CO_2 removal from the atmosphere—would not restore the marine environment for millennia [*Mathesius et al.,* 2015].

Regarding the biosphere, the Earth may be approaching a third fundamental stage of evolution because of a wide range of human pressures [*Williams et al.,* 2015]. The contemporary biosphere differs significantly from previous stages of evolution due to many anthropogenic modifications and perturbations. These include global homogenization of flora and fauna; human appropriation of 25–40% of net primary production (likely to increase along with population growth); extensive use of fossil fuels to break through photosynthetic energy barriers; human-directed evolution of other species; and increasing interaction of the biosphere with technological systems [*Haff,* 2014; *Williams et al.,* 2015].

The degree of stabilization of biospheric change equivalent to that needed to stabilize the climate system would require ecosystem restoration and careful stewardship, a rapid reduction in the extinction rate, innovative approaches to agricultural production, full recycling of nutrients such as nitrogen and phosphorus and other materials, the spread of "living (green) infrastructure" in urban areas, and so on. This scenario requires a fundamental change in the nature of the anthroposphere, so that its dynamics become more synergistic with those of the biosphere [*Williams et al.,* 2015]. Yet even this dramatic shift could not undo the past alteration of the biosphere relative to the Holocene, an alteration that already represents a regime shift in the Earth System.

Figure 6b illustrates an alternative possible future for the Anthropocene, an extension of its current trajectory that could be called an unmitigated Anthropocene trajectory. Here greenhouse gas emissions continue to rise or are maintained at high levels for several decades at least, driving the global average surface temperature rise toward 2°C by mid-21st century. Warming continues to weaken the terrestrial and marine carbon sinks that sequester a significant fraction of anthropogenic emissions [*Raupach et al.,* 2014], further amplifying the warming. The climate system begins to cross tipping points [*Lenton et al.,* 2008], triggering, for example, the loss of much of the Amazon rainforest [*Hirota et al.,* 2011], a completely or nearly ice-free Arctic Ocean in summer [*Kirtman et al.,* 2013], and a rapid increase in outgassing of CH_4 and CO_2 from thawing permafrost [*Ciais et al.,* 2013]. These positive feedbacks would accelerate the warming so that even deep cuts in greenhouse gas emissions could no longer bend the warming trajectory. This scenario would likely push the Earth System into a much longer, much warmer, persistent state [*Ganopolski et al.,* 2016]. An ultimate sea-level rise of tens of meters would become unavoidable [*Dutton et al.,* 2015; *Clark et al.,* 2016].

Given continuance of a supply of CO_2 or some equivalent, this new state of the Earth System could persist for millions of years. As *Lenton and Williams* [2013] note, the glacial-interglacial cycles that typify the late Quaternary climate could be a rare condition of potential instability in the Earth System, where positive feedbacks dominate during the transitions between the glacial and interglacial states and relatively small external forcing triggers the passage from one state to another. More common in Earth history are long periods of very slow change (e.g., the greenhouse phases of Figure 2b), where negative feedbacks dominate and the Earth System is generally insensitive to perturbations. While variations in the pattern of solar radiation are still reflected in climate variability during these periods, they are less prominent than during the pronounced Quaternary-style climate oscillations [*Gale et al.,* 1999; *Naish et al.,* 2001; 2009].

The equivalent trajectory for the biosphere, if sustained over millions of years, might represent a third stage of evolution of life on Earth, characterized by the many changes described above [*Williams et al.,* 2015]. If continuation of these trends were also to increase the likelihood of a sixth mass extinction event within the Phanerozoic Eon [*Barnosky et al.,* 2011], then that extinction would mark a major biostratigraphical boundary in the geological record, perhaps comparable to that separating Mesozoic and Cenozoic biotas.

7. Conclusion

Over the past several decades, the relationship between stratigraphy and Earth System science has changed significantly. Diverse tools now allow scientists to observe, record, test, and model Earth System processes directly and to synthesize them into the overarching concept of the Earth as a single complex system. Stratigraphy has benefitted from an increase of methods, data, and conceptual and explanatory frameworks; Earth System science has consequently benefitted from new types of stratigraphical inputs. The type of materials and proxies that can be examined in the sedimentary record has expanded greatly to include a plethora of materials of exclusively human origin. Much greater temporal and spatial resolution of various layers in the stratal record can now be achieved, especially in the recent past. The concept of the Anthropocene has provided a trigger for the Earth System science and stratigraphic communities to integrate their knowledge, tools, skills, and rapidly growing masses of data in unprecedented ways.

From both Earth System science and stratigraphic perspectives, the Earth has been pushed out of the pre-industrial Holocene norm by human activities. This has led scientists to ask: How will the Anthropocene evolve? Even with a rapid and decisive shift of contemporary human societies toward sustainable development, the Anthropocene will remain a distinctly different epoch from the Holocene.

The current trajectory of human societies would lead to an Anthropocene that is a much warmer and biotically different state of the Earth System, one that is no longer governed by the late Quaternary regime of glacial–interglacial cycles, and with far fewer species. Earth in a much warmer greenhouse state would be nothing new. However, it would be novel for *Homo sapiens*, which evolved only 200,000 years ago. Under this scenario, the Earth System would be markedly different from the one humans now know, and from the state that supported the development of human civilization. Which trajectory the Anthropocene follows depends on the decisions and actions of global society today, and over the next few decades.

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