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Synchronizing terrestrial and marine records of environmental change across the Eocene–Oligocene transition

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ABSTRACT

Records of terrestrial environmental change indicate that continental cooling and/or aridification may have predated the greenhouse–icehouse climate shift at the Eocene–Oligocene transition (EOT) by ca. 600 kyr. In North America, marine-terrestrial environmental change asynchronicity is inferred from a direct comparison between the astronomically tuned marine EOT record and published $^{40}Ar/^{39}Ar$ geochronology of volcanic tuffs from the White River Group (WRG) sampled at Flagstaff Rim (Wyoming) and Toadstool Geologic Park (Nebraska), which are type sections for the Chadronian and Orellan North American Land Mammal Ages. We present a new age-model for the WRG, underpinned by high-precision $^{206}Pb/^{238}U$ zircon dates from 15 volcanic tuffs, including six tuffs previously dated using the $^{40}Ar/^{39}Ar$ technique. Weighted mean zircon $^{206}Pb/^{238}U$ dates from this study are up to 1.0 Myr younger than published anorthoclase and biotite $^{40}Ar/^{39}Ar$ data (calibrated relative to Fish Canyon sanidine at 28.201 Ma). Giving consideration to the complexities, strengths, and limitations associated with both the $^{40}Ar/^{39}Ar$ and $^{206}Pb/^{238}U$ datasets, our interpretation is that the recalculated $^{40}Ar/^{39}Ar$ dates are anomalously old, and the $^{206}Pb/^{238}U$ (zircon) dates more accurately constrain deposition. $^{206}Pb/^{238}U$ calibrated age–depth models were developed in order to facilitate a robust intercomparison between marine and terrestrial archives of environmental change, and indicate that: (i) early Orellan (terrestrial) cooling recorded at Toadstool Geologic Park was synchronous with the onset of early Oligocene Antarctic glaciation and (ii) the last appearance datums of key Chadronian mammal taxa are diachronous by ca. 0.7 Myr between central Wyoming and NW Nebraska.

1. Introduction

During the Eocene–Oligocene transition (EOT, 34.0–33.5 Ma) the Earth's climate shifted abruptly from greenhouse to icehouse mode, resulting in the development of a continent-scale Antarctic ice-sheet (Ivany et al., 2006; Shackleton and Kennett, 1975; Zachos et al., 2001). Marine records of the EOT are characterized by a stepwise 1.2–1.5‰ positive shift in benthic foraminiferal $\delta^{18}O$ values, which took place over ca. 400 kyr, and was synchronous across ocean basins (Cramer et al., 2009; Coxall et al., 2005; Pälike et al., 2006; Pearson et al., 2008; Zachos et al., 1996). The timing of events surrounding the marine EOT is established by the astronomical tuning of the ODP Site 1218 record from the equatorial Pacific (Pälike et al., 2006; hereafter ATPS06), which provides continuous coverage between chrons C1n–C19n (0–41.5 Myr). The detailed pattern of the $\delta^{18}O$ shift varies between localities and is dependent on stratigraphic completeness and sampling resolution, but two major events are widely recognized: (i) a precursor event (EOT-1) marked by a ca. 0.5‰ $\delta^{18}O$ increase around 34.0–33.8 Myr associated with >2 °C decrease in sea-surface temperatures, and (ii) a ca. 1.0‰ $\delta^{18}O$ positive shift (Oi-1 event) at 33.6 Myr, close to the base of magnetochron C13n, related to further cooling and Antarctic ice-sheet expansion (Coxall et al., 2005; Katz et al., 2008; Wade et al., 2012). Coeval terrestrial records

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from the Americas, Europe, and Asia exhibit a wide range of responses to marine cooling and Antarctic ice-sheet growth, from relative climatic stability (Grimes et al., 2005; Kohn et al., 2004; Retallack et al., 2004) to a >4 °C drop in mean annual temperature (MAT) (Hren et al., 2013; Wolfe, 1994; Zanazzi et al., 2007, 2009), and a shift towards more arid conditions (Boardman and Secord, 2013; Dupont-Nivet et al., 2007; Xiao et al., 2010; Zhang and Guo, 2014). Where significant environmental changes are present in the terrestrial record, their timing relative to the marine EOT is established based on magnetostratigraphy (e.g. Hren et al., 2013; Dupont-Nivet et al., 2007) and to a lesser extent $^{40}Ar/^{39}Ar$ dating of volcanic tuffs (e.g. Boardman and Secord, 2013; Zanazzi et al., 2007, 2009) and floating astronomical time scales (Xiao et al., 2010). Combined, these studies indicate that although terrestrial environmental change broadly coincided with the EOT-1 and Oi-1 interval at some localities (Hren et al., 2013; Xiao et al., 2010), at others it apparently predates changes associated with the marine EOT by 100–600 kyr (Boardman and Secord, 2013; Zanazzi et al., 2007, 2009; Zhang and Guo, 2014).

Extensive radio-isotopic dating of the terrestrial EOT has so far only been carried out on volcanic tuffs intercalated in the White River Group (WRG) in North America (Obradovich et al., 1995; Swisher and Prothero, 1990). The predominantly fluvial and eolian deposits of the WRG host one of the richest known late Eocene–Oligocene mammal fossil assemblages, which form the basis for the definition of the Chadronian, Orellan and Whitneyan North American Land Mammal Ages (NALMA) (Prothero and Emry, 1996; Prothero and Whittlesey, 1998; Wood et al., 1941). The Chadronian–Orellan boundary is considered broadly equivalent to the EOT (Prothero and Swisher, 1992; Swisher and Prothero, 1990). Stable isotope analyses of fossil mammal teeth and bones from Toadstool Geologic Park (hereafter TGP), a key WRG locality in NW Nebraska (Fig. 1.A), show a 1.0–1.5‰ increase in mean $\delta^{18}O$ across the Chadronian–Orellan transition, interpreted as 7.1 ± 3.1 °C drop in MAT (Zanazzi et al., 2007, 2009). A ca. 8 °C drop in MAT is also supported by regional paleobotanical studies from western North America (Wolfe, 1994) across this interval. However, in an alternative interpretation of the TGP stable isotope record, Boardman and Secord (2013) attributed the Chadronian–Orellan shift in tooth enamel $\delta^{18}O$ to increased aridity, resulting in a decline of wet habitats and a proliferation of less water-dependent mammals, rather than cooling.

The accuracy of published $^{40}Ar/^{39}Ar$ data from the WRG, and the TGP record itself (Obradovich et al., 1995; Swisher and Prothero, 1990), is a critical factor in the correlation of environmental change in North America to the marine EOT. The accuracy of $^{40}Ar/^{39}Ar$ dates is controlled by the accuracy of the ^{40}K decay constant, the assigned age of the mineral standard used (usually Fish Canyon sanidine, hereafter FCs), and the nature and complexity of the analyzed material. $^{40}Ar/^{39}Ar$ dates from the WRG were reported relative to an FCs age of 27.84 Ma (Swisher and Prothero, 1990), and the ^{40}K decay constant recommended by Steiger and Jäger (1977). Over the last two decades the age of FCs has been the topic of ongoing revisions, through calibration relative to primary K-Ar standards, astronomically dated tuffs, and the U–Pb system. Recent results converge towards an FCs age of ca. 28.20 Ma with an uncertainty of less than 0.1 Myr (Kuiper et al., 2008; Renne et al., 1994, 1998, 2010; Rivera et al., 2011; Wotzlaw et al., 2013). The ^{40}K decay constant has also been revised through intercalibration and statistical optimization of the $^{40}Ar/^{39}Ar$ and U–Pb systems (Min et al., 2000; Renne et al., 2010).

Recalculation of published $^{40}Ar/^{39}Ar$ data from the WRG (Swisher and Prothero, 1990) relative to an FCs age of 28.201 ± 0.046 Ma (Kuiper et al., 2008) and a ^{40}K decay constant value of 5.37×10^{-10}/yr (Min et al., 2000), both adopted in the 2012 edition of the Geological Time Scale (GTS12) (Gradstein et al., 2012), results in a 1.28%, or ca. 450 kyr increase in numerical age. This increase exceeds the typical age uncertainty quoted for the WRG tuffs, which is on the order of ±0.1–0.2 Myr (all uncertainties are 2σ unless otherwise stated), and has a significant impact on the age of events recorded in the WRG when considered relative to the marine EOT chronology based on ATPS06. Recalculated $^{40}Ar/^{39}Ar$ dates from tuffs found within magnetochrons C16n.1n–C12n (Prothero, 1996; Prothero and Swisher, 1992) are up to 600 kyr older than expected based on the ATPS06. Additionally, calibration of the TGP stable isotope record (Boardman and Secord, 2013; Zanazzi et al., 2007, 2009) relative to these recalculated $^{40}Ar/^{39}Ar$ dates suggests that the Chadronian–Orellan $\delta^{18}O$ shift predates cooling in the marine realm by ca. 600 kyr. The possible causes of these discrepancies include potential inaccuracies in the $^{40}Ar/^{39}Ar$ dataset, errors in the magnetic polarity pattern of the WRG, and/or inaccuracy of the ATPS06. However, if both the recalculated $^{40}Ar/^{39}Ar$ dates from the WRG, and the ATPS06 are accurate, the implication is that cooling and/or aridification in central North America was offset from the early Oligocene Antarctic glaciation.

Published mineralogical data (Larson and Evanoff, 1998) and a pilot study of tuffs from E Wyoming (Scott et al., 1999) point towards high-precision U–Pb dating of zircon as a viable alternative for refining the numerical age calibration of the WRG record. The accuracy of U/Pb zircon data is controlled by the accuracy of the ^{238}U decay constant, determined through alpha counting experiments (Jaffey et al., 1971), and the gravimetric calibration of isotopic tracer solutions which is traceable to SI units (Condon et al., 2015; McLean et al., 2015). As such there is a potential to produce $^{206}Pb/^{238}U$ (zircon) based radio-isotopic ages with total uncertainties of ca. 0.12% which have a resolving power (i.e., precision which does not include systematic sources of uncertainty) on the order of 0.05%. When coupled with the availability of multiple closely spaced tuffs, the high resolving power of the method allows for the assessment of complex zircon populations, and the accurate identification of analyses affected by pre- and post-eruptive bias, resulting in robust eruption ages.

In this paper we present high-precision $^{206}Pb/^{238}U$ chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) zircon dates for 15 WRG tuffs from central Wyoming and NW Nebraska (Fig. 1), six of which have been previously dated using the $^{40}Ar/^{39}Ar$ technique (Obradovich et al., 1995; Swisher and Prothero, 1990). These dates provide an improved age model for the deposition of the WRG, and are used to (i) assess whether environmental and faunal change across the EOT in North America was offset from, or coincident with, and possibly related to, changes in the marine realm, and (ii) to improve the numerical age calibration of the Chadronian–Whitneyan NALMAs.

2. Geological setting of the WRG

The WRG succession comprises fluvial and eolian deposits that accumulated in the North American midcontinent (Fig. 1.A) and adjacent Rocky Mountain basins during the late Eocene and early Oligocene (ca. 37–29 Myr). Deposits consist of fine-grained reworked volcanic sediments and, to a lesser extent, siliciclastic material derived from the Hartville, Laramie and Black Hills uplifts (Clark, 1975; Stanley and Benson, 1979), interspaced with primary air-fall tuffs. The volcanic material was sourced from explosive volcanism in Nevada and Utah (Larson and Evanoff, 1998), ca. 500–800 km south-west of the main WRG outcrops. As a result, both the thickness of individual stratigraphic units within the WRG, and the grainsize of primary volcanic tuffs decrease from south-west to north-east, as distance from the source area increases (Emry et al., 1987). The lithostratigraphic nomenclature