Earth-Science Reviews 116 (2013) 17–34

Contents lists available at SciVerse ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Stratigraphic expressions of the Holocene–Anthropocene transition revealed in sediments from remote lakes

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ARTICLE INFO

Article history:
Received 19 March 2012
Accepted 3 November 2012
Available online 12 November 2012

Keywords:
Anthropocene
Holocene
Diatoms
Nitrogen stable isotopes
Palaeolimnology

ABSTRACT

Stratigraphic boundaries are ideally defined by distinct lithological, geochemical, and palaeobiological signatures, to which a chronological framework can be applied. We present a range of observations that illustrate how the Holocene–Anthropocene transition meets these criteria in its expression in sediments from remote arctic and alpine lakes, removed from direct, catchment-scale, anthropogenic influences. In glaciated lake basins, the retreat of glaciers commonly leads to lithological successions from proglacial clastic sedimentation to non-glacial organic deposition. Sediments from the majority of lakes record marked depletions in the nitrogen stable isotopic composition of sediment organic matter, reflecting anthropogenic influences on the global nitrogen cycle. In all cases, siliceous microfossil assemblages (diatoms and chrysophytes) change markedly and directionally, with regional nuances. These stratigraphic fingerprints begin to appear in the sediment record after AD 1850, but accelerate in pulses between AD 1950 and 1970 and again after AD 1980. Our review indicates that recent environmental changes associated with humankind's dominance of key global biogeochemical cycles are sufficiently pervasive to be imprinted on the sediment record of remote lakes. Moreover, these changes are of sufficient magnitude to conclude that the Holocene has effectively ended, and that the concept of Anthropocene more aptly describes current planetary dynamics. The synthesis of these observations pertains directly to ongoing discussions concerning the eventual formalization of a new stratigraphic boundary.

Contents

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http://dx.doi.org/10.1016/j.earscirev.2012.11.001

1. Introduction

Although the subdivision of geological time is fundamental in earth science, new stratigraphic boundaries are relatively rare. For example, the designation of the Ediacaran at the level of Period in the terminal Proterozoic was the first interval elevated to this status in 113 years, and the first application of Phanerozoic subdivisions to deeper time (Knoll et al., 2004). The Ediacaran serves in many ways as an exemplary template, in that it is bounded by distinct lithostratigraphic, chemostratigraphic, and biostratigraphic features. Ediacaran rocks succeed Marinoan glacial sediments and conformably overlie cap carbonates that register an extreme global negative $\delta^{13}C$ excursion. The fossil content of Ediacaran-aged rocks includes enigmatic but distinctive clades (e.g., vendobionts and rangeomorphs), as well as first occurrences of putative animal embryos, bilaterian body plans, calcified fossils, and locomotive traces. These all occur well before the Cambrian diversification of shelly organisms and the widespread distribution of bioturbation. Another prominent $\delta^{13}C$ excursion conveniently demarcates termination of the Ediacaran (Knoll et al., 2004).

In the Quaternary, important boundaries have recently been ratified formally and designated their respective Global Stratotype Section and Point (GSSP). The bases of the Quaternary System/Period and of the Pleistocene Series/Epoch have been assigned a common stratotype at Monte San Nicola in Sicily (Italy), dated to 2.58 Ma, and corresponding to accelerated cooling of the climate system (Gibbard et al., 2009). The boundary between the Pleistocene and Holocene Series/Epochs has also been assigned a new stratotype, in Greenland ice (the NGRIP core, 75.1°N, 42.32°W), which dates to 11,700 yr BP and coincides with rapid warming of the northern hemisphere (Walker et al., 2009). The ice core record, which is primarily chemical in nature with some lithostratigraphic support (Holocene ice is less dusty), is bolstered by five auxiliary stratotypes, which include sediments from four lakes and one marine basin. Importantly, these exceptionally well-resolved records illustrate the breadth of sedimentological and palaeobiological change associated with the Pleistocene–Holocene transition.

These formal stratigraphic enquiries, coupled with the current acceleration of environmental changes associated with humankind (IPCC, 2007; Hansen et al., 2008; Kaufman et al., 2009), have stimulated the following question: does a boundary between the Holocene and the Anthropocene merit similar attention? We are not the first to ask this very question (Zalasiewicz et al., 2008, 2010). Instead, the objective of this review is to identify whether consistent stratigraphic markers of anthropogenic impacts can be identified in sediment records from remote lakes, thereby augmenting the available data array with which this emerging issue can be addressed. We use the term Anthropocene in the original sense of Crutzen and Stoermer (2000), Crutzen (2002), and Steffen et al. (2007), as referring to the interval of demonstrable human alteration of global biogeochemical cycles, beginning subtly in the late 18th century following James Watt's invention of the coal-fired steam engine, and accelerating markedly in the mid-20th century. A full account of the Anthropocene concept, including the temporal evolution of human processes that drive it and respond to it, is provided elsewhere (Steffen et al., 2011). While there is no question that humans have strongly influenced the environment for millennia prior (Ruddiman, 2003), impacting both terrestrial and aquatic ecosystems (Birks, 1986; Renberg et al., 1993), our view is that these effects were for the most part local to regional in scale, although some produce geochemical signatures that are preserved in Greenland ice (Hong et al., 1994; Ferretti et al., 2005). However, the Anthropocene sensu stricto is more insidious than pre-industrial human activity because its consequences are unquestionably global and because the rates of several key components, including climate change associated with greenhouse gas emissions and anthropogenic emissions of reactive nitrogen (Nr), both have the potential to accelerate rapidly in the future (Galloway and Cowling, 2002; Hansen et al., 2008). Despite these realities, current suggestions for a Holocene–Anthropocene boundary focus on stratigraphic evidence that records direct and localized human modification of landscapes (Zalasiewicz et al., 2011) or of soils (Certini and Scalenghe, 2011). Here, we take an alternate approach by examining highly-resolved lake sediment records from regions removed from local human influences, thus targetting stratigraphic signatures expressed in relation to diffuse, but nonetheless discernible, anthropogenic influences. Lake sediments offer interpretable and reproducible archives of recent environmental change because they integrate efficiently the physical, chemical, and biological dimensions of the basin. This type of information is particularly useful for remote localities with fragmentary or lacking observational records (Smol, 2008).

2. Study sites and summary of methods

We present palaeolimnological evidence pertaining to the Holocene–Anthropocene transition from lakes in the Canadian and American sectors of the Rocky Mountains, Baffin Island in the eastern Canadian Arctic archipelago, west Greenland, and Spitsbergen in the Svalbard archipelago of the Norwegian High Arctic (Fig. 1). Arctic and alpine lakes share several features including nival hydrological regimes, prolonged ice cover, short growing seasons, and typically low primary production. As such, both are recognized as sentinel ecosystems with regards to anthropogenic environmental change (Smol and Douglas, 2007a; Parker et al., 2008; Williamson et al., 2009). Weather station data, augmented by palaeoclimate proxies, reveal the amplitude and pattern of 20th century warming in each region, which can be visualized alongside trends of anthropogenic Nr emission and deposition as well as the inexorable rise of atmospheric CO_2 concentrations (Fig. 2).

We synthesize data from sites that are both published and unpublished (Table 1), and thus keep methodological details to a minimum here. All sediment cores are gravity-driven, preserving an intact mud-water interface, and extruded in the field at 0.25–0.50 cm continuous increments (Glew et al., 2001). Geochronology is based on sediment excess ^{210}Pb activities measured by α-spectroscopy, to which the CRS model has been applied (Appleby, 2001). Nitrogen isotopes were measured by isotope-ratio mass spectrometry (IRMS), and are expressed as $\delta^{15}N$ relative to air ($\delta^{15}N = 0‰$). Sedimentary pigments were quantified using reverse-phase high-pressure liquid chromatography (Vinebrooke and Leavitt, 1999). Diatoms were prepared and enumerated using standard protocols (Battarbee et al., 2001), whereas data manipulations, including diatom flux and