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Abstract: The Anthropocene deposits of the UK, here regarded as those formed after ~1950 CE, are now extensive, take various forms, and may be characterized and recognized by a number of stratigraphic signals, such as artificial radionuclides, pesticide residues, microplastics, enhanced fly ash levels, concrete fragments and a novel variety of 'technofossils' and neobiotic species. They include the uppermost parts of both 'natural' deposits such as the sediment layers formed in lakes and estuaries, and more directly human-made or human-influenced ones such as landfill deposits and the 'artificial ground' beneath urban areas and around major constructions. 'Negative deposits' include the worked areas of quarries and regions such as the Fenland, where thick peat deposits have ablated to leave a strongly modified underlying landscape, and extend beneath into the subterranean realm as mine workings and boreholes. The production of these deposits is still rapidly increasing and evolving in character, while the early signs of global change, such as warming, sea level rise and modifications to biotic assemblages, are beginning to further modify the emerging geology of this new phase of Earth history.

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25 January 2017

Dear Dr Woods

Please find attached, our submission to the special issue on the Geology of England.

‘The stratigraphical signature of the Anthropocene of the UK’

Our paper deals with the geology of England, Scotland and Wales, and we realise we have transgressed the geographical boundaries of the special issue. However, in the case of the Anthropocene, it really is impossible to distinguish such boundaries within the UK. We hope that our manuscript will be a suitable contribution to the volume.

Yours sincerely

Mark Williams, for the authors

The stratigraphical signature of the Anthropocene of the UK

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ABSTRACT

The Anthropocene deposits of the UK, here regarded as those formed after ~1950 CE, are now extensive, take various forms, and may be characterized and recognized by a number of stratigraphic signals, such as artificial radionuclides, pesticide residues, microplastics, enhanced fly ash levels, concrete fragments and a novel variety of 'technofossils' and neobiotic species. They include the uppermost parts of both 'natural' deposits such as the sediment layers formed in lakes and estuaries, and more directly human-made or human-influenced ones such as landfill deposits and the 'artificial ground' beneath urban areas and around major constructions. 'Negative deposits' include the worked areas of quarries and regions such as the Fenland, where thick peat deposits have ablated to leave a strongly modified underlying landscape, and extend beneath into the subterranean realm as mine workings and boreholes. The production of these deposits is still rapidly increasing and evolving in character, while the early signs of global change, such as warming, sea level rise and modifications to biotic assemblages, are beginning to further modify the emerging geology of this new phase of Earth history.

Keywords: Anthropocene, stratigraphy, neobiota, technofossils, anthroturbation

1. Introduction

The Anthropocene is a term improvised by the atmospheric chemist Paul Crutzen and the limnologist Eugene Stoermer (2000; also Crutzen, 2002) and introduced as a widely used term through Crutzen's deep involvement in the

Earth Systems science community, where the term soon was widely adopted (e.g. Steffen et al., 2004). The geological community first took interest when the term, while still informal and having gone through none of the usual stratigraphical validation, appeared widely in publications as a geological time unit, usually without qualification as to its informal nature. Initial assessment by the Stratigraphy Commission of the Geological Society of London suggested that the term 'had merit' as a geological time unit (Zalasiewicz et al., 2008) and this led to invitation by the Subcommission on Quaternary Stratigraphy to constitute a Working Group on the 'Anthropocene', more commonly known as the Anthropocene Working Group (AWG). The group has been active since then in exploring the stratigraphic character and potential definition of the Anthropocene (e.g. Williams et al., 2011; Waters et al., 2014, 2016).

The Anthropocene, as emerging from these studies, does not primarily reflect local to regional human impact as regards changes to patterns of terrestrial biology, sedimentation, chemical character and so on (that is, it is not a synonym for 'significantly anthropogenic'), though of course such patterns are considered in its definition. It rather reflects substantial change to the Earth System in key parameters such the carbon, phosphorus and nitrogen cycles, in overall rates of erosion and sedimentation, in biospheric changes and so on - as initially recognized by Paul Crutzen and his colleagues. These forms of change have a distinct stratigraphic expression via an array of patterns of proxy signals (summarized in Waters et al., 2016) that include:

- marked changes to CO_2 and methane atmospheric concentrations (preserved in polar ice layers);
- concomitant changes to patterns of carbon isotopes (specifically, a marked $\delta^{13}C$ anomaly via the Suess effect) and fly ash contents within sediments;
- changes to nitrogen isotope patterns from massive increase in fertilizer use;
- the dissemination of novel 'minerals' such as plastics and novel 'rocks' such as concrete within recent sediments;
- marked changes in the rate and character of sedimentation and erosion;

- marked changes to the ‘neopalaeontological’ signal within recent sediments, from a combination of species introductions, assemblage modifications (especially through farming) and extinctions;
- incorporation of radionuclides scattered worldwide from atomic bomb tests.

Although some of these changes have been emerging over thousands of years, and spreading gradually and diachronously across the world, others are of much more recent origin, dating back to the Industrial Revolution or to the ‘Great Acceleration’ of human population growth, economic development and energy use in the mid-20th century (Steffen et al., 2007, 2015). While early studies suggested the beginning of the Industrial Revolution as marking the beginning of the Anthropocene (Crutzen, 2002; Zalasiewicz et al., 2008), subsequent analysis shows that a greater array of correlatable stratigraphic signals is associated with the mid-20th century event, and that that level would make a more effective chronostratigraphic boundary for general geological use (Waters et al., 2014; Zalasiewicz et al., 2015).

As regards the scale of the Anthropocene, and hence its potential position within the hierarchy of geological time, the assessment of Waters et al. (2016) suggested that the scale of change overall was at least as great as that associated with the Pleistocene-Holocene transition, and significantly greater than the changes linked with the proposed subdivision of the Holocene into ages/stages (Walker et al., 2012). Hence – and giving effective geological validation of Crutzen’s *de facto* hypothesis (2002) that conditions of the Holocene have terminated, the Anthropocene is currently being investigated as a potential new epoch (and, chronostratigraphically, a series) of the Quaternary. If such a proposal (currently being formulated) is eventually accepted by the International Commission on Stratigraphy and ratified, that would mean that the Holocene would have terminated, and that a new epoch (still within the Quaternary Period, and the Cenozoic Era) would have begun.

Until then, we continue to live, formally, within the Holocene Epoch, and the Anthropocene remains an informal unit. However, one of the long-term tests of the Anthropocene will be to examine how well it functions in practice as a unit of the International Chronostratigraphic Chart (that is, the Geological Time Scale of general use). The UK, because of its diverse geological construction, its fundamental role in the early inception of geological study, its long history of human occupation and modification of the landscape, and notable instigator of the Industrial Revolution that may be considered to have set in train the process of global transformation, provides a good opportunity for such practical examination. This paper provides an initial sketch of how the Anthropocene might be recognized within British geology.

2. How may one define UK Anthropocene deposits?

The question of distinguishing Anthropocene geological strata from Anthropocene geology-related phenomena arises here. For instance, much of the UK's housing stock, its roads, railways and airports (and the cars, trains and airplanes that use them), its farm soils - and, indeed, its natural soils – are made largely from geological materials, which have been put together within Anthropocene time, as that time is interpreted here, commencing in ~1950 CE (see Waters et al., 2016).

These materials and objects are not normally interpreted as geological strata or elements within them, even though they are largely derived from rocks and will ultimately (probably within decades or centuries) go back to become components of future strata. Hence, one might consider that they are already within a human-modified sedimentary cycle of the Anthropocene, and also part of the technosphere (*sensu* Haff, 2014), which has a material bulk that may now be considered on a global scale (Zalasiewicz et al., 2016 online). However, they do not fall within the currently accepted norms of geology, and so we will not consider them further in this account, except as elements within, or affecting, more typically understood 'strata'.

What kinds of Anthropocene strata are there? One might firstly consider those strata forming by more or less natural processes, within lake, river and coastal systems, distinguished by stratigraphic markers characteristic of the Anthropocene. Secondly, there are deposits that have been created largely or wholly by human activities since the mid-20th century, and here a major question is how these may be distinguished from anthropogenic deposits formed in earlier times. And thirdly, there are subterranean structures, created within rock and sediment layers, and modifications of rock of various sorts, largely not stratiform, and frequently with crosscutting relationships. While there are gradations between all these three categories, they represent a preliminary model (cf. Zalasiewicz et al., 2014) by which Anthropocene strata may be illustrated.

3. Lacustrine and fluvial sediments

3.1 Lakes

Lacustrine strata are good archives of Anthropocene history. This is partly because they tend to form simply organized strata with little disturbance where superposition dominates, commonly in the form of seasonal varves and where disruptive bioturbation tends to be less pervasive than it commonly is in marine deposits; and partly because lakes are repositories for a variety of environmental signals, both natural and anthropogenic. These signals might be swept in by rivers or blown in by the wind, to be directly deposited within the strata or to affect the lake biota, which may in turn be preserved as a biotic signal in the lake floor sediments.

There have been few studies of UK lacustrine or related deposits that have been directly carried out to establish a putative Holocene-Anthropocene boundary. However, one such study has been carried out in related peat bog deposits of Malham Tarn Moss, in Yorkshire (Swindles et al., 2015: Fig. 1 herein). Here, the primary indicator used was a sharp increase in fly ash particles, from increased hydrocarbon burning associated with the 'Great Acceleration', while this pattern was mirrored also by other indicators such as greatly elevated atmospheric deposition of lead and increased iron concentrations and loss-on-ignition as a consequence of greater soil erosion in response to changes in agricultural practices.

The general consistency of this pattern was illustrated by Rose (2015, figs. 2, 3), who showed summaries of 14 logs of fly ash concentrations, mainly from lakes, in the British Isles and Ireland (part of a suite of 71 such logs depicted worldwide). In each case the signal showed that at the mid-20th century there was either an appearance, or a sharp increase, of fly ash in sediments.

These records, calibrated by ^{210}Pb dating, show that fly ash is a useful indicator of the Anthropocene, and indeed they were proposed as a primary marker for a potential Anthropocene Global boundary Stratotype and Point (GSSP, or 'golden spike') by Rose (2015).

Other indicators may be used, too. Muir and Rose (2007) investigated novel persistent organic pollutants (mainly pesticides and their breakdown products) in the sediments of Lochnagar, Scotland. In their sharp increase, mainly within a decade of 1950, they also appear to be capable of characterizing Anthropocene strata in such settings. A similar function may be served by artificial radionuclides from the atmospheric nuclear bomb tests that began to form a detectable global signal ~1954 CE (Waters et al., 2014; Arienzo et al., 2016). The Chernobyl nuclear power station accident on 26th April 1986 produced hemispheric fallout, which accumulated most notably in Scotland, northern England and North Wales, initially in vegetation and soils, ultimately accumulating in lakes.

Biotic changes to lakes in the UK have been driven by multiple factors, including increased agricultural activities, industrialization, air pollution, acidification and eutrophication (Wilkinson et al., 2014). Phosphorus pollution, for example, is the result of wastewaters and detergents, and its increased concentration in Lake Windermere, Cumbria, has, for example, been shown to be related to the expansion of tourism during the 1960s and the increased requirement for sewage treatment (Talling and Heaney, 1988).

The influence of recent eutrophication on the diatom populations of the Lake of Menteith, Scotland, was discussed by Battarbee et al. (2012) and preserves a potential biostratigraphical signature of the Anthropocene. In *ca* 1920 a stable diatom community with inferred Total Phosphorus of *ca* 10 µg l–1 changed with the introduction of a number of planktonic diatoms, including *Stephanodiscus hantzschii*, indicators of high nutrient concentrations. These authors noted that the diatom-inferred Total Phosphorus values increased gradually between 1920 and the mid-1960s but more rapidly after *ca* 1965 to double the pre-1920 levels. After about 1980, algal blooms occurred more frequently, the plankton diatom community was dominant and the proportion of low-nutrient species collapsed. Eutrophication appears to have been the result of a number of causes including agricultural activities, afforestation, increased inputs of sewage and phosphate detergents and, more recently, fish farming.

Most lakes have pH values between about 5.5 and 8.5 depending on the geochemistry of rocks and soils in the catchment area. However, acidity may vary both naturally (e.g. seasonally) and anthropogenetically. For example, during the first half of the 19th century, the diatom assemblage of the Round Loch of Glenhead, Scotland, supported a circum-neutral water diatom community, including *Brachysira vitrea* (Flower and Battarbee, 1983; Battarbee et al., 2005). During the second half of the 19th century this community began to decline to be replaced by more acidophilous species so that by the early 1980s the diatom population was dominated only by acid-tolerant taxa such as *Tabellaria quadriseptata* and *T. binalis*. During that time, pH had fallen from *ca* 5.5 in 1850 to 4.7 by 1980. Land use in the moorland catchment area had not changed during that time, but the lake sediment contained high concentrations of spheroidal carbonaceous particles, suggesting that the acidity change was the result of anthropogenically induced acid rain.

Battarbee et al. (2011) defined the characteristic reference diatom assemblages for low alkalinity lakes across the UK using samples dating to before 1850 AD to represent pre-acidification conditions. Three statistical clusters were identified. Cluster 1 is characterised by benthonic taxa such as *Brachysira vitrea*, *Cymbella microcephala* and *Fragilaria* spp., and includes sites that contain diatoms with relatively high pH optima (pH 6.4–7.4) such as Llyn Irddyn, Loch nan Eun, Lough Maumwee, Loch Uisge and Loch Corrie nan Arr, located in regions of low acid deposition in Ireland and North-west Scotland. Cluster 2 is dominated by planktonic taxa such as *Cyclotella comensis*, *C. radiosa*, *Asterionella formosa* and *Aulacoseira subarctica* and non-planktonic *Achnanthes minutissima,* and represents the most alkaline pre-acidification conditions. Although this is the smallest cluster in terms of locality sites, it includes the larger, deeper lakes such as Loch Lomond, Wastwater, and Lake Bala, which have low alkalinity water although located in areas of historically high acid deposition. Cluster 3 is characterised by the benthonic taxa *Eunotia incisa*, *Frustulia rhomboides* var. *saxonica*, *Fragilaria virescens* var. *exigua*, *Brachysira brebissonii*, *Tabellaria quadriseptata* and *Cymbella perpusilla*, diatoms that are characteristic of more acidic waters (pH optima from 4.9 to 6.4), such as those of Loch Enoch and Loch Narroch. The establishment of a reference assemblage for low alkalinity lakes is useful in monitoring recovery – which may in itself record a biostratigraphical signal - following recent acidification events (Battarbee et al., 2011).

3.2 Rivers

River deposits are more complex to study, partly because natural sediment body geometries are often strongly influenced by lateral accretion processes, and partly because many rivers are now controlled via artificial levees and embankments and dredging of channels (itself, though, a feature typical of the Anthropocene, though developing over a long period from pre-classical times, Williams et al., 2015). A clear lithological transition typical of many river systems in the UK from basal gravels with organic channel fills to an overlying capping of sandy silts is markedly time-transgressive over at least 2300 years between catchments and is interpreted as a response to introduction of intensive arable agriculture (Brown et al., 2013). This diachroneity makes this transition an unsuitable marker for the Anthropocene. Recognition of sediments associated with a mid-20th century onset for the Anthropocene may be difficult in many fluvial systems, relying mainly upon the identification of novel materials. Plastics, one of the more recognizable novel materials of the Anthropocene, tend to be buoyant and be transferred through the river system out into the sea and, where accumulating in river bedload, plastic granules can be readily abraded (Zalasiewicz et al., 2016).

However, where rivers meet the sea, superpositional relationships may be established, so that deposits since the mid-20th century can be recognized using criteria like those described above for lakes. In the Clyde estuary, increasing industrialization gave rise to elevated levels of anthropogenic organic chemicals, such as petroleum hydrocarbons (TPHs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and brominated flame retardants (polybrominated diphenyl ethers, PBDEs) (Vane et al., 2011). Peak PAH concentrations in 1915 coincide with greatest coal usage in the estuary catchment, with petroleum contamination dominating from about the 1950s, coinciding with the onset of PCB elevated values (Vane et al., 2011). $^{207/206}$Pb isotope ratios show an increase in the same estuarine sediments through the introduction of overseas Pb, used both in industry and as an additive in petrol, from 1920 (Vane et al., 2011).

3.3 Neobiotic species in lakes, rivers, and the land

3.3.1 Animal neobiota

There is potential to use recently introduced neobiotic species that might leave a fossil record in aquatic sedimentary deposits, such as the zebra mussel *Dreissena polymorpha*, which now locally dominates mollusc assemblages in the River Thames (Fig. 2). This bivalve, of Ponto-Caspian origin, was first discovered in the UK at Rotherhithe Docks (River Thames) in 1824 and has since become widely established across England and parts of Wales, Scotland and Northern Ireland (Aldridge et al., 2004). It displaces indigenous mollusc species, particularly native unionid mussels such as the endangered depressed river mussel (*Pseudanodonta complanata*), by smothering their shells and interfering with feeding, respiration and movement (Sousa et al., 2011). Since both invader and displaced species are shell bearers, there is a strong possibility that these molluscs will leave a biostratigraphical marker of the Anthropocene, not least because zebra mussels can occur in densities of 11,000 individuals per m^2 (Aldridge et al., 2004).

In North America and Western Europe, a more recent invasion by the quagga mussel (*Dreissena rostriformis bugensis*) has seen widespread replacement of zebra mussels by this competitively superior congener (Wilson et al., 2006; Van der Velde et al., 2010). Quagga mussels were first discovered in the UK in 2014 (Aldridge et al., 2014) and have already established widely in the lower Thames and Lea catchments. Quagga mussels can displace zebra mussels at a rate of 36% per year (Heiler et al., 2012), suggesting that such species replacement may produce a pronounced biostratigraphical marker in the future.

Many other neobiotic species in rivers and lakes may be used in this way, including decapod crustaceans such as the American signal crayfish (*Pacifastacus leniusculus*) and the Chinese mitten crab (*Eriochier sinensis*), which could potentially leave a fossil record in their arthropod exoskeleton. The UK has no native decapods in freshwater, although seven neobiotic species have now established (Keller et al., 2009). The dates of introduction of decapods into the UK is relatively well known, beginning with the European white clawed crayfish, (*Austropotamobius pallipes*) in the 15th century, the mitten crab in 1935 and the signal crayfish in 1976, suggesting that the presence of these different species may provide useful biostratigraphical markers.

The UK's freshwaters are currently experiencing a dramatic increase in the establishment of invasive neobiota from the Ponto-Caspian region of Eastern Europe (Gallardo and Aldridge, 2013), including many crustaceans such as killer shrimps (*Dikerogammarus villosus*) and demon shrimps (*Dikerogammarus haemobaphes*). Ponto-Caspian biota often display facilitative interactions resulting in 'invasional meltdown' (Gallardo and Aldridge, 2015), and so particular community assemblages of neobiota may provide additional Anthropocene markers.

Invasive neobiota may not only leave a biostratigraphic marker from their shells and exoskeletons. Many invaders are important ecosystem engineers, driving marked changes to the physical environment and resulting in pronounced changes to associated biota. Invasive bivalves can increase sedimentation rates and bioturbate the benthos (Sousa et al., 2009), while crayfish and mitten crabs can form extensive networks of burrows in riverbanks that might form a trace fossil record of their presence.

3.3.2 Floral neobiota

Mainland Britain has only 35 native tree species, and there have been extensive introductions of plant neobiota in three main phases (Peterken, 2001) that might demarcate biostratigraphical signatures from their pollen and spores: (i) prehistoric and Roman times associated with the arrival of European deciduous trees; (ii) the 16th to 19th century, when a very wide range of species were brought in from across the British Empire, especially from North America and Eurasia; and (iii) the 20th century, with massive importation of conifers from the Pacific Northwest of North America. The more recent introductions are mainly located in gardens, arboreta, ornamental parks and urban streets (Peterken, 2001). In addition there has been large-scale translocation of species within

Britain to areas where they were not native (Peterken, 2001). The large-scale transformation of ancient semi-natural woods into plantations has occurred mainly since 1950 (Spencer and Kirby, 1992). Since 1895, the forest cover of Britain has increased from 4.5% to 11% of the land area, mainly through planting conifers on soils of low agricultural value, and by about 1960 conifer forests became dominant with *Picea sitchenensis* (the Sitka Spruce) – native to northern California to southern Alaska - becoming Britain's commonest tree species (Peterken, 2001). Development of the coniferous plantations can also reduce the diversity and biomass of ground vegetation (Peterken, 2001).

4. Coastal and marine strata

Coastal strata, whether wave-dominated (e.g. beaches) or tide-dominated (e.g. tidal estuaries) or sub-tidal deposits of the UK continental shelves, may presumably be distinguishable as Anthropocene, though little work has been done to specifically discriminate such units. An additional characteristic here is the presence of plastic fragments, both macroplastic fragments, and in particular microplastics, such as fibres detached from artificial fabrics (Zalasiewicz et al., 2016) which recently have been recognized to accumulate and concentrate in the marine realm, mostly having been washed in from land. Microplastics are now almost ubiquitous in coastal environments (Thompson et al., 2004) and, since plastics are almost entirely a post-mid-twentieth century phenomenon as a sedimentary component, they are an unambiguous identifier of Anthropocene strata. However, since the manufacture and subsequent environmental dissemination of plastics grew steadily from ~1 mT/pa in ~1950 CE to its present ~300 mT globally/pa now, its pattern of stratigraphic distribution might not be able to precisely identify a Holocene/Anthropocene boundary in continuously accumulated strata, in the way that the sharp onset of artificial radionuclides from nuclear bomb tests, or the stratigraphic patterns of fly ash or some persistent organic pollutants (see above), may be used. Off the coast of Plymouth microplastic fragments and fibres have been found in most samples, being most abundant in sub-tidal deposits, with a marked increase in abundance in the 1980s and 1990s compared with the 1960s (when the earliest plastic fragments were recognized) and 1970s (Thompson et al., 2004).

The NE Atlantic waters around the UK are the most contaminated waters for radionuclides in the world (Aarkrog, 2003). Contributing to this are the radioactive releases into the Irish Sea that peaked in the mid-1970s from Calder Hall, Cumbria, which opened in 1956 as the world's first commercial nuclear power plant, and the subsequent reprocessing plant at Sellafield that recovers U and Pu from spent fuels (Aarkrog, 2003). The Sellafield reprocessing plant caused radioactive discharges of ^{137}Cs, Pu isotopes, ^{241}Am, ^{106}Ru and ^{125}Sb and was a major source of ^{99}Tc and ^{129}I (Aarkrog, 2003). ^{241}Am is rapidly removed from seawater, to migrate laterally via current-driven bed-load transport, to then accumulate in sediments present in the Ravenglass Estuary, also in Cumbria, but some 20 km to the south, after about 2.5 years (Aston and Stanners, 1982).

However, the controlled releases from Sellafield from 1952 to the mid-1980s are only a small, regional component of the total anthropogenic radionuclide budget, the majority of which is sourced from fallout from nuclear weapons testing, mainly in the 1950s and early 1960s (UNSCEAR, 2000; Waters et al., 2015). The commoner radioactive products of these detonations, such as ^{137}Cs and ^{90}Sr are concentrated in the mid-latitudes of the Northern Hemisphere (from 30–60^{o} North), though with a short half-life measured in decades they will not provide a long-lived signal that could represent the Anthropocene. ^{239}Pu, though less abundant in the fallout, has a much longer half-life and should be detectable in sediments for ~100,000 years; it is considered a strong candidate for the primary signal for recognizing the base of the Anthropocene (Waters et al., 2015). Fallout from the Chernobyl accident in 1986 is the third major contributor to the radionuclide content of marine sediments of the UK coast. In contrast, radioactive waste dumping sites, mainly in the NE Atlantic until 1982, have not generated a signal above background values for the areas around these sites (Livingston and Povinec, 2000).

Anthroturbation of sea-bed sediments on the UK continental shelf since the mid-20th century is likely to be extensive, through processes such as trawler fishing, the development of oil and gas exploration and extraction facilities and the working of offshore sand and gravel deposits for aggregates. This widespread disturbance of the upper sedimentary accumulations in UK waters produces a layer mainly developed during the Anthropocene, but the disturbed sediments will also include intermixed older Holocene sediments.

The biotic composition of UK waters have been modified by processes such as warming, overfishing, deliberate introduction of aquaculture, indirect introduction of species (for example in ballast waters), eutrophication from increased influx of nutrients washed offshore either as part of sewage treatment or changed agricultural practices (notably increased use of nitrate fertilisers), and pollution. These changes are expressed in marine sediments as changed biotic assemblages.

Some 90 alien species have been identified in coastal and brackish water settings around the UK (Minchin et al., 2013). The fossilization potential of these organisms in recent sedimentary deposits waits to be assessed. They include, for example, the erect (arboreal) bryozoan *Tricellaria inopinata* – possibly of NE Pacific origin - introduced into European waters in the 1980s, which now has an extensive range from the Mediterranean to the NE Atlantic coastline (Cook et al., 2013), including the UK. Also introduced to UK waters is the barnacle *Balanus amphitrite*. This species may have its origin in the tropical Indian Ocean or Pacific, where it has a fossil record extending back into the Pleistocene or possibly earlier (Cohen, 2005 and references therein). *B. amphitrite* has a very wide geographical distribution from New Zealand to California, and has well documented first occurrences as a neobiotic species, for example on benthic substrates of San Francisco Bay from 1938-9. Its first occurrence in UK waters is documented at about the same time, from Shoreham Harbour, Sussex in 1937 (JNNC, 2016), making it a potentially widespread global marker of human impacts on shallow marine biota in the mid-20th century.

Several species of North American origin are known to have been introduced into the estuaries of southeastern England in association with American oysters: the polychaete worm *Clymenella torquata*, the American slipper limpet *Crepidula fornicata*, the American oyster drill *Urosalpinx cinerea,* the ostracod *Eusarsiella zostericola*, and the American piddock *Petricolaria pholadiformis*. The non-indigenous ostracod *E. zostericola* appeared when the American oyster *Crassostrea virginica* was introduced into the Thames estuary for human consumption and now has a distribution including the Blackwater

Estuary, Essex, and the River Medway, Kent (Kornicker, 1975; Bamber, 1987). Its first appearance into England is unclear, but it was probably during the early to mid- twentieth century. More recently it has spread from southeast England across the North Sea to colonize Oosterschelde, near Zierikzee, The Netherlands (Faasse, 2013).

5. Anthropogenic deposits of the Anthropocene

Humans have significantly modified the terrestrial landscape of the UK for much of the Holocene, by deforestation, farming, the building of settlements, and then towns and cities, leaving significant traces, that can take the form of an archaeological or geological record or both – in the latter for instance modifying the nature of alluvial deposits via the construction of milldams**.** In mainland Britain it is estimated that over 66,530 Mt of sediment has been moved through just the extraction and processing of major mineral resources in around 200 years (Price et al., 2011), although what percentage relates to the Anthropocene is not quantified. In 2014 alone 210 million tonnes of minerals were extracted from onshore UK, with ~84% being construction minerals, ~10% industrial minerals and ~5% coal, with an additional 89.7 million tonnes of oil and gas and aggregates sourced from the UK Continental Shelf http://www.bgs.ac.uk/mineralsUK/statistics/ukStatistics.html. In and around major long-lived settlements, such as formed the nuclei of our present cities, and in long-farmed areas, there is a substantial 'archaeosphere' (Edgeworth et al., 2015) that is a layer of artificially reworked ground, often containing implements and building debris ranging from Stone Age to present-day in age.

Where these artificial deposits are of substantial distribution and thickness, it appears on British Geological Survey maps as various forms of Artificial Ground (Price et al., 2011; Ford et al., 2014). This equals the 'Made Ground' which may include soil and rubble layers from demolished buildings or colliery spoil, 'Landscaped Ground' associated with general urban development, and also the 'Infilled Ground' of backfilled quarries as landfill sites (Fig. 3), and may be subdivided in various ways on lithological and relational characteristics. But it also includes the 'Worked Ground' areas of excavations, such as quarries and road cuts, which are not associated with deposits. It is estimated that 1.4%

of mainland Great Britain is currently covered by significant areas of artificial ground (Price et al., 2011). The deposits of Artificial Ground may attain thickness of 65 m or more in Great Britain (Ford et al., 2014), of thicknesses becoming comparable to those of the natural Holocene deposits despite a duration more than two orders of magnitude shorter.

The sedimentary component of archaeosphere deposits represents a lithostratigraphical unit that regionally is diachronous and ranges across much of the Holocene. Because of the UK's involvement in the development of the Industrial Revolution, beginning in the early 18th century, a significant component of artificial deposits, especially associated with mineral extraction, will pre-date the Anthropocene as discussed here. Within the artificial deposits, though, one may locally separate a post-WWII unit that approximates to an Anthropocene chronostratigraphic unit, on the basis of a range of stratigraphical signals. These signals may include the kind noted above, such as artificial radionuclides and fly ash traces. However, because of the heterogeneous and often coarse and rubbly nature of the deposits, the most effective stratigraphic signals result from a kind of human-related fine-scale biostratigraphy, relating to either materials or artefacts. In the UK, deposits associated with ground engineering are a dominant component of post-1945 developments.

Materials in such settings that have time significance include plastics, as noted above, and also aluminum, which is also effectively a post-WWII phenomenon as a pure and widely used metal. Of major importance is concrete, which, although used since Roman times, saw an acceleration in use as the building material of choice in the UK (and globally) following WWII, in parallel with increased exploitation of the raw materials required for its manufacture, mainly limestone and aggregate (Waters and Zalasiewicz, in press). The presence of these materials in artificial ground, including landfill deposits, may be used to separate Anthropocene from Holocene deposits (e.g. Ford et al., 2014).

Anthropocene deposits that may be discriminated in this way are common, and substantial, not least because of the combination of population growth and the increase in energy use and industrial production after WWII accelerated the rate of production of such deposits. Although little systematic discrimination of this kind has been attempted, given the newness of the

Anthropocene term, and its continuing informal status, an impression of their distribution may be given by, for instance, the wide distribution of post-mid-20th century landfill sites (Fig. 4). These deposits have undergone a marked change in their composition over time. Prior to the Clean Air Act of 1956 most houses were fueled by coal, and so ash and cinders from domestic fires comprised a significant component of landfill in the UK (Ford et al., 2014). Landfills originating during the Anthropocene show a significant reduction in the proportion of ash, but with marked increases in the proportions of paper and card, kitchen and organic wastes, plastic, glass and wood (Fig. 5).

The possibility of fine-scale 'biostratigraphic' subdivision may be carried out on these deposits using artefacts that, often having substantial preservation potential, are referred to as 'technofossils' (Zalasiewicz et al., 2014). There has been an unprecedented, almost explosive diversification of such biologically-made structures (Zalasiewicz et al., 2016 online) and the temporal resolution attainable using such evidence is geologically precise.

6. Subterranean Anthropocene structures

Humans have long dug into the ground, mainly to extract materials of various kinds. Notable examples include the shallow pits to work flint from Chalk deposits at Grime's Grave, near Thetford, from about 3000 BCE and extraction of copper at Parys Mountain, Anglesey at least by 2000 BCE. The resulting pits, quarries and mines are typically localized structures, though more extensive 'landscape removal' sometimes occurs, exemplified by the removal of a layer of peat, originally up to 4 m or more thick, from the surface of some 2000 km^2 of the English Fenland, mainly by drainage and drying of the surface peat for agriculture since the 19th century, the peat subsequently drying, oxidizing and blowing away (Smith et al., 2010). This has revealed a pre-existing landscape surface that now may be more than 2 m below sea level (the sea being held back by a wall and rivers being 'perched' between levees, with water from the surrounding fields continually needing to be pumped into them).

As with most of kinds of activity, excavation underground has intensified since the Industrial Revolution and especially since WWII, to include widespread mines for coal, salt metal ores, oil shale, limestone, building stone, slate, fluorspar, gypsum/anhydrite and potash (see Zalasiewicz et al., 2014). At times, older workings were revitalized, such as Parys Mountain in North Wales, which dominated the global market in the 1780s. The proliferation of underground activity in the UK during the Industrial Revolution was facilitated by the invention of the first practical steam engine by Thomas Newcomen, used to pump water from mine workings in the Black Country near Dudley in 1712. In contrast to many other parts of the world, the extent of subsurface mineral extraction of solid mineral resources (especially coal) has seen a marked decrease during the second half of the 20th century.

During the Anthropocene the main focus of underground activity in the onshore UK is associated with shallow structures, typically to depths <10 m, such as foundations for buildings and tunnels for transport, utility and sewerage distribution networks and shallow excavations for basements. The drilling of boreholes for the exploration and extraction of oil, water and other resources and as part of ground engineering assessment has resulted in over a million notified boreholes in the UK, the vast majority post-dating WWII. As the resulting structures are well below the reach of erosion, these giant-scale 'anthroturbation' structures have excellent long-term preservation potential (Zalasiewicz et al., 2014), although modified in various ways by processes underground such as compaction. Particular forms might be identified as proxies for the processes associated with the Anthropocene, such as the large complex structures of metro systems, which can be considered as trace fossils of human activity (Williams et al., 2014, and in submission).

7. A biostratigraphical signature of extirpation

It may be possible to characterize sedimentary deposits accumulating over the past *circa* 200 years in the UK (Fig. 6a,c), from their record of local species extirpations. The Model of Ecological Degradation was first discussed by Yasuhara et al. (2012) to demonstrate the impact of human activity on marine microbiota, simply by taking published records of anthropologically induced change within the microfossil record and plotting them against time. The model shows that a 'Phase of Inception' (between *ca* 5000 years BP and *ca* 1800 A.D) passes into a 'Phase of Acceleration' during the 20th century (particularly between 1940–1945 A.D.) and culminates in an Apogee (in about 1950-1952). In a few isolated instances during the late 20th and early 21st century, a 'Phase of Recovery' can be recognized, as a result of national and international laws and regulations concerning the environment. This model can be adapted to provide a biostratigraphical definition of the Holocene/Anthropocene transition in both marine and paralic successions. Wilkinson et al. (2014) demonstrated the response of unicellular organisms (diatoms, dinoflagellates, foraminifera) and small metazoans (ostracods) to anthropogenic ecological stress from a range of aquatic ecosystems. They used the data to suggest that the commencement of the Anthropocene was during the early 1940s.

Wilkinson (in press) tested the value of the model for distinguishing the Anthropocene from extirpation of English terrestrial taxa including fungi, plants, birds, mammals, insects, etc., using data published by the Species Recovery Trust (www.speciesrecoverytrust.org.uk/Images/ll/England's lost species.pdf). Of the 421 species that have disappeared from England since 1800, the date of extirpation is known accurately for 333. A plot of this data shows the expected 'Phase of Inception', 'Phase of Acceleration' (which was particularly rapid in the early 1940s), and 'Phase of Recovery' during the last quarter of the 20th century. Wilkinson et al. (2014) concluded that the phase of rapid acceleration during the early 1940s could be adopted as the Holocene/Anthropocene transition. However, an alternative and perhaps better position for the Holocene/Anthropocene transition, is the apogee during the two or three years immediately following 1950 (Fig. 6b). This hypothesis remains to be tested through analysis of which species extirpations will be preserved in the fossil record, though the disappearance of pollen from extirpated plants, for example, might provide a long-term stratigraphical signature.

8. Discussion

It is clear that the deposits of the Anthropocene of the UK, although very young geologically, are extensive, varied, and locally thick – and are still growing and reworking Holocene and older deposits into new patterns. They have been relatively little studied as the geological material evidence of a new epoch (whether or not it ultimately becomes formalized as part of the Geological Time

Scale) – not least because in the ~70 years in which it has been in existence, there has been increasingly detailed human observation, archiving and recording of events and processes both human and geological. Nevertheless, the material record present, in the form we have outlined it here, presents an unrivalled opportunity to place recent human activity not just in the context of earlier human history, but also in the context of the approximately 3 billion year geological history of the UK. This ancient history is known to us through proxy evidence in the rocks, and so the evidence preserved in the strata of the past are a means to make direct links with the Earth's deep history. The UK is an ideal laboratory for the study of this new kind of geology, because of the scale and breadth of past geological activity preserved within its borders, because of its long history of human activity, and also because of its tradition of local geological study (of which the history of the Geologists' Association is a fine example).

There is clearly much to do to continue the rudimentary assessment described here. While parts of the task are relatively straightforward (for instance to make more detailed and wide-ranging analyses of the proxy data available in lacustrine and related deposits), others are more challenging. In urban areas, for instance, Anthropocene deposits are highly diverse and in some ways not immediately accessible – or appealing - as research objects (the strata within landfill deposits, for instance). They possess very considerable geometrical complexity too, commonly exacerbated by their links with underground excavations of various kinds, where relationships go from being (more or less) stratiform to being cross-cutting (Edgeworth et al., 2015). Nevertheless, their study may yield important information on this remarkable recent phase of history, and the forming of cross-disciplinary links with archeologists, historians and others will undoubtedly lead to insights of value to a wider community than just the geological one.

There is a further aspect here. An important 'functional' aspect of the Anthropocene (Waters et al., 2016) is that this time interval is marked by a trajectory of key Earth System parameters, notably by enormous ongoing perturbation of the carbon, nitrogen, phosphorus and other cycles, that is sharply different from that of the Holocene, which was essentially stable in these respects. This perturbation is already beginning to affect other properties of the

Earth System, such as global temperature and sea level, and the changes here seem likely to intensify over coming decades and centuries, meaning that the geology of the UK will continue to change – with, for instance, marine inundation of low-lying areas such as the Fenland, and biotic and other changes driven by increased temperatures and changed precipitation patterns. There are other, less predictable geological changes likely with the continued rapid evolution (in essentially currently unknowable directions) of the technosphere (*sensu* Haff, 2014), through which almost all of human activity, including human geological activity, is now mediated. As the geology of the present UK continues to evolve, then the geology of the future – whatever it might be – looks set to appear even more remarkable, and challenging, to future generations.

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Figures

Fig. 1. Anthropocene strata of Malham Tarn Moss, Yorkshire, can be distinguished from underlying Holocene deposits on the basis of spherical carbonaceous (fly ash) particles (SCPs), lead and iron concentrations. The first occurrence of SCPs in the section is in the 1850s, but there is a marked increase in abundance in the 1950s, with a peak in the 1970s. Atmospheric lead pollution from industrial activity and additives in petrol and increased soil erosion

(reflected in the Fe and loss-on-ignition data) and change in water table show comparable upturns in the mid-20th century. Figure from Swindles et al. (2015).

Fig. 2. The invasive zebra mussel *Dreissena polymorpha,* from the River Thames tideway at Teddington. During managed drawdowns of the tideway the riverbed is exposed, revealing localized shell deposits >1m deep. Scale bar is 10cm.

Fig. 3. View of Tir John Landfill site forming a prominent mound deposited since the 1960s on top of peat deposits of the Crymlyn Bog, near Swansea, Wales. The site shows selective grading of materials and dispersal of materials in different parts of the site at any one time, resulting in non-stratiform deposits. Photo taken in 2005 by Paul Witney. BGS (C) NERC 2005. All rights reserved.

Fig. 4. Distribution and age of landfill sites in part of London. Those identified as dating post-1960 will comprise Anthropocene deposits up to several tens of metres thick, while some of those denoted 1940-1960 may include layers spanning a putative Holocene-Anthropocene boundary (from Zalasiewicz et al., 2016).

Fig. 5. Changes to the composition of household Municipal Solid Waste in Great Britain by weight percentage (modified from Ford et al., 2014). WEEE- Waste Electrical and Electronic Equipment).

Fig. 6. a. Annual extirpation of terrestrial organisms in England since 1800 (of a total of 421 extirpated species, 333 species have accurately known extirpation dates). b. Graphical representation of ecological degradation in England as represented by the number of extirpated species with time generalised on a decadal scale to show that the phase of Inception was followed by a phase of Acceleration culminating in apogee. Based on data from the Species Recovery Trust (www.speciesrecoverytrust.org.uk/Images/ll/England's lost species.pdf).

Figure 1

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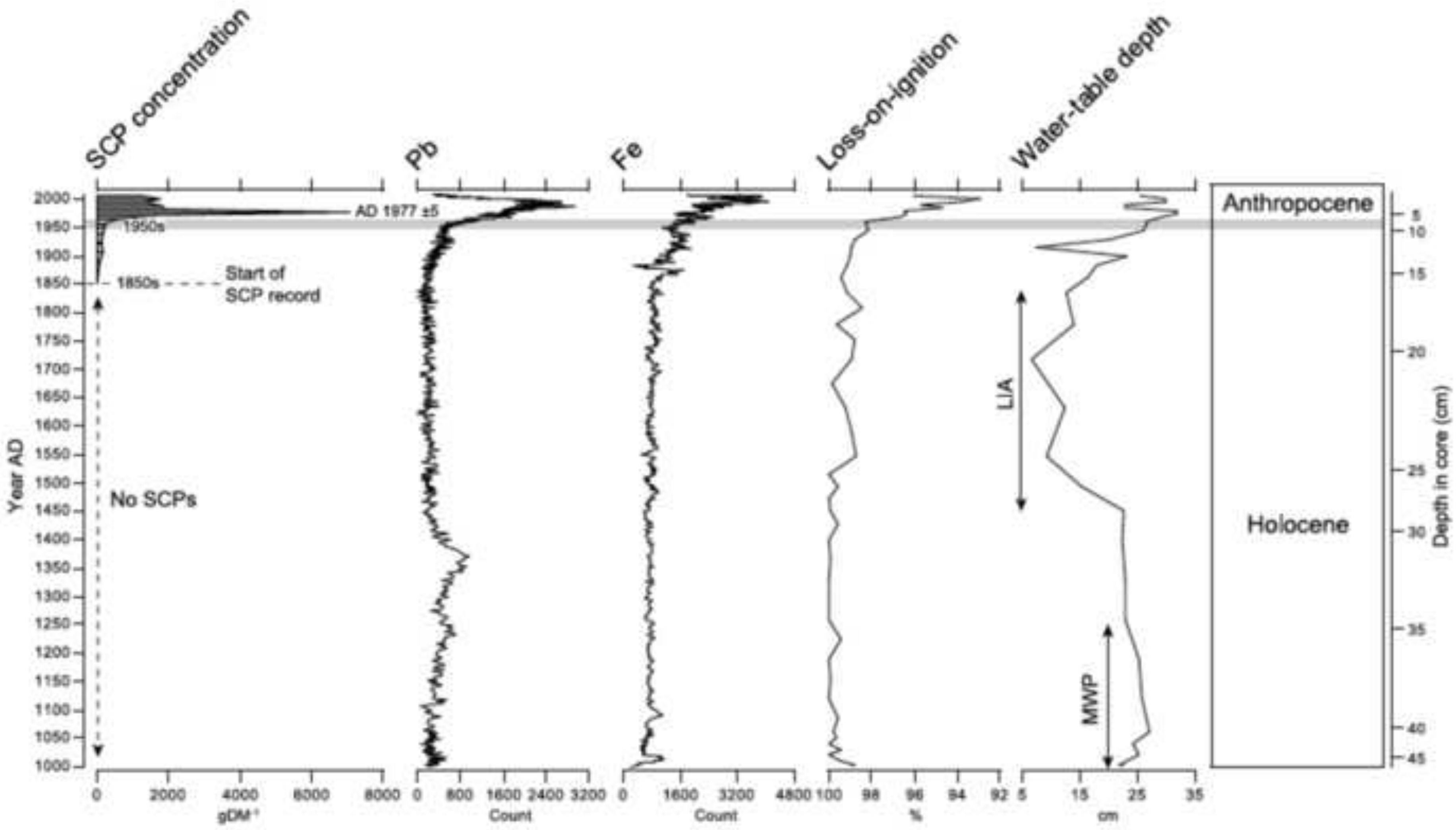

Figure 2

Figure 3

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Figure 4

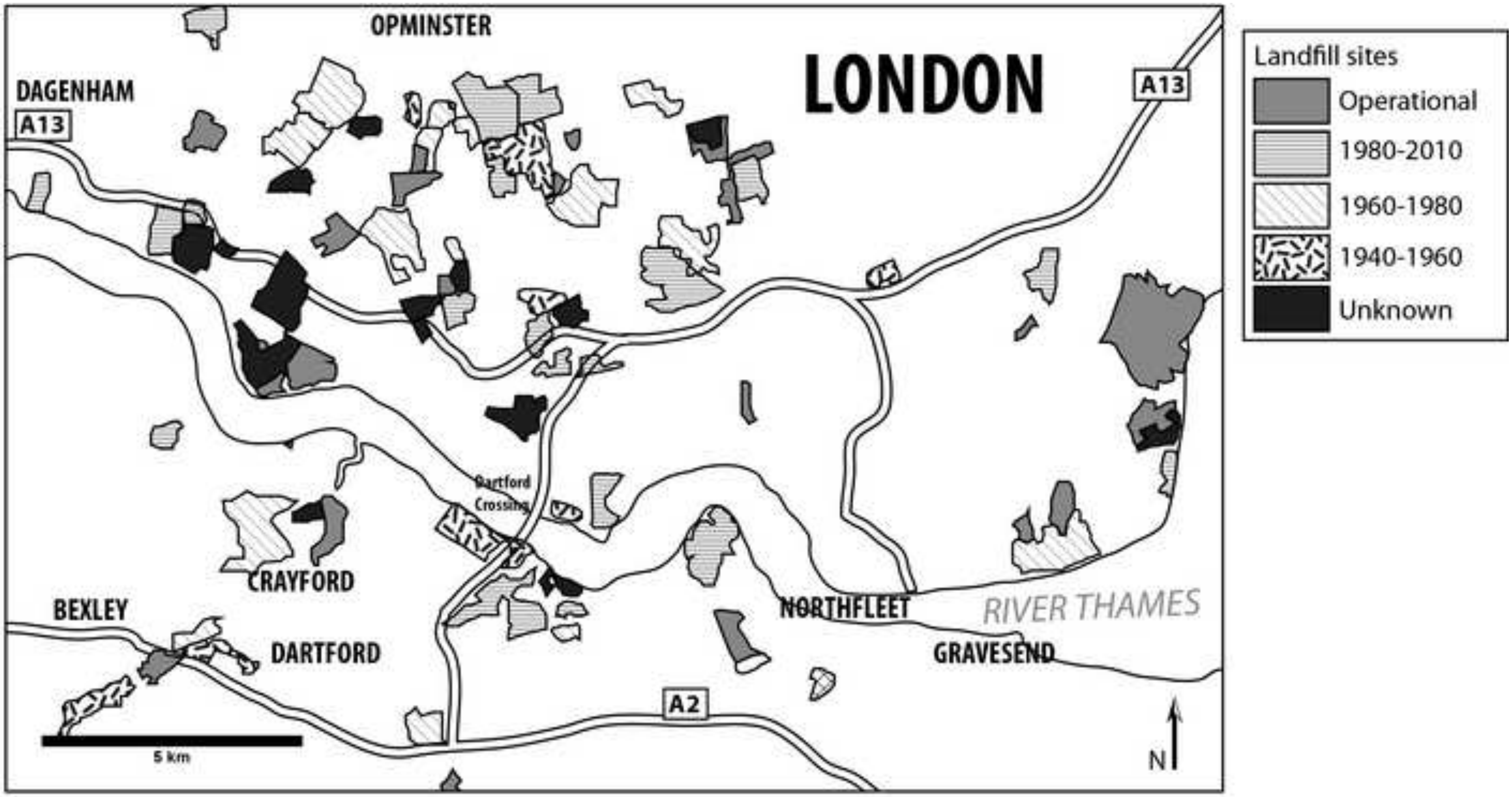
OPMINSTER
LONDON
DAGENHAM
A13
A13
Landfill sites
Operational
1980-2010
1960-1980
1940-1960
Unknown
Dartford Crossing
CRAYFORD
BEXLEY
DARTFORD
NORTHFLEET
RIVER THAMES
GRAVESEND
A2
5 km
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Figure 5

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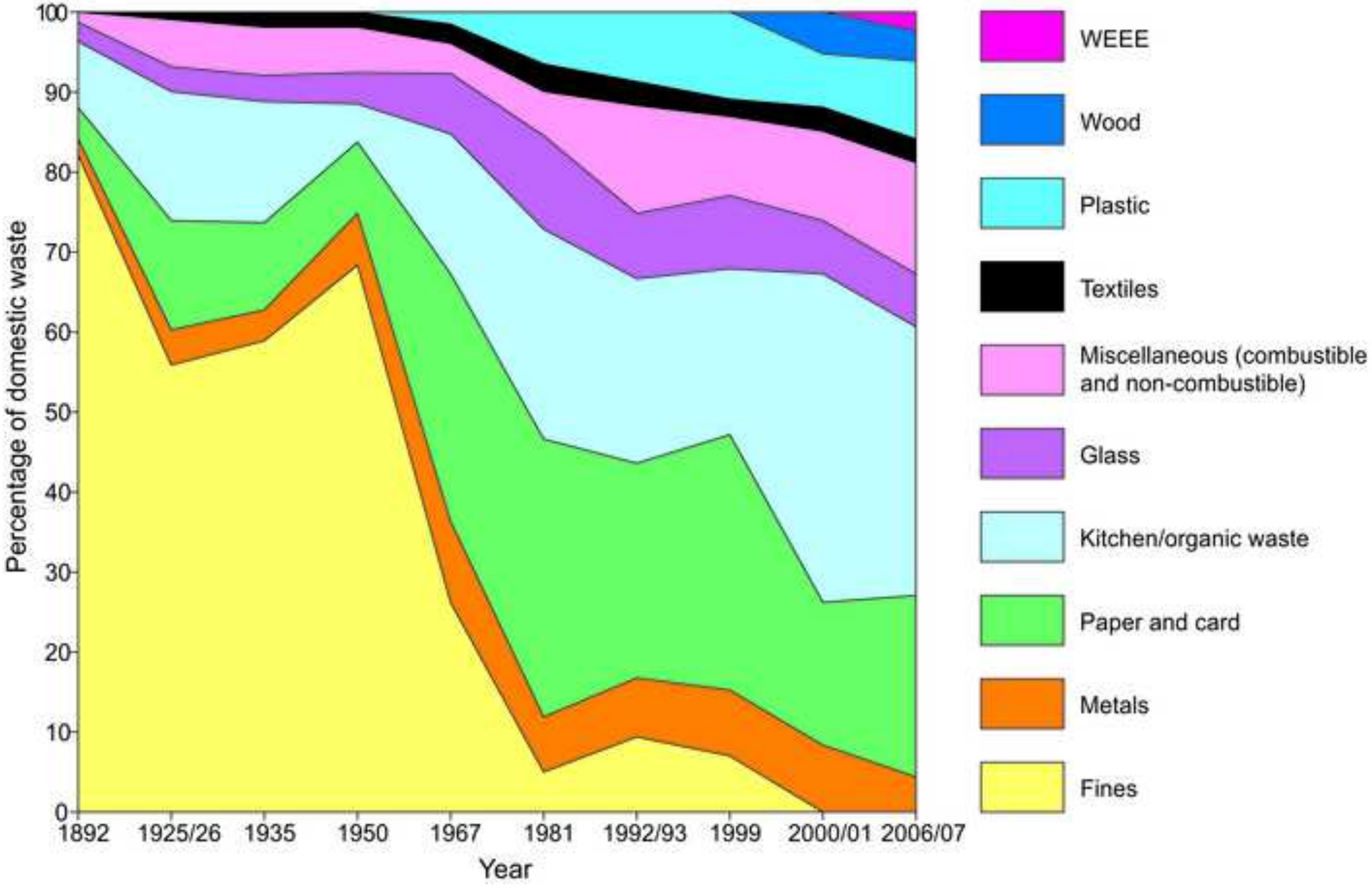
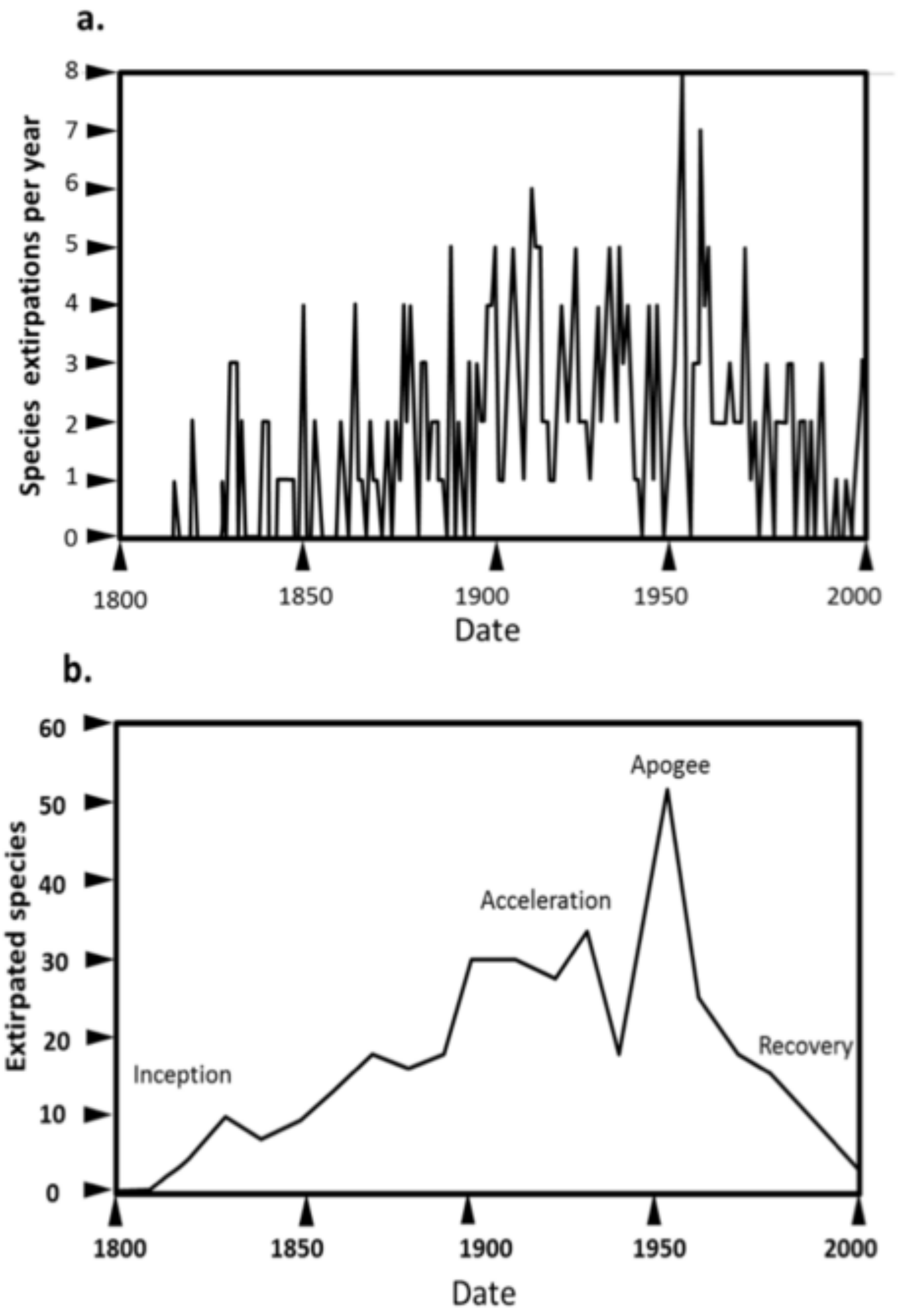


Figure 6


a.
Species extirpations per year
0
1
2
3
4
5
6
7
8
1800
1850
1900
1950
2000
Date
b.
Extirpated species
0
10
20
30
40
50
60
Inception
Acceleration
Apogee
Recovery
1800
1850
1900
1950
2000
Date