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Notes

Palaeontological evidence for defining the Anthropocene

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Abstract: Palaeontology formed the basis for defining most of the geological eras, periods, epochs and ages that are commonly recognized. By the same token, the Anthropocene can be defined by diverse palaeontological criteria, in accordance with commonly accepted biostratigraphic practice. The most useful Anthropocene biostratigraphic zones will be assemblage and abundance zones based on mixes of native and non-native species in both the marine and terrestrial realms, although lineage zones based on evolution of crop plants may also have utility. Also useful are human-produced trace fossils, which have resulted in prominent biohorizons that can mark the onset of the Anthropocene, especially the paved road system, widespread through terrestrial regions, and microplastics, ubiquitous in near-shore and deep-water marine sediments. Most of these palaeontological criteria support placing the Holocene–Anthropocene boundary near 1950. Continuation of current extinction rates would produce an extinction biohorizon on the scale of the Big Five mass extinctions within a few centuries, but enhanced conservation measures could prevent making mass extinction an Anthropocene signature. A grand challenge for palaeontologists now is to define Anthropocene biostratigraphic zones rigorously, not only as a necessary precursor to formalizing the epoch, but also to more fully understand how humans have restructured the biosphere.

Geological epochs are geochronological units (Murphy & Salvador 1999; NACSN 2005) – that is, they are ‘*divisions of time*’ [italics added] traditionally distinguished on the basis of the rock record as expressed by chronostratigraphic units’ (NACSN 2005, p. 1583; NACSN as here used is the abbreviation for North American Code of Stratigraphic Nomenclature). Chronostratigraphic units are bodies of rock ‘established to serve as the material reference for all constituent rocks formed during the same span of time’ (NACSN 2005, p. 1581). Put more simply, epochs, as geochronological units, are abstract slivers of time – you cannot hold them in your hand. Nevertheless, epochs are based on something you can actually touch – rocks – more specifically, the rocks that were deposited during a certain span of time.

These distinctions are important in any attempt to formally recognize the Anthropocene as an epoch in the Geological Time Scale. In order for the Anthropocene to be equivalent to already-defined epochs, it is not enough to simply designate it as a period of time when human impacts were (and are) abundant. In addition, there must be a material basis – something you can touch – that already is and will remain a lasting part of the geological record, and that is distinctive enough to differentiate the chronostratigraphic unit that forms the ‘material basis’ for the Anthropocene from all others. That ‘something you can touch’ can include distinctive lithology, chemical signatures or physical indicators of time (such as palaeomagnetic signals), but for all of the epochs that have been formally recognized, the distinctive signature that

originally led to their definition came from palaeontological remains – fossils.

In the strict sense of geological nomenclature, fossils are used to define biostratigraphic units, that is, lenses and layers of rock that are characterized by certain types or abundances of fossils. Each biostratigraphic unit generally also demarcates a certain span of time. Using fossils to divide geological time is possible because the evolution of life has resulted in an irregularly paced turnover of species through Earth’s history, meaning that the species that dominate the fossil record of each successive era, period, epoch or age are distinct from those of preceding and later times.

Palaeontology’s role in defining recognized epochs

Fossils led Charles Lyell to define the first three geological epochs in 1833 – the Eocene, Miocene and Pliocene – the latter of which he differentiated as Older Pliocene and Newer Pliocene (Lyell 1833). The material bases for Lyell’s epochs were mollusc fossils contained in successively higher strata in the geological sequence of Europe, especially Italy and France. Lyell defined the Eocene chronostratigraphic unit (although he did not use that term as it was not in existence at the time) as those rocks containing an assemblage of mollusc fossils that included about 97% extinct species. The Miocene as Lyell originally defined it encompassed the rocks that had about 83% extinct mollusc species, the Older Pliocene had somewhere

between 50 and 67% extinct species, and the Newer Pliocene had only 5% extinct species. Although modern taxonomy now makes those percentages somewhat different, the general principle of fewer extinct species occurring in younger strata still applies.

Similarly, fossils figured prominently in the recognition of subsequently defined geological epochs. In 1839, Lyell (1839) changed the name of his Newer Pliocene to Pleistocene, a term that had previously been applied to geologically young alluvial sediments of the River Po, and in 1846 geologist Edward Forbes (1846) equated the onset of the Pleistocene with the onset of glacial cycles, a connotation that stuck despite the original characterization based on fossils (Walker *et al.* 2008, 2009). Heinrich Beyrich (1854) argued that certain rocks in northern Germany and Belgium contained assemblages of fossils that had fewer modern species than were found in Lyell's Miocene, but more modern species than were characteristic of Lyell's Eocene (Vandenbergh *et al.* 2012). He named the epoch, so represented, the Oligocene, which means 'few recent' in Greek, referring to the lower percentage of modern species relative to the Miocene. The Paleocene ('ancient recent') was carved out of Lyell's Eocene in 1874 by Wilhelm Schimper (1874) on the basis of certain fossil plants that occurred in some older strata of Lyell's Eocene, but not in overlying strata (Vandenbergh *et al.* 2012). The concept for the most recent epoch, the Holocene, also originated with Lyell's fossil-based subdivisions of European strata in 1833. Lyell's 'Recent' was defined as the deposits formed during the time that 'has elapsed since the earth has been tenanted by man' (Lyell 1833). Lyell noted the fossil evidence that would distinguish Recent deposits, notably 'Some *recent* [italics Lyell's] species, therefore, are found *fossil* . . . and others, like the Dodo, may be *extinct*, for it is sufficient that they should once have coexisted with man, to make them referrible [sic] to this era' (Lyell 1833, Ch. V, p. 52). In 1885, the Third International Geological Congress renamed Lyell's 'Recent' as the 'Holocene', a term meaning 'wholly recent' in reference to the percentage of extant species found as fossils (Gibbard & Kolfshoten 2004; Pillars & Gibbard 2012). Paul Gervais (Gervais 1867–1869; Gibbard & Kolfshoten 2004), in his study of fossil vertebrate animals, had coined the word Holocene to categorize deposits that corresponded to post-glacial times. Afterwards, as with the Pleistocene, the climatic association of the Holocene being post-glacial became more prominent than its palaeontological basis.

The definitions for geological epochs have been much refined in the two centuries since they were originally proposed, most recently by precisely

stipulating their beginnings with Global Boundary Stratotype Sections and Points (GSSPs), or more informally, 'golden spikes'. Nevertheless, palaeontological criteria still factor into the definition or at least the recognition of most of them. The Paleocene as presently defined begins at the iridium geochemical anomaly that is interpreted to have resulted from a bolide impact about 65.5 million years ago. Important palaeontological markers include a major extinction event (dinosaurs, ammonites, several kinds of foraminifera, etc.), assemblages of echinoids that define the Danian, which is the earliest Stage of the Paleocene, and the assemblages of calcareous nannoplankton, planktonic foraminifera and dinoflagellate cysts that are used to formally subdivide the Danian and other Paleocene Stages into shorter chronostratigraphic units through biostratigraphic zonation (Vandenbergh *et al.* 2012). The beginning of the Eocene is also set at a geochemical event, a pronounced negative carbon isotope excursion that indicates a rapid global warming event 55.8 million years ago. Correlative palaeontological criteria, however, include the beginning of the Ypresian Stage, the base of which 'also defines the base of the Eocene', which is in part recognizable by associations of fossil dinocysts and calcareous nannoplankton (Vandenbergh *et al.* 2012). The beginning of the Eocene likewise is associated with a deep-sea benthic-foraminiferal extinction event, diversifications in planktonic foraminifera, calcareous nanofossils and larger foraminifera, and a mammal dispersal event in North America that defines the base of the Wasatchian North American Land Mammal Age (Vandenbergh *et al.* 2012). The key marker for the beginning of the Oligocene is the extinction of the hantkeninid planktonic foraminifera, and other palaeontological criteria have also figured in its definition, for example, a major transcontinental immigration and extinction event evident in the mammal record, the 'Grand Coupure,' which until recently was regarded as contemporaneous with the beginning of the Oligocene (the definition now places the Grand Coupure slightly above the Eocene–Oligocene boundary) (Vandenbergh *et al.* 2012). The beginning of the Miocene is recognized at the co-occurrence of the calcareous nanofossils *Sphenolithus dephix* and *S. capricornatus*, and with the first appearance of three species of foraminifera (Hilgen *et al.* 2012). The beginning of the Pliocene begins with the first appearance of the nannoplankton species *Coccolithus miopelagicus* and the extinction of *Discoaster kugleri* (Hilgen *et al.* 2012), and the beginning of the Pleistocene with the first appearance of the microfossils *Geophyrocapsa oceanica* and *Globigerinoides tenellus* and extinction of *Discoaster brouweri* (below), *Globigerinoides obliquus*

extremus and *Cyclococcolithus macintyreii* (Pillans & Gibbard 2012). The onset of the Holocene is now placed at 11 700 years, formally set at the first signs of climatic warming after the Younger Dryas as reflected in the North Greenland Ice Core Project (NGRIP) core, but also correlating with the last phases of extinction of the Pleistocene megafauna (Bell *et al.* 2004; Walker *et al.* 2008, 2009; Pillans & Gibbard 2012).

Although almost all of the palaeontological changes formally specified to characterize the Cenozoic epochs come from the marine realm, each epoch also coincides with distinct palaeontological changes evident in terrestrial deposits, for example, with the beginning of various land-mammal ages defined for different continents. The beginning of the Paleocene correlates with the beginning of the Puercan North American Land Mammal Age (NALMA), the MP1 Zone of Europe and the Shanghuan Asian Land Mammal Age (ALMA); the Eocene with the Wasatchian NALMA, MP7 and Bumbanian ALMA; the Oligocene with the Orellan NALMA, MP20 and Hsandagolian ALMA; the Miocene with approximately the Arikareean 3 NALMA and MN1; the Pliocene with the Blancan NALMA, MN14 and Yushean ALMA; and the Pleistocene with MN17 (Hilgen *et al.* 2012; Pillans & Gibbard 2012; Vandenberghe *et al.* 2012).

It is probably no coincidence that each of the epoch boundaries correlate with major global climate changes as well as with palaeontological criteria. The Paleocene starts with major climatic disruptions that resulted at least in part from the K–T bolide impact, the Eocene with a major warming event corresponding to the Paleocene–Eocene Thermal Maximum (PETM) carbon-isotope excursion, and both the Oligocene and Miocene with major expansions of the Antarctic Ice Sheet (Hilgen *et al.* 2012; Vandenberghe *et al.* 2012). The Miocene–Pliocene boundary is set at the ‘basal Pliocene flooding of the Mediterranean following the (Messinian) salinity crisis’ (Hilgen *et al.* 2012), and the Plio–Pleistocene boundary is placed at the first obvious onset of global cooling sufficient to cause northern hemisphere glacial advances (Van Couvering *et al.* 2000; Hilgen *et al.* 2012). Like the formal definition of the Pleistocene (Walker *et al.* 2008, 2009; Pillans & Gibbard 2012), definition of the Holocene also relies on recognition of the geological evidence of global climate change. It seems likely that the major palaeontological differences that help in differentiating each epoch reflect, at least to some extent, the biotic response to these major climatic events, as species contracted or expanded their geographic ranges in concert with shifting habitats, went extinct as habitats disappeared, or kept pace with environmental changes by evolving.

Palaeontological criteria and the Anthropocene

The palaeontological distinctiveness of each existing epoch requires that a newly defined Anthropocene Epoch also be characterized by distinctive organic remains if it is to be equivalent in rank to the Paleocene through Holocene epochs. This is despite the fact that definition of the Paleocene through Holocene epochs followed a different trajectory than has the recognition of the Anthropocene. Past definitions began with recognizing distinctive features of the material rock record, primarily the fossils contained therein and their implications for defining biostratigraphic and chronostratigraphic units. From those stratigraphic entities, geochronological units (epochs) were then recognized. The development of the Anthropocene has gone in exactly the opposite direction. An arbitrary unit of time (a geochronological unit), characterized as the time of intensified human impacts, was first proposed (Crutzen 2002*a, b, c*; Steffen *et al.* 2007), and now the material ‘rock’ record – deposits that have accumulated in the past few centuries – is being scoured for distinctive signs that could provide an objective material basis for an epoch (Zalasiewicz *et al.* 2008, 2011*a, b*; Merritts *et al.* 2011; Price *et al.* 2011; Steffen *et al.* 2011*a, b*; Syvitski & Kettner 2011; Tyrrell 2011; Vane *et al.* 2011; Vince 2011; Syvitski 2012).

Given the importance of fossils in providing that material basis for other epochs, a key question is whether the biotic signals in deposits that accumulated in the past few decades or so can, in fact, be distinguished using palaeontologically significant criteria that parallel those used in characterizing pre-Anthropocene epochs. These criteria demand recognizing and defining biostratigraphic zones and/or prominent biohorizons, such as major extinction episodes or biotically significant events that leave a clear sedimentary signature (a so-called boundary layer). Usually, this requires morphological identification of decay-resistant parts of organisms (for instance, shell or bone for animals, or pollen, seeds and phytoliths for plants) or their trace fossils (tracks, trails, habitation structures such as burrows for animals; leaf or other imprints for plants). In some cases, for fossils less than a few thousand years old, it is also possible to use preserved DNA to obtain highly resolved taxonomic identifications (Willerslev & Cooper 2005).

Anthropocene biostratigraphic zones

Commonly recognized biostratigraphic zones include range zones, lineage zones, assemblage zones, abundance zones and interval zones

Table 1. *Biostratigraphic units useful in characterizing the Anthropocene*

Range zone. The body of strata representing the known stratigraphic and geographic range of occurrence of a particular taxon (a taxon-range zone) or combination of two taxa (a concurrent-range zone) of any rank.

Lineage zone. The body of strata containing specimens representing a specific segment of an evolutionary lineage. It may represent the entire range of a taxon within a lineage or only that part of the range of the taxon below the appearance of a descendant taxon.

Assemblage zone. The body of strata characterized by an assemblage of three or more fossil taxa that, taken together, distinguishes it in biostratigraphic character from adjacent strata.

Abundance zone. The body of strata in which the abundance of a particular taxon or specified group of taxa is significantly greater than is usual in the adjacent parts of the section.

Interval zone. The body of fossiliferous strata between two specified biohorizons. A 'biohorizon' is typically either the highest or lowest stratigraphic occurrence of a given taxon. Interval zones differ from range zones in that they are defined on the first or last occurrences of different taxa, whereas taxon-range zones are defined by the uppermost and lowermost occurrence of a single taxon, concurrent-range zones by the co-occurrence of two taxa, and assemblage zones by the co-occurrence of three or more taxa.

See the North American Stratigraphic Code (NACSN 2005) and the International Stratigraphic Guide (Murphy & Salvador, 1999) for detailed discussions and definitions of these zones.

(Murphy & Salvador 1999; NACSN 2005). Table 1 summarizes the differences between these. Conceptually, assemblage zones and abundance zones formed the basis for Lyell's original recognition of the Eocene, Miocene and Pliocene, and for the subsequent recognition of the Paleocene, Oligocene, Pleistocene and Holocene. Assemblage and/or abundance zones still characterize each epoch, although they are now much refined with respect to those Lyell and his contemporaries used. In recent decades, interval zones and range zones have taken on great importance in both recognizing the boundaries between epochs, and in subdividing epochs. Some, but not all, of these biostratigraphic zones may be useful in identifying Anthropocene strata, as detailed in the following discussion. However, applying the biostratigraphic zone concept to the Anthropocene in many cases would be limited to defining only the lower boundary of the zone, given that many biostratigraphic zones restricted to the Anthropocene would extend into the present. Nevertheless, applying the biostratigraphic zone concept has great utility, in that recognizing a biostratigraphic zone that defines the beginning of the Anthropocene also defines the end of the Holocene and thereby helps to place the Holocene–Anthropocene boundary unequivocally.

Anthropocene range zones

It is not presently possible to use range zones to define or effectively characterize the Anthropocene as it is colloquially conceived – that is, the time that humans have been so abundant and technologically advanced that they are noticeably and irrevocably altering most parts of the planet (Crutzen 2002a, b, c; Steffen *et al.* 2007, 2011a; Price *et al.* 2011).

This is because no new species are known to have originated during the past few hundred years, so using any existing species to define a range zone would inevitably place the beginning of the range zone long before the Anthropocene (as the term is now used) is thought to have begun.

For instance, the single most pertinent taxon for defining a range zone in the Anthropocene would be *Homo sapiens*. This range zone by definition would begin with the first appearance of *H. sapiens*, currently dated at around 195 000 years ago (McDougall *et al.* 2005), and has not yet ended, as we are still extant (Fig. 1). This means that the *H. sapiens* range zone would encompass not only the Anthropocene – but also all of the Holocene and part of the Pleistocene. In this context, *H. sapiens* is at best a characteristic taxon of the Anthropocene (but also characteristic of the late Pleistocene and Holocene), rather than a defining taxon.

The co-occurrence of *H. sapiens* and another taxon could in theory be used to define a concurrent-range zone much shorter than the *H. sapiens* range zone (Fig. 2). In practice, candidate species (or subspecies) include those that humans have domesticated, such as *Equus caballus* (horse), *Bos primigenius* (cow), *Capra hircus* (goat), *Ovis aries* (sheep), *Sus scrofa* (pig), *Canis lupus familiaris* (domestic dog), *Felis catus* (domestic cat) or crop plants such as maize (or corn as it is commonly called in the US) (*Zea mays*). However, all of these domestic species have their first known records extending back to at least eight thousand years ago, which encompasses most of the Holocene and therefore concurrent-range zones based on them would not be restricted to the Anthropocene as it is generally conceived (Mysterud *et al.* 2001;

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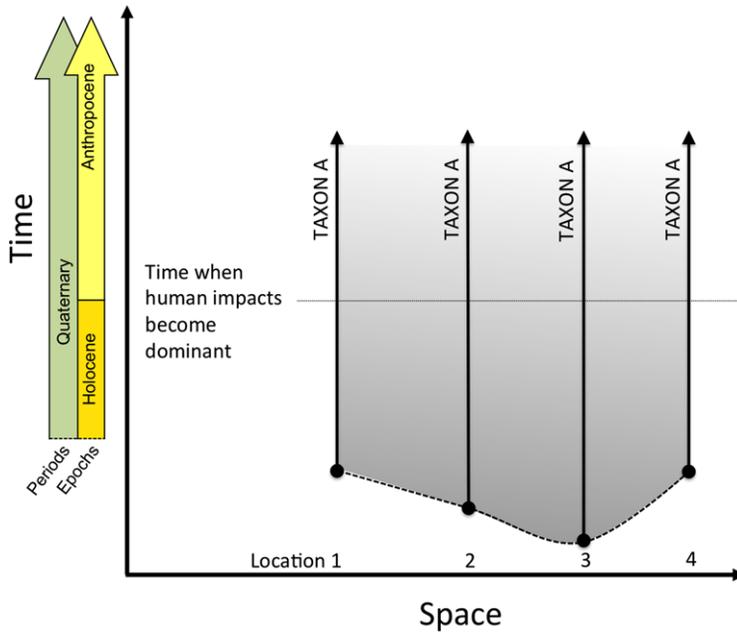


Fig. 1. A range zone based on a single taxon. Usually, these are based on evolutionary first appearances. This type of zone probably has limited utility for defining the Anthropocene, assuming the eventual boundary will be placed sometime within the past 300 years, because no new, widespread, easily fossilizable species are known to have originated within that time. Vertical lines represent ranges of taxa. Dots on the ends of lines indicate first (lowermost) or last (topmost) appearance in a region. Arrows indicate the taxon was already present in a region (downward facing arrow) or continues to persist (upward facing arrow). For most Anthropocene biostratigraphic zones it will only be possible to define a lower boundary (i.e. the Holocene–Anthropocene boundary) because the future is unknown.

Piperno & Flannery 2001; Vila *et al.* 2001; Pedrosa *et al.* 2005; Chen *et al.* 2006; Fernandez *et al.* 2006; Larson *et al.* 2007).

Anthropocene lineage zones

Lineage zones may be more amenable to characterizing the Anthropocene than range zones, but their utility in this regard remains to be proven. Lineage zones do not rely on the origin and/or extinction of species. Rather, they are underpinned by rapid, morphologically significant changes within an evolutionary lineage (typically within species), and can be defined when it is possible to trace the evolutionary sequence that leads from basal members of a species to more derived representatives. Usually the recognition of different parts of the lineage relies on morphological criteria. For example, the varying dimensions of the lower first molar in the muskrat lineage represented by *Ondatra zibethicus* and in species leading up to *O. zibethicus* allow Pleistocene and Holocene strata in which the teeth are fossilized to be subdivided into more resolved chronostratigraphic units (Martin 1993; Mihlbachler 2002).

Defining lineage zones based on crop plants may well be feasible, although this has not yet been done (Fig. 3). A leading candidate is corn, *Zea mays* subspecies *mays*, which is widespread on all continents except Antarctica, and which cannot reproduce in the absence of human cultivation. The earliest evidence of *Zea mays mays* is from archaeological deposits in Mexico that date to nearly 9000 years ago (Piperno & Flannery 2001; Tenaillon & Charcosset 2011). However, since 1847 the most commonly grown strains derive from the so-called Yellow Dent hybrid, so named because of a characteristic dent on each kernel. By 1930, new hybrids began to produce distinctive strains characterized by larger cobs (Wallace & Brown 1988; Troyer 1999, 2004; Duveck 2005). Maize kernels and cobs are commonly preserved in strata for thousands of years, and given their ubiquity now it is likely that fossil remains of today's maize will be preserved in the sedimentary record that is now accumulating. Therefore, should the morphology of kernels or cobs from strains that first appeared after 1800 be shown to be distinguishable from the older varieties, bounding Anthropocene lineage zones by the presence of certain

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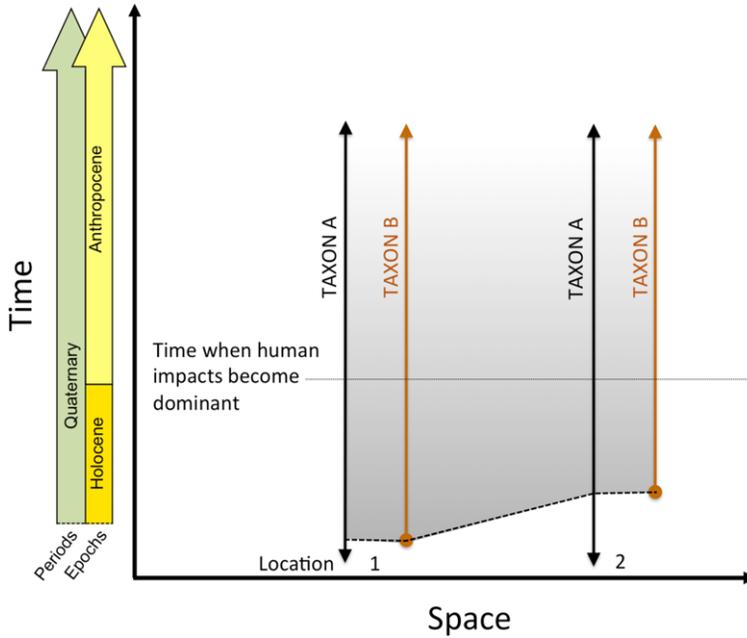


Fig. 2. Concurrent-range zone based on co-occurrence of two taxa. Like range zones, concurrent-range zones have limited utility for defining the Anthropocene because all living taxa have stratigraphic ranges that extend back at least thousands of years. See Figure 1 for further explanation.

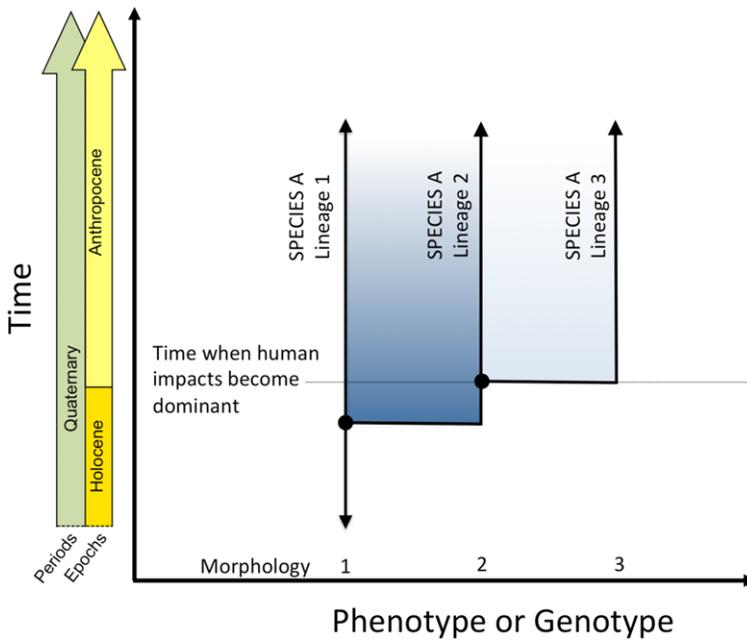


Fig. 3. Lineage zone. Such zones based on the evolution, hybridization and genetic modification of crop plants are potentially useful for characterizing and subdividing the Anthropocene. See Figure 1 for further explanation.

maize strains may well be feasible. Given that molecular biology techniques are already capable of differentiating various varieties of *Zea mays mays*, and that those techniques can be used on fossil material up to several thousands of years old, it will probably be possible for palaeontologists of the future to recognize an unusual genetic mutation that produced supersweet corn (maize) around 1950 (Erwin 1951; Tracy 1997), and the genetically modified varieties of maize that humans began producing and marketing widely in 1998. Similar principles apply to defining lineage zones for other crop plants, such as wheat, rice and soy beans. However, the long-term preservation potential for most crop plants is probably considerably less than for corn.

Anthropocene assemblage zones

Assemblage zones offer a practical way to define the beginning of and characterize the Anthropocene. Defining an assemblage zone depends on recognizing the co-occurrence of three or more fossilizable species that are unique associates with respect to the fossils of previous epochs. Assemblage zones differ in species composition in different biogeographic settings, so are region-specific. However, for the Anthropocene the defining criterion in each region relies on recognizing strata characterized by many human-introduced species (so-called alien species) with respect to underlying strata that are characterized only by taxa native to the region. Such unique associations of introduced aliens plus native species are now widespread as a result of human transport of many species outside their pre-anthropogenic range (Vitousek *et al.* 1997; Pejchar & Mooney 2009).

Most previous epoch definitions originally relied on shallow-water marine assemblages. Parallel criteria for defining the Anthropocene exist in the sea-floor deposits accumulating in proximity to major shipping ports. In these regions, the introduction of alien species has been particularly efficient, because organisms are transported across the oceans when they attach to the hulls of ships or are inadvertently taken in with ballast water, which is then released in the destination port (Bax *et al.* 2003). Such introductions of alien marine species probably started as early as the 1500s, but the first well documented cases date to the 1800s, by which time shipping traffic had increased markedly. For example, in San Francisco Bay (Thompson *et al.* 1997; Cohen & Carlton 1998) off the coast of California, US, the barnacle *Balanus improvisus* was first recorded in 1853 living on ships' hulls, but subsequently it has spread throughout the world. Atlantic oysters (*Crassostrea virginica*), the predatory snail *Urosalpinx cinerea*, the soft-shell clam *Mya arenaria*, the gem clam *Gemma*

gemma and the ribbed mussel *Arcuatula demissa* were introduced in 1869. The striped bass (shipped by railroad) *Morone saxatilis* arrived in 1879, Atlantic shipworms (*Teredo navalis*) in 1913, and Japanese oysters (*Crassostrea gigas*), Manila clams (*Venerupis philippinarum*) and Asian mussels (*Musculista senhousia*) in 1932. Beginning in 1940–1950, ship traffic intensified during and following World War II, bringing with it increased rates of introductions of alien species, which were further increased by 1975 as supertanker traffic became common and shortened transoceanic travel times enhanced the survival of exotic organisms in ballast water. Shipping by air also introduced alien species through such avenues as the seaweed used to pack fresh lobsters. As a result, alien species that were introduced to San Francisco Bay between 1940 and 1980 include channelled whelks (*Busyconotus canaliculatus*), oriental prawns (*Palaemon macrodactylus*), red beard sponges (*Microciona prolifera*), European green crabs (*Carcinus maenas*), Chinese mitten crabs (*Eriocheir sinensis*), Asian clams (*Potamocorbula amurensis*), amphipods (*Corophium* sp.) and rough periwinkles (*Littorina saxatilis*). Presently, there are more than 212 exotic species in San Francisco Bay (Thompson *et al.* 1997; Cohen & Carlton 1998; Bax *et al.* 2003). Such chronologies indicate that a geologically unique 'fossil' assemblage began to characterize the floor of San Francisco Bay and environs by the mid-1800s or even earlier, and was dramatically apparent by 1950, providing clear basis for defining Anthropocene assemblage zones there (Fig. 4). The coastal deposits of other port cities, now extending along a large portion of the world's coastal areas, have experienced similar invasions of exotic species, although the species compositions differ among coastlines (Bax *et al.* 2003).

Likewise, opportunities for defining Anthropocene assemblage zones abound in the terrestrial realm, where nearly every ecosystem now incorporates several introduced plant species (Vitousek *et al.* 1997; Ellis 2011; Ellis *et al.* 2012). In the coterminous US, for example, at least 2100 species of plants that were originally found only on other continents are now common constituents of the flora over wide regions – indeed, the aliens make up more than 10% of the flora (Vitousek *et al.* 1997). These introductions began in earnest with arrival of Europeans in the late 1400s and through the 1500s, but accelerated in the 1800s. For instance, in the early 1800s, tamarisk (salt cedar, *Tamarix* spp.) was introduced to the American SE and has since become widespread in riparian areas, where fossilization potential is high for pollen, leaves, seeds and twigs. In the last 50 years, cheat grass (*Bromus tectorum*), originally introduced as cattle feed, has become dominant in

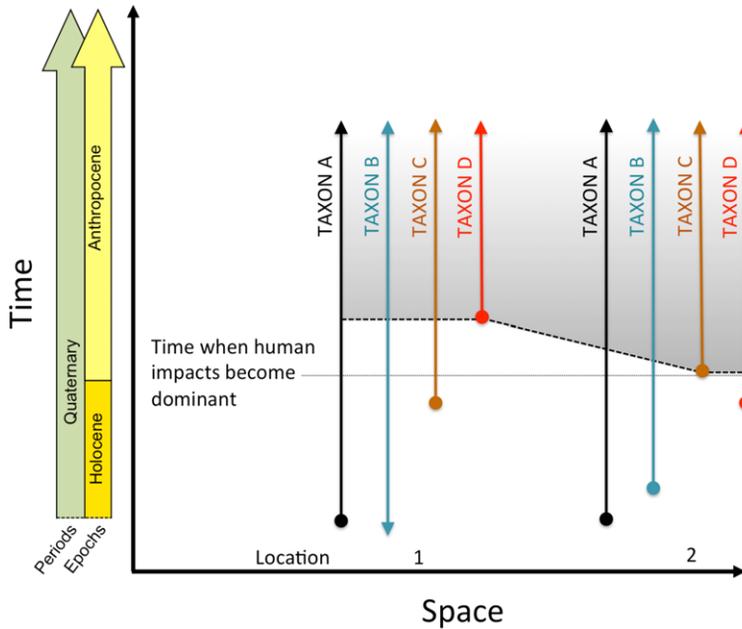


Fig. 4. Assemblage zone. These have great potential for characterizing and defining the Anthropocene, based on clearly specified combinations of alien and native species in various regions. Such zones can already be recognized in many parts of the world. See Figure 1 for further explanation.

many western grasslands and continues to spread. In South America, plants of Eurasian origin such as scotch broom (*Cytisus scoparius*), several species of wild roses (*Rosa* spp.) and thistle (*Onopordum* spp.) were introduced by the mid-1800s and have since become a major constituent of regional floras, even in remote regions. In Chile and Peru alone, there are more than 990 alien plant species, comprising about 13% and 2% of their respective floras (Vitousek *et al.* 1997). In Europe there are more than 6600 recognized introduced plant species (DAISIE 2012; DAISIE is the abbreviation for the database ‘Delivering Alien Invasive Species Inventories for Europe’). In Australia, approximately 27 500 introduced plant species now outnumber the native plant species (about 24 000 species) (Thuillier 2012). The net effect of human activities that have moved plant species around the globe is homogenization of the world’s flora and alteration of floral composition and abundance patterns.

Such changes are already detectable in the palynological record obtained from lake-sediment cores. The preservation of pollen for thousands and millions of years in such deposits is well documented, so much so that the discipline of palynology has become a vital part of the toolkit that geologists, palaeontologists, ecologists and climatologists use to interpret Earth history, especially

for the Pleistocene and Holocene. This means that pollen assemblage zones based on a mix of introduced and native species hold promise in placing the Holocene–Anthropocene boundary in terrestrial settings throughout the world (Coombes *et al.* 2009; Armesto *et al.* 2010).

Successive waves of animal invasions have also characterized the terrestrial realm over the past few hundred years. Since about the 1600s, domestic species such as cattle (*Bos taurus*), pigs (*Sus scrofa*), goats (*Capra hircus*), sheep (*Ovis aries*), horses (*Equus caballus*), dogs (*Canis lupus familiaris*), cats (*Felis catus*), chickens, Norway rats (*Rattus norvegicus*) and house mice (*Mus musculus*) have become common throughout the world. Since the 1800s, various deer species (such as *Cervus elephus*, *Odocoileus virginianus*, *Odocoileus hemionus* and *Dama dama*) have been introduced for sport hunting into continents where they were previously unknown and subsequently integrated into the regional ecosystem, in some places (like New Zealand) becoming dominant herbivores. All of these vertebrates have great potential to become part of the fossil record.

Anthropocene assemblage zones based on co-occurrence of native and alien species are also readily definable from animal remains in lakes and rivers. For example, zebra mussels (*Dreissena polymorpha*), an eastern European native, were

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introduced into the US Great Lakes area in 1988, and since then have spread through most of the eastern US waterways and as far west as California (Pejchar & Mooney 2009; USA National Atlas 2012). Similarly, introduced sport fish such as brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*) have proliferated in many rivers and lakes throughout the Americas, and Atlantic salmon (*Salmo salar*) have been introduced into Pacific waters off the coasts of both North and South America. Fossil remains of such species are particularly likely to be relatively abundant constituents of the future palaeontological record, as they occur in depositional basins where preservation is likely, and because shells, bones, fish scales and otoliths are often identifiable with high taxonomic resolution.

Anthropocene abundance zones

Like assemblage zones, abundance zones are readily definable in sediments that have accumulated over the past two centuries and that are accumulating now. Whereas assemblage zones simply recognize the presence or absence of a taxon, abundance zones rely on recognition of the percentage of specimens that represent a given species in the fossil record. Abundance zones are widely employed in palynological records to identify the boundary between the Pleistocene and Holocene, for example, with Pleistocene zones containing high

percentages of pollen from taxa that tend to thrive under cool glacial regimes (for instance, spruce and fir trees in eastern North America), and Holocene zones containing higher percentages of taxa adapted to warmer conditions (various deciduous trees, grasses and shrubs) (Jackson *et al.* 2000; Williams *et al.* 2004). Similar zonations that relied on abundances of native v. introduced genera may well provide a clear record of the onset of the Anthropocene. Such approaches are already proving useful with diatoms preserved in lake sediments, which have been proposed as a marker for the Holocene–Anthropocene transition (Wolfe *et al.* 2012).

Defining abundance zones that specify percentages of native v. introduced taxa also has great utility in the near-shore marine sedimentary record (Fig. 5). In San Francisco Bay, alien species were found to typically comprise 40–100% of the common species, as much as 97% of the total number of individuals, and up to 99% of the biomass (Cohen & Carlton 1998). Another relevant study (Byrnes *et al.* 2007) documents that worldwide, introduced species combined with local extirpations result in skewing the trophic structure, such that the relative percentages of species in highest trophic levels (top predators and carnivores) are reduced relative to percentages of species in lower trophic levels (primary consumers such as macroplanktivores, deposit feeders and detritivores) (Fig. 6). For instance, in the Wadden Sea along the

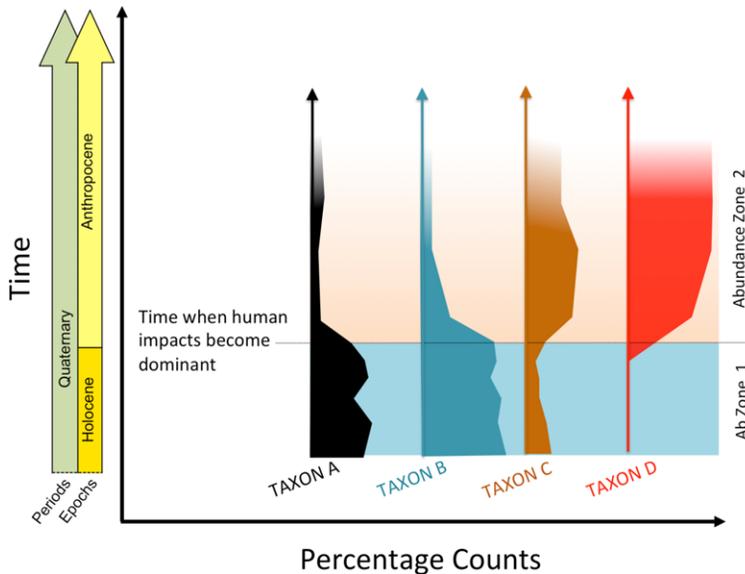


Fig. 5. Abundance zones. These are based on relative percentages of individuals within a taxon and can already be used to characterize sediments formed in the past few centuries and decades. Abundance zones should prove useful in defining and characterizing the Anthropocene. See Figure 1 for further explanation.

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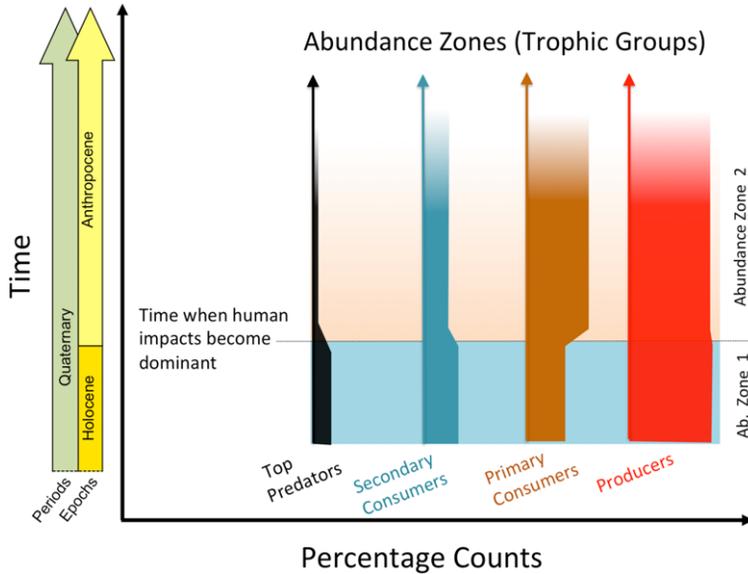


Fig. 6. Abundance zones can be based on the number of species representing major trophic groups that have been documented to have changed recognizably over the last several decades. See Figure 1 for further explanation.

NW coast of Europe, the post-invasion fauna (which could be considered the Anthropocene fauna) is characterized by a 14.0% decrease in top predator/carnivore species, and an 8.6% increase in primary consumer species (Byrnes *et al.* 2007) (Fig. 6).

It is also feasible to define Anthropocene abundance zones based on relative percentages of large-mammal species preserved in the composite fossil record of a given biogeographic region by assessing the number of specimens that represent human remains preserved in cemeteries or elsewhere, remains of domestic megafauna (cows, horses, pigs, sheep, goats, etc.) preserved in sediments, and remains of wild megafauna (animals such as deer, bighorn sheep, antelope, large carnivores, elephants, etc.). Such compilations will probably clearly document that the percentages of human and domestic animal remains increase markedly relative to wild megafauna in two phases, the first beginning around 1750 as the Industrial Revolution began (Barnosky 2008), and the second beginning around 1950, when human population growth began to climb rapidly from about 2 billion people to the present 7 billion.

Anthropocene interval zones

First appearances of certain widespread taxa are typically used to specify interval zones, with each zone defined as the stratigraphic interval between the earliest appearance of an older taxon and the

earliest appearance of a younger taxon (Fig. 7). Alternatively, the bounding biohorizon for an interval zone can be an extinction event, for example the last appearance of a taxon. In theory, the interval zone concept is widely applicable to recognizing the Anthropocene–Holocene boundary and to characterizing the Anthropocene, but, in practice, it is probably not possible to use the evolutionary first-appearance biohorizon of a species as an Anthropocene boundary definer. This is due to the same difficulty that applies in recognizing Anthropocene range zones – there are no known species that have originated within the last few hundred years. However, human-produced trace fossils (also known as ichnofossils, which are geological records of biotic activity, but not actual parts of organisms) may well have practical utility in this regard. (There probably is justification for regarding cultural remains produced by humans as a particular kind of trace fossil that would warrant a taxonomy somewhat distinct from other ichnofossils, but for ease of discussion here, the general term ‘trace fossil’ remains appropriate.) Since 1950, abundant trace fossils in the form of microplastics (eroded fragments of large plastic items, and ‘nurdles’ used widely in industrial abrasives, exfoliants and cosmetics) have become an easily identifiable constituent of near-shore and deep-water marine sediments (Barnes *et al.* 2009; Fendall & Sewell 2009; Ryan *et al.* 2009; Watters *et al.* 2010; Zarfl & Matthies 2010; Andrady 2011; Cole *et al.* 2011; Zarfl *et al.* 2011). These micro-trace

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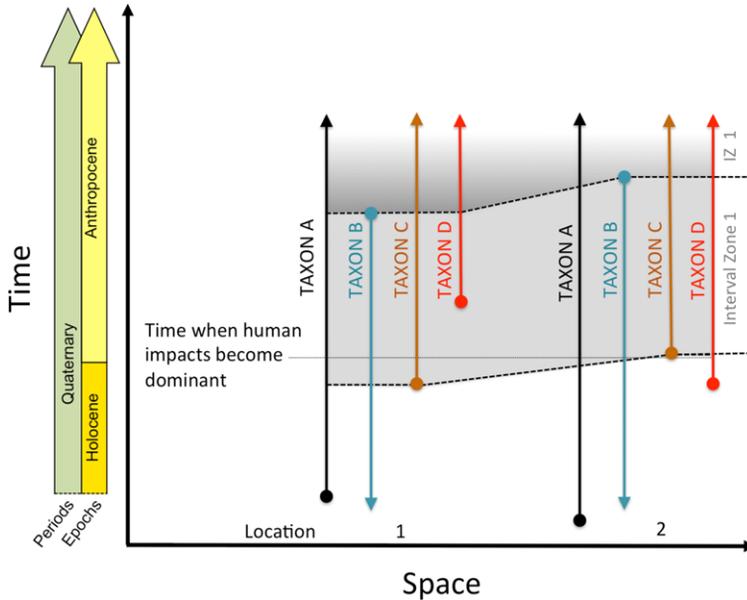


Fig. 7. Interval zones. Useful Anthropocene interval zones can already be defined based on widespread appearances of certain human trace fossils in the sedimentary record since 1950, especially microplastics and the paved road system. In the future it may be possible to define biohorizons useful for bounding interval zones based on extinction horizons, should currently too-high extinction rates not be arrested. So far, extinctions have not been extensive enough to leave a lasting fossil record, although continuation of current trends would ensure a recognizable extinction biohorizon within a few centuries, if not sooner. See Figure 1 for further explanation.

fossils occur in depositional settings that are similar to those that preserve the foraminifera and calcareous nannofossils used to define interval zones corresponding to pre-Anthropocene epochs. Still unknown, however, are whether microplastics or recognizable derivatives will last in the geological record for millions of years, although available information suggests they will persist for at least thousands of years.

Defining an Anthropocene interval-zone boundary based on extinctions may be feasible but is not without complications. More than 900 species have gone extinct since the year 1500 (ESI 2011; ESI abbreviates Endangered Species International), but most of them were not widespread or are species that would have little chance of leaving a fossil record (IUCN 2012; IUCN abbreviates International Union for the Conservation of Nature). Thus, using any single species to define a worldwide Anthropocene biohorizon that was easily recognizable in the fossil record is problematic. Nevertheless, a useful approach may be to use the historically recorded extinctions of different species in different regions to define correlated regional biohorizons that cover much of the world (Fig. 7). Such a composite biohorizon would be most evident within the twentieth century, when

approximately 500 extinctions occurred. This represents a clear peak with respect to the number of extinctions that are known in previous centuries: fewer than 50 extinctions per century in the 1500s, 1600s, and 1700s, and about 125 in the 1800s (ESI 2011).

Mass extinction

The K–T mass extinction – the fifth of the so-called Big Five mass extinctions – marks the beginning of the Paleocene Epoch, the Paleogene Period, and the Cenozoic Era (Vandenbergh *et al.* 2012). Recognition that thousands of species are currently threatened with extinction, and that more than 900 have gone extinct in the past five centuries, has led to suggestions that a sixth mass extinction may also be characteristic of the Anthropocene (Leakey & Lewin 1995; Pimm *et al.* 1995; Pimm & Brooks 1997; Pimm & Raven 2000; Wake & Vredenburg 2008; Barnosky *et al.* 2011). Although there is no doubt that extinction rates are elevated, at a minimum 3–12 times above normal background rates, so far less than 1% of the IUCN-evaluated species have actually died out (Barnosky *et al.* 2011), and there is no evidence that species

commonly used in biostratigraphy, such as marine calcareous plankton, have disappeared in historic times. Therefore, current extinction levels have not yet approached Big Five mass extinction levels, which are characterized by an estimated 75–96% loss of known species (Barnosky *et al.* 2011). Neither are present levels yet at the magnitude of the Late Quaternary Megafauna Extinction, which took place near the Pleistocene–Holocene transition and resulted in the loss of about 50% of the large-bodied mammals in the world, or 4% of all mammal species (Barnosky 2008). Thus, there is presently no justification for associating a mass extinction horizon with the Anthropocene.

However, avoiding introducing a mass extinction biohorizon in the foreseeable future will require enhancing and accelerating biodiversity conservation measures. If currently elevated extinction rates continue, the sixth mass extinction (75% species loss) would occur within three to five centuries (Barnosky *et al.* 2011). Even sooner than that, it is likely that without enhanced conservation effectiveness, an extinction threshold exceeding the late Quaternary Megafaunal Extinction would occur, given that currently 22% of mammals, 14% of birds, more than 30% of amphibians, and 29% of evaluated reptiles are threatened with extinction according to IUCN criteria.

Boundary layers

The bolide impact that contributed to the K–T mass extinction resulted in a so-called boundary clay (Alvarez *et al.* 1980; Schulte *et al.* 2010). This thin geological marker, which usually contains an iridium spike and other distinctive features, is recognizable in geological sections in many parts of the world, and is a key feature in defining the end of the Mesozoic and beginning of the overlying epoch, period and era (Vandenberghe *et al.* 2012). Even more widespread are the trace fossils of humans, in the form of roads, cities, open pit mines, dams and levees. The network of roads alone now extends through more than two-thirds of Earth's ice-free land surface (Gloabaia 2011). The paved portion of this network, comprising a crushed rock and gravel foundation, cement and asphalt, will certainly be preserved in the geological record worldwide. Other trace fossils that will stand the test of time include buildings, the steel bars used to reinforce concrete (rebar), and the myriad metal and plastic items discarded in refuse dumps associated with every human settlement. The net effect of these trace fossils will be to produce a boundary layer that is more widespread than the iridium-rich clay used to recognize the K–T boundary.

Placement of the Holocene–Anthropocene boundary

Most discussions on the placement of a potential Holocene–Anthropocene boundary advocate beginning the Anthropocene near the year 1800 or the year 1950 (Crutzen 2002*a, b, c*; Crutzen & Steffen 2003; Crutzen & Ramanathan 2007; Steffen *et al.* 2007, 2011*a, b*; Zalasiewicz *et al.* 2008, 2011*a, b*). The former would reflect the acceleration of the Industrial Revolution, the latter the dramatic increase in human impacts worldwide that occurred with globalization and human population growth following World War II. The approach of selecting a calendar year at which to place the Holocene–Anthropocene boundary differs conceptually from dating the boundaries between most other epochs, and indeed between most divisions of geological time (notable exceptions being some divisions of the Precambrian that have numerical definitions). For pre-Anthropocene epochs of the Cenozoic, the geological and palaeontological breaks were first noted to identify where in the rock record the boundaries occurred, then geological-dating techniques were applied to estimate the age of the boundary. Those age estimates were used to define the limits of the corresponding geochronological units. Further refinement of age estimates and precise definition of boundaries came after seeking and deciding upon the most continuous, best stratigraphic section to use for the Global Boundary Stratotype and Point. Because no geological dating technique can pinpoint an exact number-of-years-before-present, the dates for all epoch boundaries are in fact approximations, each with their own error bar, rather than precise points in time. Similar principles can be applied to define the Holocene–Anthropocene boundary, and in fact are necessary if the Anthropocene is to be equivalent in status to other epochs, even though it is possible to tie the Holocene–Anthropocene boundary to a precise age because the boundary would fall within historic time.

A separate problem is designating a physical representation of the geochronological boundary that is temporally equivalent throughout the world. This point is particularly relevant in thinking about the utility of biostratigraphy in the Anthropocene compared to older boundaries. In cases where biostratigraphic zones form the basis for recognizing a geochronological boundary, the physical manifestation (where the fossils occur in the rocks) of the boundary is in theory always time-transgressive to some extent, because a new taxon always has to have a single place of origin, and then spreads out from there. Even though, by definition, biostratigraphically useful taxa are those that are common and spread rapidly, that spread can take centuries

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to millennia or longer – instantaneous in geological time, but long with respect to pinning a boundary to a given year. Furthermore, even though the goal of a biostratigraphic zone is in many cases to pinpoint the ‘first’ or ‘last’ occurrence of a taxon, in reality this is probably never achieved, because the fossil record is far from complete (Signor & Lipps 1982; Wang & Marshall 1994; Marshall 2010). Most taxa are characterized by very low abundance (i.e. few individuals of that taxon exist, and usually in a restricted geographic area) for a period of time after they make their first evolutionary appearance. They may then increase in abundance and geographic range until they are prolific and widespread (Vrba & DeGusta 2004). Usually prior to extinction, both abundance and geographic range decline over some period of time until eventually the last individual dies. Because individuals are so rare and geographically restricted in the earliest and latest parts of their evolutionary history, the chances of fossilization then are extremely small. Therefore, the ‘first’ and ‘last’ occurrences of biostratigraphically useful taxa in practice most likely record the first and last times a taxon occurred with enough abundance in a given area to be incorporated into the fossil record (Fig. 8). It is in this sense that ‘first’ and ‘last’ appearances are so useful in characterizing GSSPs.

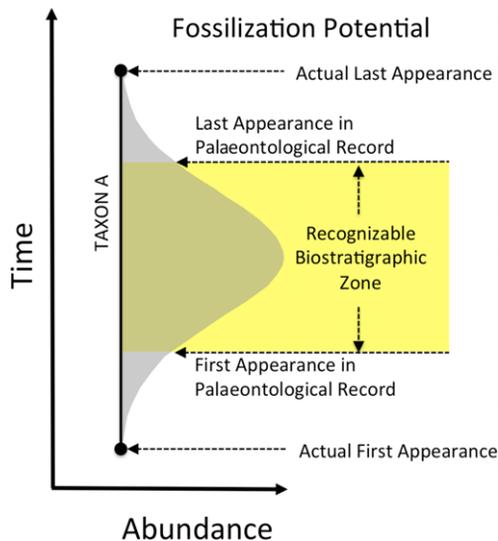


Fig. 8. Biostratigraphic zones typically define the time a taxon or taxa occur in high enough abundance to become a common part of the fossil record, rather than representing the actual first or last occurrences. This consideration is relevant to deciding where to place the boundary for the Anthropocene – the biostratigraphic signal should be obvious and widespread.

Applying these principles and considerations to defining the Holocene–Anthropocene boundary suggests the most robust palaeontologically based boundary would fall closer to 1950 than to 1800. The most useful and easily recognized biostratigraphic zones would be assemblage and abundance zones based on mixes of introduced and native species. The introduction of non-native species began centuries before 1800 in many of the world’s ecosystems coincident with early ship-based exploration, but there is no definitive cluster of introductions that would distinguish the 1800s from the few preceding centuries. However, intensified shipping traffic and air travel beginning in the mid-twentieth century correspondingly accelerated the number of introduced species, causing a relatively sudden jump (over a few decades) in both the percentages of introduced v. native species, and in the abundance of individuals of introduced species. These intensified introductions started around 1940, and accelerated through the latter half of the century. Taking into account that the physical manifestation of a biostratigraphic boundary is likely to vary slightly in age from geographic region to geographic region for the reasons given above, and that the ‘first’ fossil records of taxa typically record the time a taxon’s abundance grew to critical levels, it is likely that 1950 would closely approximate the time at which mixes of native and non-native species became widespread in the sedimentary record.

Likewise, the most viable biohorizons that can be used to define Anthropocene interval zones – based on correlation of several regional extinctions, or on widespread distribution microplastic trace fossils – also date to the twentieth century. Finally, the trace-fossil boundary layer that was emplaced with the development of the worldwide paved road system was deposited during the mid-twentieth century, and most of it after automobiles became dramatically more abundant after 1950.

For lineage zones, a case might be made for placing the boundary nearer to 1800, from recognizing a Dent-Corn (Maize) Lineage Zone, which would begin in 1847. However, other significant dates in maize evolution include 1920–1930, when strains that produced larger cobs were developed, near 1950, with mutations that produced supersweet corn, and in 1998, when genetically engineered strains were first marketed and became widespread. Other crop plants would feature more change after the Green Revolution intensified around 1960 than before that time.

Conclusions

All previously defined geological epochs either incorporate palaeontological criteria into their

definition, or are characterized by distinctive aspects of the palaeontological record. Therefore, for the Anthropocene to be equivalent in rank, it too should be definable and characterizable by its palaeontological signature. The same principles of biostratigraphic zonation can be applied to the Anthropocene as have been applied for earlier epochs. The most useful Anthropocene zones will probably be assemblage and abundance zones based on mixes of native and non-native species. These may be especially useful in near-shore marine environments, in as much as marine fossils have been so critical in defining and characterizing other epochs. Other useful biohorizons that could clearly demarcate the lower boundary of Anthropocene interval zones can be based on the first occurrence of various kinds of human-produced trace fossils, especially microplastics, which have become widespread in marine sediments worldwide. The boundary layer now in place from the world's paved road system is more extensive than the boundary clay produced by the K–T asteroid strike and will form a lasting marker in the geological record. All of these biostratigraphic criteria are most compatible with placing the beginning of the Anthropocene near 1950. It is also possible to recognize lineage zones based on crop plants, which might provide weak justification for placing the Anthropocene boundary somewhat earlier.

An Anthropocene extinction biohorizon may emerge from the composite record of at least 500 extinctions that are known to have occurred in the twentieth century, but given the kinds of species involved and their geographic distributions and fossil record, it is not clear that there would be a lasting palaeontological signature of their disappearance. Current extinction rates are elevated far above background and would result in an extinction biohorizon equivalent to those that characterize the Big Five mass extinctions within a few centuries, should those rates not be slowed. Therefore, intensive biodiversity conservation efforts will be required to ensure that an obvious mass extinction signal does not eventually characterize the Anthropocene, even though such a biohorizon is not yet evident.

A remaining challenge for palaeontologists is to document the nascent palaeontological evidence that has accumulated in the sedimentary record of the past few hundred years in order to develop a biostratigraphic zonation capable of rigorously characterizing the Anthropocene. This is essential not only to define the Anthropocene in a way that is parallel to other epoch definitions, but, even more importantly, to understand the extent to which humans have restructured the biosphere since they became the dominant species on Earth.

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