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Early mining and smelting lead anomalies in geological archives as potential stratigraphic markers for the base of an early Anthropocene

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Abstract

This article reviews possible lower boundaries for an early Anthropocene period. Although a noticeable environmental impact of humans, caused by hunting, the use of fire, forest clearance, animal domestication and agriculture had already occurred in the Neolithic, these early signals are strongly diachronous and localised. Here, we examine early significant, synchronous and regional stratigraphic signals indicating an anthropogenic influence as consequences of mining and smelting-related trace metal contamination. A first regional lead contamination event in the Northern Hemisphere is recognized during the (Eastern Mediterranean) Late Bronze Age to Early Iron Age, between 3500 and 2800 BP, with a peak at around 3000 BP. Another pronounced anthropogenic lead peak is recorded around 2000 BP, during the Roman period. These events, as defined by lead enrichment and changes in lead isotope ratios, accompanied by other trace metal enrichments, are found in several types of archives, such as Arctic ice-cores and European peat-bogs, speleothems as well as fluvial, lake and marine records. Potential stratigraphic correlations and secondary markers may be present using tephrochronology, climate events, and magnetostratigraphy. Such a definition of the base of a formally defined (early) Anthropocene stage/period allows the application of the GSSP (Global Stratotype Section and Point) concept by using a point in a physical archive, and, in contrast to the late Anthropocene, includes a significant quantity of anthropogenic strata as evidence for an Anthropocene chronostratigraphic unit.

Keywords

early Anthropocene, geochemistry, Iron Age, isotopes, lead, pollution, Roman, smelting

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Introduction

Since its conceptual formulation by Crutzen and Stoermer (2000), the Anthropocene has been the subject of intense discussions, including attempts to define its base, both within the Anthropocene Working Group (AWG) of the Subcommission of Quaternary Stratigraphy of the International Commission of Stratigraphy (e.g. Edgeworth et al., 2015; Waters et al., 2016; Zalasiewicz et al., 2014a, 2017) and outside the group (e.g. Lewis and Maslin, 2015; Smith and Zeder, 2013). Besides responding to other major issues, challenges and evaluating the numerous pros and cons in potentially defining the Anthropocene as a formal chronostratigraphic unit within the Geological Time Scale (Finney, 2014; Finney and Edwards, 2016; Gibbard and Walker, 2014; Lewis and Maslin, 2015; Ruddiman et al., 2015; Waters et al., 2014, 2016; Zalasiewicz et al., 2008, 2011, 2014a, 2014b, 2017), the questions of how and when to define the base of the Anthropocene are amongst the core questions addressed by the AWG.

The problem of a formally defined base in terms of a chronostratigraphic unit (e.g. Finney, 2014; Finney and Edwards, 2016; Gradstein et al., 2012) is closely linked to the wider and extremely diverse discussion of the Anthropocene in the media and across academic disciplines, from the natural sciences to history, sociology and politics (Monastersky, 2015), with an exponentially growing number of publications and citations on the topic (Zalasiewicz et al., 2017; Figure 1). This discussion centres on the questions of when the human impact on the Earth System, and especially on geological processes, started to be significant and fundamental enough to substantiate the definition of a new geological time unit that succeeds or even replaces the Holocene (e.g. Autin and Holbrook, 2012; Braje and Erlandson, 2014; Certini and Scalenghe, 2015; Chakrabarty, 2009; Crist, 2013; Crutzen, 2002; Fischer-Kowalski et al., 2014; Foley et al., 2013; Gale and Hoare, 2012; Lewin and Macklin, 2014; Lewis and Maslin, 2015; Malm and Hornborg, 2014; Visconti, 2014; Waters et al., 2016; Zalasiewicz et al., 2017).

In defining a potential base for the Anthropocene (for overviews see Gale and Hoare, 2012; Lewis and Maslin, 2015; Zalasiewicz et al., 2011, 2014a), members of the AWG recently discussed the feasibility of placing it in the mid-20th century. Zalasiewicz et al. (2014a) originally suggested using the explosion of the first nuclear bomb, on 16 July 1945, at Alamogordo, New Mexico, USA. This event and following nuclear tests caused a significant global distribution of artificial radionuclides, including caesium (^{137}Cs) and plutonium (^{239} Pu, ^{240}Pu), that could be used as the primary chemostratigraphic marker for the base of the Anthropocene. Waters et al. (2015) proposed the first appearance of plutonium 239, in the early 1950s, as a potential base. Although such a boundary placement still needs further evaluation and detailed specifications (see Lewis and Maslin, 2015; Waters et al., 2015), the general mid-20th century placement is related to the ‘Great Acceleration’ concept (Steffen et al., 2007, 2015; Waters et al., 2014), based on an exponential increase in the rate of change of various human-influenced Earth System trends, leading to critical tipping points (‘planetary boundaries’, Steffen et al., 2007, 2015) into a new state of the Earth System, rendering a definition of a new geological epoch useful and appropriate (Steffen et al., 2016; Waters et al., 2016; Zalasiewicz et al., 2017). Slightly earlier (but still within historical times) potential definitions and markers for the base of the Anthropocene include the rise of greenhouse gases during the Industrial Revolution (e.g. Crutzen, 2002) and the Columbian Exchange, which is the widespread transfer of animals, culture, diseases, human populations, ideas, plants and technology between the Americas and the Old World (Crosby, 1972; Fischer-Kowalski et al., 2014; Lewis and Maslin, 2015) in the aftermath of the discovery of America in year 1492.

The basic concept of the definition, as originally suggested by Zalasiewicz et al. (2014a), is that of a Global Standard Stratigraphic Age (GSSA); that is, a chronostratigraphic (‘time’) definition that uses a point in time in the geological/historical archive (an ‘age’, in the case of the Anthropocene, utilising

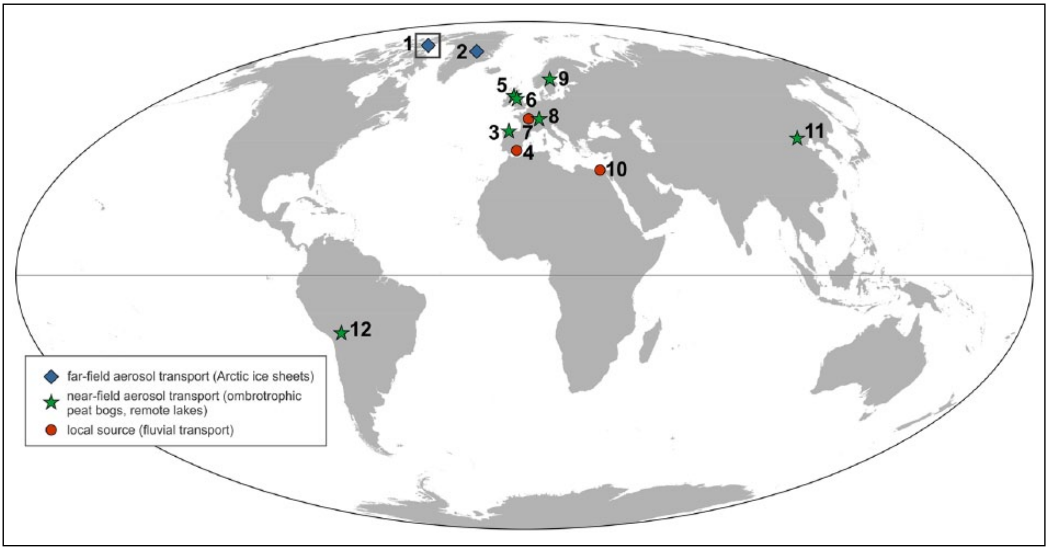

Figure 1. Localities of early Anthropocene lead event mentioned in the text; potential ice core GSSP marked by square. (1) Devon Island (Canada, Zheng et al., 2007), (2) Greenland Ice Core Project (GRIP, Hong et al., 1994), (3) La Molina (Spain, Martínez Cortizas et al., 2016), (4) Laguna di Rio Secco (Spain, García-Alix et al., 2013), (5) Leadhills (UK, Mighall et al., 2014), (6) Lindow bog (UK, Le Roux et al., 2004), (7) Loire River valley (France, Négrel et al., 2004), (8) Étang de la Gruère (Switzerland, Weiss et al., 1999), (9) several lakes in Sweden (Brännvall et al., 2001; Renberg et al., 2002), (10) Alexandria (Egypt, Véron et al., 2006), (11) Daihai Lake (China, Jin et al., 2013), (12) Laguna Taypi, Chaka (Bolivia, Cooke et al., 2008).

the human calendar that may be precise up to a day or even a second in time). In contrast, and following more traditional stratigraphic and geological procedures (Remane et al., 1996), Zalasiewicz et al. (2017) proposed that the base be defined by a Global Boundary Stratotype Section and Point (GSSP). The GSSP concept in chronostratigraphy, which uses a point in a geological section, defined by a primary marker event, such as the first or last occurrence of a fossil taxon or a chemostratigraphic marker, as the chronostratigraphic boundary definition, is applied as a standard procedure in geology for most Phanerozoic chronostratigraphic boundaries (e.g. Gradstein et al., 2012).

Evidence for a considerably older, for example, before year 1 Common Era (CE), impact of humans on the Earth System, and thus a possible older base for the Anthropocene, has been proposed by several authors (e.g. Burchard, 1998: Ellis et al., 2013; Krachler et al., 2008, 2009; Ruddiman, 2003). This led to the concept of an early Anthropocene (or the 'Early Anthropocene Hypothesis', see Ruddiman, 2003, 2013; Smith and Zeder, 2013) or Palaeoanthropocene (Foley et al., 2013; although the latter was not suggested to be a chronostratigraphic unit). As an interdisciplinary field combining archaeology with geology, geoarchaeology may play an important role in the search for the base of the early Anthropocene (e.g. Cremaschi, 2014). So far, many possible markers and dates have been discussed (e.g. Krachler et al., 2009; Lewis and Maslin, 2015). However, no GSSPs or GSSAs have been proposed for the base of the early Anthropocene, apart from the potential use of anthropogenic soils and sediments (Certini and Scalenghe, 2011; but see Edgeworth, 2014; Gale and Hoare, 2012; for a critical assessment).

This paper accepts the concept of an early Anthropocene and discusses possible chemostratigraphic early Anthropocene marker signals and possible GSSPs, both to add to the discussion on the formal definition of the Anthropocene and to sharpen debates on possible boundary levels. An early Anthropocene, based on a human geochemical/isotopic pollution record, has clear advantages: (1) in this way a GSSP can be defined, as for most other chronostratigraphic boundaries, (2) a GSSP definition based on an ice core record would represent a similar concept related to the Holocene GSSP definition of Walker et al. (2009), (3) the proposed marker can be found in several types of terrestrial and marine geological archives, such as ice cores, peat bogs, speleothems, fluvial, lake and marine records and last, but not least (4) an early Anthropocene would ensure considerably more and stratigraphically thicker relevant deposits compared to a mid-20th century definition. The paper also evaluates the boundary marker concepts, and the stratigraphic usefulness of such an early Anthropocene boundary level.

Stratigraphy, stratigraphic nomenclature, and its relationship to the Anthropocene

A definition for the base of a formally defined Anthropocene as a unit of Earth history has to follow stratigraphic rules and principles, especially those put forward for the definition of a chronostratigraphic unit, i.e. a globally accepted unit of the Geological Time Scale (Finney, 2014; Finney and Edwards, 2016; Gradstein et al., 2012; Remane et al., 1996; Salvador, 1994). Thus, according to the rules and current usage of geological terms, a ‘chronostratigraphic’ Anthropocene has to be a time-rock unit (rock in a broader sense including geological archives such as ice cores, see, e.g. Walker et al., 2009) that by definition has a synchronous base. Physical (rock-unit) boundaries are a matter of lithostratigraphy, and may be diachronous. Thus, a diachronous lower physical boundary of the Anthropocene, as suggested by Edgeworth et al. (2015; see also Foley et al., 2013), falls into the category of lithostratigraphy, and such a concept may not be applied formally to a chronostratigraphic unit.

Chronostratigraphy in deep time (before the Quaternary, that is, older than 2.58 Ma) is traditionally connected to the concepts of biostratigraphy, with marker fossils and fossil-defined zones (biozones). Again, biozones may have regional diachronism, and vary considerably in extent and duration from one section to the other, but the base (and tops) of bio-chronozones, taken as the observed first and last occurrences of a new species worldwide in the rock record, are commonly used as markers for a stratigraphic unit in time (Salvador, 1994). In the Anthropocene context, one has to keep in mind two major limitations: (1) most of the marker fossils in the geological record are diachronous to some extent, as they migrate in time and space from the area of their first occurrence to other regions of the globe; (2) none of the marker fossils used have a truly worldwide distribution; some are restricted by environmental conditions, such as temperature, water salinity, bio-provincialism, biogeography, their habitat or a combination of some of these factors. Thus, classical biostratigraphy provides neither perfectly synchronous nor global markers, and, consequently, chronostratigraphic units defined by fossils are, per se, to some extent diachronous. Geologists have learned how to work around this fact by defining a GSSP (Gradstein et al., 2012; Remane et al., 1996). This sets the base of a chronostratigraphic unit at a physical point within a single section, defined there by a primary marker (a fossil or another stratigraphic marker, such as a chemostratigraphic peak), that can be correlated (with some imprecision) to markers and regions elsewhere (i.e. auxiliary stratotypes, e.g. Molina et al., 2009). Besides biostratigraphy, nearly globally synchronous stratigraphic tools do exist, such as magnetic reversals and chemostratigraphy (Gradstein et al., 2012), although these stratigraphic methods have their problems, too. When observed in deep-time, magnetic reversals seem instantaneous and globally synchronous. However, looking in more detail, reversals may take some time (years to 1000 years (ka)), resulting in times of intermediate polarity, and that there may be secular and regional trends involved if observed on a more detailed timescale, especially on a historical timescale (Laj et al., 2004; Snowball et al., 2014).

Several major stratigraphic boundaries of the Geological Time Scale have already been compared to the Anthropocene, such as the Precambrian/Cambrian boundary (Williams et al., 2013) and the Ordovician–Silurian boundary (Zalasiewicz and Williams, 2014). The closest example of a major chronostratigraphic boundary in deep-time that is nearly synchronous and globally recognized, and thus may be a better analogue to the desired base of the Anthropocene is provided by the Cretaceous/Paleogene (K/Pg, formerly K/T, Cretaceous/Tertiary) boundary (Molina et al., 2006, 2009).

The K/Pg boundary, one of the big five mass extinctions, seems to be unusual in Earth history, as it was (mainly) produced by the sudden impact of an asteroid (Schulte et al., 2010). This event provided a geologically instantaneous phenomenon that had a severe and global impact on most, if not all ecosystems and organism groups, from planktonic life to non-avian dinosaur megafauna, influencing significantly the climate, atmosphere, oceans and land surface (e.g. Kring, 2007) and thus constitutes a real dramatic change in the Earth System. Without going into detail, the impact fallout (much similar to atomic bomb fallout) was distributed globally, forming a significant ‘rusty boundary clay’ layer, geochemically characterized by an elemental peak of iridium (Schulte et al., 2010). So far, concerning the big five extinctions in Earth history, an impact-related scenario seems only plausible for the K/Pg, while other major boundaries are mainly interpreted as longer time intervals of severe climate detoriation related to extreme volcanic pulses and global warming leading to stepwise extinctions and recoveries (see, e.g. the Permian/Triassic boundary, Song et al., 2013). But even for the impact-related K/Pg boundary, there is still debate about the interpretation of some sections, whether the timing is established correctly for each geological section, and to what extent and duration was volcanism involved (see, e.g. Keller et al., 2010). Thus even with the most instantaneous event so far proposed for a major chronostratigraphic boundary in deep time, scientific discussion continues, diachroneity is an issue and some questions remain unsolved.

Scale and precision is another important issue of chronostratigraphy when applied to the Anthropocene. The Anthropocene, if formally defined, would be the youngest, shortest and understandably the only still ongoing chronostratigraphic unit of Earth history (characteristics attributed presently to the Holocene), in a historic time interval that can be resolved in terms of calendar years and days, and with some events even in seconds (Zalasiewicz et al., 2014a). At present, the youngest epoch boundary, the base of the Holocene, was defined by chemostratigraphic markers in a Greenland ice core at an age of 11,700 BP, having an estimated maximum error of ±99 years, caused mainly by uncertainties in back counting annual ice layers (Walker et al., 2009). Thus, the error range of the Pleistocene–Holocene boundary of nearly 200 years includes essentially the same time span that separates the original proposals for the beginning of the Anthropocene in the Industrial Revolution, year 1784 (Crutzen, 2002), year 1945 (Zalasiewicz et al., 2014a), year 1952 (Waters et al., 2015) and year 1963 (Lewis and Maslin, 2015). Also, a chronostratigraphic formalization of the Anthropocene as an Epoch, by defining its base, would also define the end of the Holocene Epoch (and the Late Holocene Stage, see Zalasiewicz et al., 2017).

The pronounced climatic shift defining the Pleistocene–Holocene boundary is most clearly reflected in an abrupt change in deuterium excess values in the ice core, accompanied by more gradual changes in concentrations of $\delta^{18}O$, dust accumulations, a range of chemical species, and annual layer thicknesses (Walker et al., 2009). Even proposed subdivisions of the Holocene have errors in the range of decades; for example, the base of the late Holocene is set at 4.2 ka, related to a climate event that spans some 375 years (Walker et al., 2012). The minimum age uncertainty of this GSSP in the speleothems of the Mawmluh Cave in northeast India (Walker et al., 2012) may be below 30 years. This range translated into a (late) Anthropocene base would mean sometime between 1934 and 1964, effectively bracketing all the hitherto proposed Great Acceleration processes and markers of Steffen et al. (2007, 2015), Lewis and Maslin (2015), Waters et al. (2016). Thus, 'synchronous' and 'precise' Anthropocene definitions in a chronostratigraphic context using years or even higher resolution dates may translate into boundaries which are 'slightly diachronous' and 'within an error range' if a historical context and calendar time scale is applied (see also Zalasiewicz et al., 2011), an observational bias introduced by looking back from the Recent when the error bar becomes larger as the level traced becomes older.

Definition of the beginning of a stratigraphically defined Anthropocene

Three main time frames have been proposed for a base of the Anthropocene: (1) an early Anthropocene (see also Palaeoanthropocene of Foley et al., 2013), beginning at least before more than 2 millennia BP (i.e. older than year 1 CE); (2) a c. 1500 to 1900 CE (500 to 100 BP2k) time interval of 'early globalization' that includes the Columbian Exchange (Crosby, 1972) and the Industrial Revolution (Crutzen and Stoermer, 2000; Fischer-Kowalski et al., 2014; Lewis and Maslin, 2015; Zalasiewicz et al., 2011) and (3) a beginning in the mid-20th century related to the Great Acceleration (from 1945 to 1964, e.g. Lewis and Maslin, 2015; Waters et al., 2015, 2016; Zalasiewicz et al., 2014a, 2017). In addition, a diachronous beginning was suggested, based on horizon A, the unconformable physical base of the Archaeosphere (Edgeworth et al., 2015). However, the latter proposal resembles both a lithostratigraphic and biostratigraphic unit, representing the layer with the first observable human influence, and hence is regarded as unsuitable for defining a formal chronostratigraphic boundary.

Zalasiewicz et al. (2014a), Lewis and Maslin (2015) and Waters et al. (2015) recently proposed that nuclear test fallout signals could be used for the definition of the base of the Anthropocene. Several of these artificially produced radionuclides in the sedimentary archive could be used to define an Anthropocene boundary (Dean et al., 2014) within the time interval from 1945 to 1964 CE. A possible Anthropocene boundary in this period may function quite well, although it is not resolved in detail, and a GSSP proposal is still missing. However, should it start at the date of the first detonation of a nuclear device, in 1945 (Zalasiewicz et al., 2014a), at the start of the measurable rise in the physical radiogenic signal in sediment/ice (Waters et al., 2015), or at the peak of that signal (Lewis and Maslin, 2015). Problems with a possible boundary in this period arise with respect to the exact timing, because the artificial radionuclides produce different peaks with considerable time lag after the proposed marker event (Aoyama et al., 2006; Cochran et al., 1987; Dean et al., 2014; Waters et al., 2015, 2016). Waters et al. (2015) suggested that the best one to use was ^{239}Pu, as this radionuclide, produced during atomic bomb explosions, has a relatively long half-life and will be preserved for ~100 ka. In addition, a wealth of supplementary stratigraphic markers can be used for a Great Acceleration-based definition of the Anthropocene, such as plastic particles, CDs, and other technofossils (Zalasiewicz et al., 2014c) as well as chemostratigraphic, mineral and magnetic markers (Gałuszka et al., 2014; Snowball et al., 2014; Zalasiewicz et al., 2014c). However, although technofossils were dispersed nearly instantly when considered in a geological time frame, and, sadly for our environment, globally (e.g. plastics, Jambeck et al., 2015; Zalasiewicz et al., 2016), using the high time resolution applicable in historic time, technofossil markers also have a diachronous appearance with respect to their (regional) production and thus global spatial distribution.

Possible chemostratigraphic markers in the early Anthropocene

Boundary marker concepts for an early Anthropocene involving diachronous steps in human cultural evolution and interaction with the Earth System (e.g. Edgeworth, 2014; Edgeworth et al., 2015; Gale and Hoare, 2012; Zalasiewicz et al., 2014a) have been strongly criticised. Human artefacts (technofossils, Zalasiewicz et al., 2014c) remain too ambiguous (Edgeworth, 2014), diachronous (Edgeworth et al., 2015) and debateable in their Anthropocene context; the first artefacts and figurative art works date back to tens and hundreds of ka BP (Conard, 2009). The record of greenhouse gases, as suggested by Ruddiman (2003, 2013) 'related to the Early Anthropocene Hypothesis' is hard to decipher in the geological archive and is itself very ambiguous (e.g. Broecker and Stocker, 2006). As an alternative, here we propose a chemostratigraphic approach to defining the base of the early Anthropocene and suggest using widespread or global geochemical signals of anthropogenic contamination within the Earth System as a possible marker signal.

The sedimentary record – including ice sheets – yields primary archives of human-induced contamination (Choi and Wania, 2011). Therefore, dated sediment, speleothem, bog and ice sections can be used to reconstruct the extent and chronology of contamination (Boyle et al., 2015; Buckley et al., 1995; García-Alix et al., 2013; Küttner et al., 2014; Lee et al., 2008; McFarlane et al., 2014; Martínez Cortizas et al., 2016; Mighall et al., 2014; Pontevedra-Pombal et al., 2013; Shotyk et al., 1998; Veselý, 2000). Anthropogenic anomalies above the geogenic background may provide useful chemo-/isotopic-stratigraphic markers for the Anthropocene (e.g. Selinus and Esbensen, 1995) of regional and global scale, as suggested by Krachler et al. (2009). Current anthropogenic fluxes of several elements, such as chromium, antimony, platinum group metals and gold, predominate over their natural counterparts (Gałuszka and Migaszewski, 2011; Sen and Peucker-Ehrenbrink, 2012). Mining and smelting was and is the main anthropogenic process in enriching these elements in geological archives (Gałuszka et al., 2014). Therefore, these contaminations may provide a primary chemostratigraphic marker for a base of the (early) Anthropocene. Smelting provides not only a geochemical marker but also represents the transformation of an ore mineral into a more or less pure metal, an important technological/cultural innovation (Kienlin, 2016). Is there a potential human-induced geochemical or isotope-geochemical signal for the (early) Anthropocene?

Yes, there is. Several metal pollution peaks have been found in various records, starting thousands of years BP (e.g. Marx et al., 2016). Owing to (1) the local character of those early signals and (2) the fact that they pre-date the proposed base of the Late Holocene at 4200 BP (Walker et al., 2012), a more regionally distributed, younger signal is preferable. Mining-/smelting-induced metal pollution, mainly lead, that significantly exceeded the Holocene mean geogenic ('natural') background values was not only of local significance but was also transported into remote areas as dust and aerosol particles as early as around 3000 BP, at least in the Northern Hemisphere (Figure 1). Such anthropogenic trace metal pollution has been found in several geological archives, including lakes (Brännvall et al., 2001; García-Alix et al., 2013; Renberg et al., 1994, 2002; see Figure 1), ice cores (e.g. Hong et al., 1994; Zheng et al., 2007), ombrotrophic peat bogs (Martínez Cortizas et al., 2016; Shotyk, et al., 1998; Weiss et al., 1999), fluvial-estuarine (Négrel et al., 2004), coastal sediments (e.g. Buckley et al., 1995; Vane et al., 2011; Véron et al., 2006) and last but not least in humans (Settle and Patterson, 1980).

Several elements and element ratios indicate early pollution by mining and smelting. Among these, lead was the first and most widespread to have been identified, based on Arctic ice cores and several other archives (Boyle et al., 2015; Hong et al., 1994; Lee et al., 2008; Mighall et al., 2014; More et al., 2017; Shotyk et al., 1998; Veselý, 2000). Lead pollution is commonly related to silver/lead mining and smelting (Jacobson, 2012). Using lead isotopes (^{206}Pb, ^{207}Pb, ^{208}Pb) and their ratios, different sources of lead can be identified and anthropogenic versus natural background events separated more clearly (e.g. de Paula and Geraldes, 2005; Marx et al., 2016; Renberg et al., 2002; Weiss et al., 1999). Brännvall et al. (2001) used lead/lead-isotopic traces in Swedish lake sediments to document several peaks of metal pollution, including events at 3500–3000 BP, around 2000 BP (see also Rosman and Chisholm, 1996; Rosman et al., 1997), the Industrial Revolution, the Second World War and a maximum in the 1970s. More recently, Marx et al. (2016) provide a global review of anthropogenic lead contamination from geological archives.

Copper, which is also one of the earlier metals used by mankind, has a longer and older record than lead in some archives (Hong et al., 1996; Killick and Fenn, 2012; Radivojević and Rehren, 2016), locally dating back to 8000 BP (Pompeani et al., 2013, 2015). However, Cu preserves a more local record (e.g. Breitenlechner et al., 2014; De Vleeschouwer et al., 2010) and a more complex depositional pathway in some of the archives, especially in peat bogs (e.g. Bobrov et al., 2011). Thus, copper records will not be further considered herein for defining the early Anthropocene.

We thus suggest that a significant increase in lead concentrations, together with a smelting-induced lowering of the $^{206}Pb/^{207}Pb$ ratio to below the geogenic background (Weiss et al., 1999) may be used to define the (early) Anthropocene (Krachler et al., 2009). There are measurable lead pollution peaks in several types of archives around both 3000 and 2000 BP. Both represent candidates for a primary marker for defining the beginning of an early Anthropocene.

Late Bronze Age to Early Iron Age mining pollution peak

Mining/smelting activity in the Old World peaked during the Late Bronze Age (LBA) (c. 3600–3200 BP). Cyprus produced large amounts of copper during this period and became the main copper source towards the end of the LBA and probably kept this position into the Iron Age (Kassianidou, 2013); most of the Alpine copper production centres were active around 3400–2900 BP (Stöllner, 2015). A measurable increase in Pb pollution commenced at c. 3500 BP and peaked at c. 3000 BP (Boyle et al., 2015; Davis et al., 2000; García-Alix et al., 2013; Lee et al., 2008; McFarlane et al., 2014; Martínez Cortizas et al., 2016; Mighall et al., 2014; Shotyk et al., 1998; Veselý, 2000; Zheng et al., 2007). This was probably connected to major smelting activities, mainly of sulphide copper ores (Figures 2, 3). Distinctly lower $^{206}Pb/^{207}Pb$ ratios were found in the peat record of La Molina, northern Spain, between c. 3400 and 2800 BP (Martínez Cortizas et al., 2016).

Additionally, enrichments of related chalcophile elements, including Ag, As, Bi, Cd, Cu, Sb, Tl, and Zn have been measured; these show a similar behaviour and relationships with other anthropogenic activities recorded in ice core data when normalized to the geogenic background represented by immobile elements such as Sc or Al (Hong et al., 1997; Krachler et al., 2008, 2009; Zheng et al., 2007). The onset of chalcophile pollution around 3000 BP is also clearly visible in many lake records in Sweden (Brännvall et al., 2001).

Dispersion of the pollution signal to remote areas as far away as the Arctic ice sheets is not related to mining activities, but to the smelting processes. These involved high temperatures and thus led to the formation and dispersion of aerosols into the atmosphere, with subsequent transportation and deposition, similar to impact-related and nuclear fallout, but seemingly on a more regional scale. In that respect, the smelting signal is at least supra-regional and thus not strongly time-transgressive, although it is not of global extent. However, the distribution (and timing) is similar to a marker fossil used for chronostratigraphic boundaries in earlier geologic strata. Precise timing, synchronicity and widespread distribution have still to be tested in detail for the lead contamination signal, but published data indicate at least synchronicity within a range of several hundred years, considering remote sites and the different types of archives (Marx et al., 2016), such as

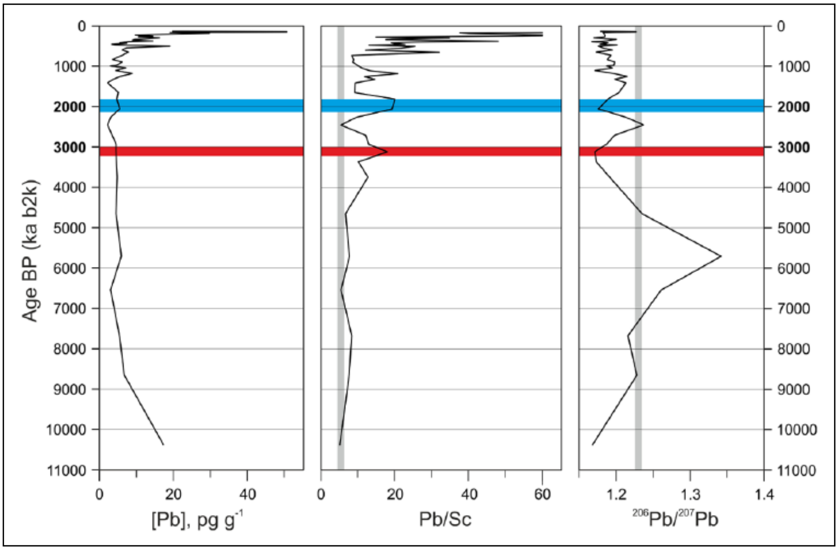

Figure 2. Holocene Pb concentration, Pb/Sc ratio and $^{206}Pb/^{207}Pb$ isotope ratios from a potential early Anthropocene GSSP in the Arctic ice core section at Devon Island, Canada (D1999 core, Devon Island Ice Cap, Nunavut), modified from Zheng et al. (2007). Grey lines mark Holocene natural background values (6.3 for Pb/Sc, 1.230 for $^{206}Pb/^{207}Pb$), red bar marks peaks at around 3000 BP, indicating the onset of atmospheric Pb contamination caused by mining and smelting in the Iberian Peninsula. Blue star marks Roman lead pollution (modified from Krachler et al., 2009; Zheng et al., 2007).

ice sheets, peat bogs and fluvial sediments (Krachler et al., 2009; Négrel et al., 2004; Weiss et al., 1999). Krachler et al. (2009) have already commented about the use of the c. 3000 BP smelting-related chemical and isotopic signals for the definition of the base of the Anthropocene.

The first peaks in lead and lead isotopes in Arctic ice cores (Figure 1), either from Greenland (Hong et al., 1996) or from Arctic Canada (Krachler et al., 2009; Zheng et al., 2007), provide plausible GSSP candidates for such a lower boundary definition of the (early) Anthropocene (Boyle et al., 2015; García-Alix et al., 2013; Lee et al., 2008; Mighall et al., 2014; Shotyk et al., 1998; Véron et al., 2006; Veselý, 2000). Additionally, this boundary is also close to an important period of archaeological turmoil in the broader Mediterranean area, with the collapse of the LBA societies and the tumultuous transition to the Early Iron Age, which is broadly archaeologically dated into the 12th century Before Common Era (BCE) (Cline, 2014; Dickinson, 2006).

Classical Greek to Roman Empire mining pollution peak

During the Classical Greek, Hellenistic and Roman periods, the Old World experienced a level of proto-industrial production of metals and many other materials that was essentially unprecedented before (Borsos et al., 2003; Healy, 1978; Hong et al., 1994; Settle and Patterson, 1980). Lead production reached a first maximum (80,000 tons/year according to Hong et al., 1994) in the golden age of the Roman Empire, the same magnitude as that of the Industrial Revolution some 2000 years later; lead poisoning was a significant problem during Roman times (Nriagu, 1983). The silver mines exploited around Rio Tinto continued to be intensively exploited in Roman times; based on isotopic signatures, Rosman et al. (1997) estimated that 70% of the lead pollution in Greenland originated from southern Spain.

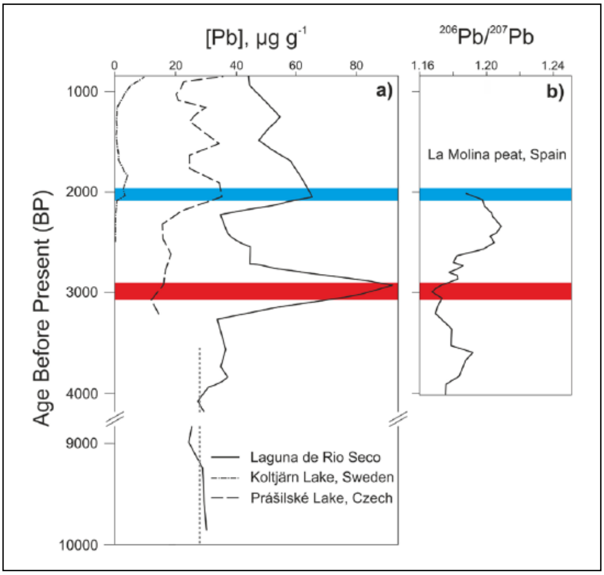

Figure 3. Holocene lead content and isotope records from different regions and archives; red and blue areas mark the c. 3000 BP and 2000 BP peaks, respectively. (a) Lead contents from lacustrine environments. Black line shows the lacustrine Laguna de Rio Seco section (calibrated radiocarbon ages; grey dotted line marks Holocene pre-mining background value for Laguna de Rio Seco; modified from García-Alix et al. (2013: figure 2)); alternating dots and dashes indicate lead contents from Lake Koltjärn (Sweden) modified from Brännvall et al. (2001: figure 5) and dashed line from Lake Prášilské (Czech Republic) from Veselý (2000: figure 3). (b) Lead isotopic ratios from the La Molina peat in northern Spain, modified from Martínez Cortizas et al. (2016: figure 4).

The pollution around 2000 BP is in most cases more pronounced and usually better defined than the earlier event at c. 3000 BP and has been found in many archives (Brännvall et al., 2001; Hong et al., 1994; Le Roux et al., 2004; Rosman et al., 1997) (Figures 2–4). Greenland ice records show increasing Pb contents between 2500 BP and 1700 BP, peaking at 2000 BP (Hong et al., 1994), which is also mirrored by decreased $^{206}Pb/^{207}Pb$ ratios between 2600 BP and 1700 BP (Rosman et al., 1997). A pronounced lead peak occurs in lakes of the Bohemian Massif (Veselý, 2000) and many lake sediments in Sweden show clearly decreased $^{206}Pb/^{207}Pb$ ratios (Brännvall et al., 2001). Le Roux et al. (2004) documented raised Pb contents in the Lindow bog near Manchester (UK) (Figures 2–4). The broad patterns of lead pollution trends in the Northern Hemisphere show consistency and have been used in lead chemostratigraphy studies as an age proxy (Zheng et al., 2007).

Discussion

Events that may define an early Anthropocene include megafauna extinction (at c. 13,000 BP; Doughty et al., 2010), deforestation, agriculture (starting at around c. 9500–8000 BP, Zohary et al., 2012), rice irrigation (at c. 5000 BP, Foley et al., 2013; Ruddiman, 2003, 2013) and early mining and smelting activities (since c. 4000 BP, Krachler et al., 2009; Wagreich, 2014). Early cities (see Childe, 1950) in Near to Far Eastern countries during the Bronze Age, and large states, such as the Roman Empire, significantly influenced local to regional environments. In fact, anthropogenic soils including human artefacts are among markers already proposed for an early beginning of the

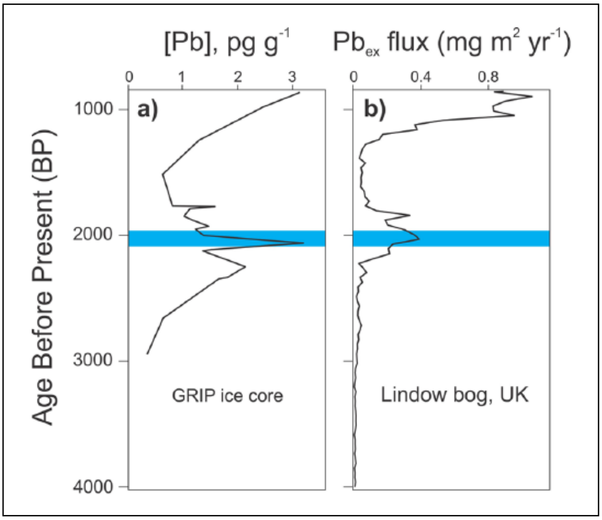

Figure 4. (a) Lead contents from the European Greenland Ice Core Project (GRIP) modified from Hong et al. (1994: figure 1). (b) Lead flux values from Lindow bog near Manchester (UK), modified from Le Roux et al. (2004: figure 5b).

Anthropocene (Certini and Scalenghe, 2011), but fail to meet some of the criteria for a base definition of a chronostratigraphic unit (Gale and Hoare, 2012). This holds true also for the Archaeosphere concept which defines a diachronous but physically recognizable boundary on continents, and may only be correlated with some difficulty, especially concerning resolution, into the marine environment (Edgeworth et al., 2015).

For the (very) old, that is, the 14,000–5000 BP proposed beginning of the Anthropocene (Barnosky et al., 2014; Doughty et al., 2010), no clear stratigraphic marker or marker event has been suggested (Smith and Zeder, 2013). Although subtle changes in greenhouse gas concentrations, such as CO_2 and CH_4, may be related to those events, separating natural trends from anthropogenic excursions in this early period is barely possible and strongly debated (e.g. Ruddiman, 2003 versus Broecker and Stocker, 2006; see also Lewis and Maslin, 2015). Consequently, Smith and Zeder (2013) propose using the same base for both the Holocene and the Anthropocene, defined as a climate event and not directly related to anthropogenic influence, as understood so far. The megafauna extinction event may give a marker fossil signal in continental sections as good as other continental mass extinction fossil markers in the deep-time record, but the event was diachronous and is probably hard or impossible to discern in the marine environment. Furthermore, such an old Anthopocene concept is approximately coincident with the recent GSSP definition of the Holocene in ice core data at 11,700 BP (Walker et al., 2009) and challenges the proposed climate-based subdivision of the Holocene, with the mid Holocene starting at 8200 BP, and the late Holocene proposed to start at 4200 BP (Walker et al., 2012). Thus, to avoid an overlap with the Holocene climate-related definitions and subdivisions (Gibbard and Walker, 2014) and especially to utilize more clearly human-related markers, we argue for a younger than 4200 BP age for the base of the Anthropocene, if one accepts the early Anthropocene hypothesis.

The first recognizable anthropogenic pollution impact in data from Arctic ice cores is provided by elevated heavy metal and other element concentrations, probably related to mining/smelting activities in the Northern Hemisphere. Lead anomalies, and later on lead isotope fluctuations, were among the first to be connected to early mining activities (Hong et al., 1994). Other elements and element ratios used, most, if not all of which are chalcophile elements and ratios (Ag, As, Bi, Cd, Cu, Pb, Sb, Tl, and Zn), reveal a significant response to human activities (Krachler et al., 2009).

Using such a geochemical signal for the definition of the base of the Anthropocene has two clear advantages in the chronostratigraphic framework of the Geological Time Scale: (1) in this way a GSSP can be defined, as for most other chronostratigraphic boundaries, and (2) a GSSP definition based on an ice core from Greenland or Arctic Canada would represent a very similar concept to the Holocene GSSP definition of Walker et al. (2009). This strategy connects and relates both definitions, the base of the Anthropocene as well as the base of the Holocene Epoch, to GSSPs in ice cores (for advantages and drawbacks on the Holocene GSSP see discussion in Walker et al., 2009). The difference is based on the different nature of the signal: whereas the Holocene is defined by a climate event and a natural variation of isotopes in the ice core, the Anthropocene would be defined by an anthropogenic event using the onset of widespread anthropogenic smelting-related pollutants, mainly lead and lead isotopes (e.g. Marx et al., 2016). This boundary definition may also answer criticism of the Holocene community on a formal chronostratigraphic Anthropocene concept in relation to interferences with definitions in the Holocene and missing stratal evidence (Gibbard and Walker, 2014). The suggested primary marker thus sets a physical signal that can be correlated with other archives such as lake sediments, river sediments and peat bogs, and can also be related to secondary markers, such as tephra layers and the historical calendar.

Timing

Timing and time resolution of the early Anthropocene onset is of course not as straightforward as using a more recent definition by calendar years (e.g. Lewis and Maslin, 2015) or even seconds (Zalasiewicz et al., 2014a). On the one hand both candidates for a pollution-defined early Anthropocene, around 3000 BP as well as c. 2000 BP show considerable increased metal production activities in ice cores (e.g. Hong et al., 1994; Krachler et al., 2009; Zheng et al., 2007) and other archives (e.g. Brännvall et al., 2001), but actual lead pollution intensities differ regionally in age within an interval of 3500 BP to 2500 BP and 2600–1700 BP, respectively, and are also dependent on sample resolution, age error calculation and limits of detection of signals (e.g. García-Alix et al., 2013). On the other hand, ice cores provide an archive of (theoretically) annual layer resolution, despite uncertainties in correlation, layer counting and preservation that result presently in error ranges of at least several decades (e.g. Walker et al., 2009). Dating of the sedimentary record around this time interval mostly relies on ^{14}C dates, with their inherent problems of sample resolution and age interpolations using linear sedimentation rates, dating problems, and correlation problems with calendar years (e.g. Dee et al., 2013). This is not a major drawback, especially when compared with the age uncertainties and imprecision of all other GSSP geological boundaries (e.g. K/Pg boundary, see Kuiper et al., 2008) and even for the onset of the Holocene. Clearly, further work is needed to obtain more precise dating of the onset of the anthropogenic lead signal in ice cores and correlations with secondary markers and well-dated sections around the globe.

Spatial distribution

One major shortcoming for utilizing lead pollution as a primary marker is that the anomalies have not been documented globally (Figure 1). Both events have been mainly recognized in European and Arctic sections (e.g. García-Alix et al., 2013; Hong et al., 1994; Mighall et al., 2014). There are records from outside Europe; for example in Egypt (Véron et al., 2006), and, somewhat younger (i.e. 2500 BP), in China (Jin et al., 2013; Lee et al., 2008), thus defining a Eurasian event. Even some records from the Northern Hemisphere do not show a lead increase around 3000 BP, such as that from an ombrotrophic peat bog section on the Tibetan Plateau (Ferrat et al., 2012).

The first records of anthropogenic lead contamination from the Southern Hemisphere are considerably younger (i.e. 1600 CE) (e.g. Cooke and Bindler, 2015; Cooke et al., 2008). Most of the Southern Hemisphere archives including Antarctic ice cores have not shown any sign of this early smelting, but rather show pollution around 1450 CE (Peruvian glacier ice cores, Ugliettia et al., 2015) and evidence of a late 19th century onset of lead mining contamination in Antarctic ice core data from Broken Hill mining activity in Australia (McConnel et al., 2014). The abundance of pollution traces in different archives demonstrates the potential of these data for defining the base of the Anthropocene, but further work needs be done on this issue. Also, the 2000 BP mining-related pollution peak is so far mainly documented in archives from the Northern Hemisphere; for example, from Greenland ice (Hong et al., 1994; Rosman et al., 1997), lake sediments in Sweden (Brännvall et al., 2001), and bogs near Manchester (Le Roux et al., 2004) and on the Iberian Peninsula (Martínez Cortizas et al., 2016).

Tracking the land-based records into the deep-sea sedimentary sequences is challenging, although García-Alix et al. (2013) tracked lead pollution from southern Iberia into a deep-sea drillcore (ODP 976, Alboran Sea, westernmost Mediterranean Sea). So far, no other record of this event in oceanic sedimentary archives has been reported, in either the Northern or Southern Hemispheres. We presume that the atmospheric signal, once introduced into the oceans, would have been transported, diluted and redistributed via current systems, although some more modern smelting activities are detectable in the offshore record close to mining sources (e.g. Leorri et al., 2014).

Secondary stratigraphic markers

Tephrochronology. Tephrochronology is a powerful stratigraphic correlation and dating tool, especially in historic times and for certain regions (e.g. Lowe, 2011) and may be used for defining the base of the Anthropocene (Smith, 2014). Correlations with tephra stratigraphy indicate that the anthropogenic lead event at c. 3000 BP, clearly postdates the Thera event (eastern Mediterranean; at around historic 3627–3600 BP, Bronk Ramsey et al., 2004; Friedrich et al., 2006) and the Aniakchak Tephra (Alaska) at around 3645 BP (Pearce et al., 2004), as recognized in the Greenland ice core. Using the Iceland tephrochronology, the event is bracketed by the older Hekla 4 Tephra at c. 3800 BP and the Glen Garry Tephra at c. 2100 BP (Dugmore et al., 1995), which closely fits to the Roman mining peak at 2000 BP. Regarding the New Zealand key tephras, both anthropogenic lead events lie between the 3410 ± 40 BP Waimihia tephra and the 1718 ± 30 BP Taupo tephra (Alloway et al., 2007).

Climate events. In a general review of Holocene climate evolution, Mayewski et al. (2004) identified the time interval from 3500 to 2500 BP as one of six intervals of Holocene rapid climate change (RCCs), notably younger than the proposed 4200 BP late Holocene lower boundary climate event (Walker et al., 2009). A more detailed correlation using Greenland ice-core data indicated an age of 3100 to 2900 for this climate change episode (Weninger et al., 2009), which closely coincides with the first peak from anthropogenic mining/smelting. This also correlates roughly to the onset of atmospheric methane rise (Blunier et al., 1995). A significant climate event is also reported around 2800 BP. This climate event is recorded in many continental European bogs by increased wetness (e.g. Chambers et al., 2010), related to the North Atlantic Bond event 2 (Bond et al., 1997), an event also identified in European lake records (e.g. Sadori et al., 2015) and outside the European-North Atlantic region in southern South America and southeastern Asia (Chambers et al., 2014; van Geel and Berglund, 2000; Wang et al., 2005). This corresponds to a marked reduction in solar activity, identified as a ‘Grand Solar Minimum’ (or ‘Subboreal–Subatlantic transition’), which was attributed to solar-driven changes in atmospheric circulation. The record of total solar irradiance (Steinhilber et al., 2009) indicates a short interval of very high solar activity followed by a pronounced low in solar activity, causing a marked and abrupt shift from relatively dry and warm to cool and wet conditions in northwest Europe (van Geel et al., 2014). In contrast, the Roman mining peak at 2000 BP does not correspond to a distinct climate or solar activity event (Wanner et al., 2014).

Within the Pacific area, the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) activities strengthened significantly and have prevailed since c. 3100–3000 BP (e.g. Cobb et al., 2013; Riedinger et al., 2002; Yang et al., 2014), marking climate events around 3000 BP and 2200 BP (Yang et al., 2014).

Another climate-related event at around 3000–2500 BP comprises a weathering event in equatorial Africa that may also have an anthropogenic connotation. Bayon et al. (2012) relate the event to the migration of the Bantu people and large-scale deforestation, thus indicating its own human-induced significant change. Although the timing is strongly debated and the process is unrelated to the Northern Hemisphere smelting pollution, the largely similar time frame makes this event a possible secondary marker in the Southern Hemisphere that can be correlated to the primary mining-induced markers and a possible Northern Hemisphere ice core GSSP.

The so-called ‘Roman Warm Period’ has been reconstructed from several archives around 2000 BP (e.g. Büntgen et al., 2016) and can also be used as secondary marker for the 2000 BP pollution event.

Magnetostratigraphy. Snowball et al. (2014) note that there was a global magnetic event, most strongly developed in mid- to high-latitudes, coincident with a low in dipole latitude and peak in dipole moment between 2700 and 2550 BP (the European ‘f-event’). This event separates the two mining peaks of the (early) Anthropocene. Field strength reached its Holocene peak around 2000–3000 BP, associated with distinct palaeomagnetic secular variation features across mid-latitude sites (Snowball et al., 2014).

Sedimentology. Other anthropogenic markers or events around the 3000 BP datum include human activities affecting sediment flux and altered ecosystems, for example, in the Yellow River basin in China (Syvitski and Kettner, 2011) and the Maya impact in Middle America (Beach et al., 2015: the ‘Mayacene’ from c. 3000 to 1000 BP), as evidenced by deforestation and paleosols.

In fact, the early Anthropocene base, as suggested in this article, involves a large number of already documented chemical excursions and mapped anthropogenic deposits, man-made ground and legacy sediments (Ford et al., 2014; James, 2013; Price et al., 2011), such as early mining dumps (Wagreich, 2014), that consequently form a significant and characteristic part of early Anthropocene geological strata.

Historical and archaeological context

Mining and smelting for metals began long before 3000 BP (Kassianidou and Knapp, 2005; Roberts and Thornton, 2014); in Eurasia, it commenced around 7000 BP (Radivojević et al., 2010) but this left only small and localised geochemical anomalies in geological records. In archaeological chronology, 3000 BP is situated, for example, in the Final Bronze Age (Sardinia) (Balmuth and Tykot, 1998), Proto-Geometric Period (Aegean), Cypro-Geometric I (Cyprus) (Kassianidou, 2012) or the Third Intermediate Period (Egypt) (Kitchen, 1996; Bronk Ramsey et al., 2010). Bruins et al. (2003) discuss possible correlations between Israel, Greece and Cyprus. Shortly before 3100 BP, the broader Mediterranean area experienced a very important period of archaeological turmoil, essentially the collapse of the Late Bronze Age societies and the tumultuous transition to the Early Iron Age, which is broadly archaeologically dated into the 12th century BCE (e.g. Bachhuber and Roberts, 2009; Cline, 2014; Dickinson, 2006). This change was accompanied by population decrease, reduction in large-scale long-distance exchange and writing (thus also an important historical source) was lost for a few centuries in most Mediterranean regions except Egypt. Therefore, the term 'Dark Ages' is used for this period, for example in the Aegean (Snodgrass, 1971). The lack of textual remains clearly also dramatically reduces our knowledge about mining/smelting in this period. While there is substantial information about metal production and distribution in the Mediterranean area during the Bronze Age (e.g. Betancourt and Ferrence, 2011; Day and Doonan, 2007; Tzachili, 2008), information regarding the Early Iron Age is scarce, but there is evidence for continuing metal production, as in, for example, Cyprus (Kassianidou, 2013).

The majority of the ancient lead production stems from the cupellation of Ag–Pb ores. According to Kylander et al. (2005) significant Pb and Ag/Pb mining sites during the Bronze and Iron Ages include Laurium in Greece, mines on Siphnos, Seriphos, Kea and Thera in the Aegean Sea, Iglesiente on Sardinia and mines in Almeria, Cartagena and Mazarron in SE Spain (see Figure 1 for locations).

Recent investigations indicate that metal production and distribution in early Iron Age times was probably related to Phoenician trading networks reaching from Western Europe to the Levant and that metallurgy on the Iberian Peninsula played a very important role (García-Alix et al., 2013; Olías and Nieto, 2015). Despite Sardinia's metal richness, the scale of Bronze Age and Iron Age mining is not fully understood; for example the majority of Late Bronze Age copper oxide ingots and ingot fragments seem to derive from Cyprus (Lo Schiavo et al., 2005; Stos-Gale and Gale, 1992). Silver mining on Thasos Island (Greece) probably began early in prehistory, with production peaks at 500–410 and, to a lesser extent at 370–310 BCE and even more so in Roman times (Nerantzis and Papadopoulos, 2013; Pernicka, 1981). Also Laurion in SE Attika (Greece) was already being exploited for silver during the Bronze Age (Gale and Stos-Gale, 1981; Kassianidou, 2012), but larger-scale mining probably began late in the 5th century BCE (Katerinopoulos, 2010; Κονοφάγος, 1980). Silver-containing lead ores were mined on Siphnos Island (Greece) during the 3rd and 1st millennium BCE (Wagner and Weisgerber, 1985). During the Late Bronze Age, the overwhelming part of the Mediterranean copper ingots comprised copper from Cyprus (e.g. Gale, 2011); however, the extent of Cyprus's metal production during the Early Iron Age is still a matter of research (Kassianidou, 2012).

Lead isotope evidence indicated that the Roman mining peak was essentially a product of large-scale mining in Spain, especially from southern Spain, at Rio Tinto, Mazarron and Cartagena (Rosman et al., 1997). Contributions from other mining areas, such as Italy, Sardinia, the Carpathian and Balkan regions and Britain were probably small and only local.

Conclusions

We suggest an alternative definition for the lower boundary of a formally defined early Anthropocene, based on chemostratigraphic markers related to trace metal pollution mining and smelting of ores, mainly in the Northern Hemisphere, at around either 3000 BP or 2000 BP. The 3000 BP peak relates to the first mining-induced spike of pollution, that is, the lead event, as defined by lead enrichment and changes in lead isotope ratios, namely the $^{206}Pb/^{207}Pb$ ratio, at the transition from Late Bronze Age to Iron Age in the Eastern Mediterranean. This event can also be seen in other trace elements (e.g. As, Bi) and trace element ratios (As/Sc). Although the signal has been found in more and more geological archives, it is so far largely limited to the Northern Hemisphere. This may raise critiques as to whether it can qualify for defining a global epoch. However, this problem also arises with biogeographically or facies-restricted marker fossil definitions in deep time. For the Anthropocene, potential correlations and secondary markers may be present in the Southern Hemisphere, using tephrochronology, climate events, and magnetostratigraphy.

The pronounced chemical record of mining pollution around 2000 BP, related to large-scale Roman mining and metal production activities, could represent an alternative marker for the early Anthropocene.

Such an early Anthropocene definition has several advantages over a definition of the Anthropocene at around the mid-20th century, proposed recently by Zalasiewicz et al. (2014a) and Lewis and Maslin (2015). Not least, it conforms to standard stratigraphical procedures, as noted critically by Finney (2014), Finney and Edwards (2016) and Walker et al. (2015).

(1) It encompasses significantly more time, allowing a considerably larger quantity and better quality of Anthropocene stratigraphic records in a larger variety of archives to have been established. The early Anthropocene base, as suggested, already involves a large quantity of anthropogenic deposits, man-made ground and legacy sediments, thus recording a substantial amount of 'Anthropocene' stratigraphy and allowing the Anthropocene to be defined more easily by its stratal content.
(2) By putting the base of the Anthropocene into the older archaeological record, the early Anthropocene definition conforms to some extent with the (diachronous) base of the Archaeosphere. It departs from the Archaeosphere concept in not using the physical (and thus diachronous) lower boundary (which is a lithostratigraphic boundary), but in applying a different, chronostratigraphic approach by using geochemical and/or isotope-geochemical markers.
(3) It allows the GSSP concept to be used to define the base of the Anthropocene, as is the case for most Phanerozoic boundary definitions, and thus to conform to standard stratigraphic rules and principles. Furthermore, it allows an Arctic ice core to be used for the definition of the Anthropocene GSSP, as has already used for the GSSP base of the Holocene.
(4) The proposed boundary is consistent with definitions of the Holocene and with proposed subdivisions of the Holocene, that is, with a Late Holocene base at 4200 BP. Accepting the proposed boundary, the late Holocene would comprise a shorter duration, of only c. 1200 or 2200 years, but it would remain a valid unit.
(5) Although this event is so far not recognized globally, as it is largely missing in the Southern Hemisphere and in Antarctic ice cores, there is a fairly wide distribution of the primary marker to conform with the fossil marker concept in deep-time, with fossils that are equally restricted biogeographically (low- versus high-latitude provincialism) and/or environmentally (continental versus marine or planktonic versus benthic organisms).
(6) Some global and regional events, such as in solar radiation ('Grand Solar Minimum' at 2800 BP) and climate (North Atlantic Bond event 2 at 2800 BP), magnetostratigraphy (European 'f-event' at 2800 BP), tephrochronology (2100 BP) and Southern Hemisphere events may be related and correlated to the suggested primary chemostratigraphic marker, giving secondary marker events in auxiliary reference sections around the globe.

Smelting not only produced relatively early pollution markers in geological archives, it served also as one of the first techniques that allowed humans to transform natural raw materials (minerals) into completely new matter (elements) and thus also represents an important step in the history of mankind. Obviously, much work has still to be done to make such an early Anthropocene boundary definition more precise, accurate and acceptable. More information is needed on the exact dating of the onset and the spike of the mining events within ice cores and other high-resolution continental archive such as lakes, as well as correlation into the shallow- and deep-water marine record, and correlation into the Southern Hemisphere. Based on our survey and with further refinement, trace metal peaks of early mining and smelting may provide a useful signal and more precise chronostratigraphic datum for subdividing the Late Holocene and defining an early Anthropocene.

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