Eocene–Oligocene latitudinal climate gradients in North America inferred from stable isotope ratios in perissodactyl tooth enamel

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Abstract

The Eocene–Oligocene transition (~34 Ma) was one of the most pronounced episodes of climate change of the Cenozoic. In order to investigate this episode of global climate cooling in North America, we analyzed the carbon and oxygen stable isotope composition of the carbonate component of 19 perissodactyl (horse and rhino) tooth enamel samples from the Eocene–Oligocene rocks of the Cypress Hills Formation (southwestern Saskatchewan, Canada); we then compared the results with previously published data from the US Great Plains (Nebraska, South Dakota, and Wyoming). Average (±1σ) perissodactyl enamel δ13C values (vs. V-PDB) in the Eocene (−8.8 ± 0.3‰) and Oligocene (−9.0 ± 0.3‰) are indistinguishable, suggesting no major change in mean annual precipitation in Saskatchewan across the transition. The δ18O values in Saskatchewan indicate the presence of arid ecosystems and are slightly higher than those in the US Great Plains, suggesting drier conditions at higher latitudes. With respect to oxygen isotopes, average (±1σ) perissodactyl enamel δ18O values (vs. V-SMOW) in the Eocene (19.8 ± 2.0‰) and Oligocene (20.1 ± 3.6‰) are also indistinguishable, suggesting no change in the δ18O of meteoric precipitation across the transition in Saskatchewan. Enamel δ18O variability is much larger in the Oligocene vs. Eocene, indicating a large increase in temperature seasonality. This increase in enamel δ18O variability is much larger than that recorded in the US Great Plains, suggesting that higher latitudes are more sensitive to major episodes of climate change with respect to temperature seasonality. Finally, our data indicate no major change in the Oligocene vs. Eocene latitudinal gradient in local water δ18O in North America, which suggests no change in mean annual temperature gradients across the transition. This result supports the hypothesis that ascribes the climate change of the transition to a drop in atmospheric pCO2 because climate models show that this mechanism produces uniform cooling at mid-latitudes.

1. Introduction

Investigating Earth’s climate history provides context to better understand ongoing climate change and helps predict future environmental conditions. As the transition between “greenhouse” and “icehouse” worlds, the Eocene–Oligocene transition (EOT; ~34 Ma) is undoubtedly one of the most important episodes of this history (Miller et al., 1987). The marine record of the transition has been studied for several decades and is generally well understood. The global oxygen isotope record of benthic foraminifera shows a ~1.5‰ increase across the transition over ~300 kyr (Zachos et al., 2001), and has been interpreted to reflect a combination of deep seawater cooling and ice sheet growth on Antarctica. Recent studies show that the isotopic shift occurred in different steps, the first step (precursor event “EOT-1”; 33.8 Ma) was due largely to cooling whereas the following step (event “Oi-1”; 33.5 Ma) reflects a combination of cooling and ice sheet growth (Wade et al., 2012). A possible second precursor event (“EOT-2”; 33.6 Ma) may also reflect cooling of deep sea waters (Katz et al., 2008). The isotopic shifts are associated with a deepening of the carbonate compensation depth (CCD), likely caused by increased weathering of carbonate rocks in Antarctica (Coxall et al., 2005; Basak and Martin, 2013) and with extinctions and ecological reorganizations in many biological groups (see review of Coxall and Pearson, 2007). Two hypotheses have been formulated to explain the climate transition. One hypothesis attributes the cooling associated with the EOT to the opening of Southern Ocean gateways (Kennett, 1977), another with a drop in atmospheric pCO2 (DeConto and Pollard, 2003). Most recent studies support the pCO2 hypothesis in combination with orbital configurations favoring ice-sheet growth (Coxall et al., 2005; Zanazzi et al., 2007; Schouten et al., 2008; Liu et al., 2009; Pearson et al., 2009).
The terrestrial record of the transition has received much less attention than the marine and seems to show strong spatial heterogeneity, with some areas showing little change to temperature or precipitation and others showing substantial cooling and/or drying (Kohn et al., 2004; Grimes et al., 2005; Dupont-Nivet et al., 2007; Zanazzi et al., 2007; Xiao et al., 2010; Hren et al., 2013; Kocsis et al., 2014). In addition, studies performed in the US Great Plains are characterized by some inconsistencies. Paleosol, paleontological, and sedimentological studies suggest significant aridification across the EOT (Evanoff et al., 1992; Terry, 2001; Retallack, 2007). In contrast, more recent isotopic studies suggest no major change in aridity (Zanazzi et al., 2007, 2009). Studies conducted in Europe and Greenland confirm the large cooling associated with the EOT (Schouten et al., 2008; Eldrett et al., 2009; Hren et al., 2013). Given the importance of this climatic event, it is necessary to further investigate the terrestrial climate record of the transition, particularly at higher latitude locations that are expected to be more sensitive to global climate change. The main purpose of this study is therefore to present new isotopic data of enamel from perissodactyl (horse and rhino) teeth collected in Eocene–Oligocene rocks of the Cypress Hills Formation (Saskatchewan, Canada), which preserves the northernmost record of the EOT in North America (Storer, 1994). The data presented here address the following specific questions regarding the EOT in North America:

1) What was the change in the δ18O of meteoric precipitation across the EOT in Saskatchewan? Zanazzi et al. (2007), Zanazzi and Kohn (2008), and Boardman and Secord (2013) presented tooth enamel δ18O data from the US Great Plains that suggested no change in average precipitation δ18O across the transition. Here we present similar data from the Cypress Hills to investigate whether higher latitudes responded similarly to the EOT climatic event with respect to precipitation δ18O.

2) What were the latitudinal gradients in precipitation δ18O in North America in the Eocene and Oligocene? We compare average tooth enamel δ18O from the Cypress Hills and the US Great Plains to calculate latitudinal gradients in local water δ18O in North America during the Eocene and Oligocene. Because latitudinal gradients in precipitation δ18O mainly reflect gradients in temperature, these data may provide important insights on latitudinal MAT gradients in North America in the Eocene and Oligocene and on their change across the EOT.

3) What was the temperature seasonality in the Eocene and Oligocene in Saskatchewan? How did it change across the EOT? How does that compare with the change in the US Great Plains? Zanazzi et al. (2007) used the variability in tooth enamel δ18O data to calculate the temperature seasonality in the form of mean annual range of temperature (MART) in the Eocene and Oligocene in the US Great Plains. Here we use the same approach to estimate the MART in the Eocene and Oligocene in Saskatchewan. The comparison of the change in MART across the EOT at different latitudes may shed light on the longitudinal variability in temperature seasonality in a greenhouse vs. icehouse world.

4) What was the change in mean annual precipitation (MAP) across the EOT in Saskatchewan? Were there latitudinal gradients in MAP during the Eocene and Oligocene in North America? Kohn (2010) provided a quantitative relationship between modern C3 plant δ13C and MAP. We use tooth enamel δ13C to infer Eocene and Oligocene C3 plant composition and apply the equation presented by Kohn (2010) to calculate Eocene and Oligocene MAP in Saskatchewan and in the US Great Plains. We may therefore be able to determine whether significant changes in MAP occurred across the EOT in Saskatchewan and whether latitudinal gradients in MAP existed in the Eocene and Oligocene in North America.

The answers to these questions are important to investigate how mid-continent responses to major episodes of global climate change with respect to different climatic parameters.

2. Background

2.1. Carbon isotopes in teeth

Land plants are the sole source of carbon in mammalian herbivores so the carbon isotope composition of tooth enamel tracks the carbon isotope composition of the ingested plants (e.g., Cerling and Harris, 1999). In turn, the carbon isotope composition of land plants is mainly a function of the photosynthetic pathway used to fix atmospheric CO2 (Farquhar et al., 1989). The C3 pathway is the most common, occurring in all trees, almost all shrubs and herbs, and many grasses. Under modern conditions, with an atmospheric CO2 δ13C of −8‰, C3 plants have a mean δ13C value of about −28.5 ± 3‰ (Kohn, 2010). There is no evidence for either C4 or CAM photosynthesis in the Eocene–Oligocene ecosystems we studied so they will not be considered here. C3 plants, under water stress conditions, close their stomata and show less discrimination against 13C. High δ13C values (up to −22‰) are therefore characteristic of open, arid habitats (Farquhar et al., 1989). Conversely, very negative δ13C values (down to −35‰) are found in humid closed-canopy forests due to recycling of 13C-depleted CO2 and low irradiance (van der Merwe and Medina, 1991).

Plant carbon ingested by herbivores is incorporated into the mineralized tissues of the animal. In mammals, these tissues have a mineralogy similar to hydroxyapatite [Ca10(PO4)6(OH)2] with substitutions of CO3 for PO4 and OH. The CO3 component of tooth enamel therefore relates with several factors including MAT, moisture source, and air mass trajectories. Several other physiological, environmental, and behavioral factors can affect tooth enamel δ18O (Kohn, 1996). The most critical of these factors is the degree of water dependence of the animal (Kohn, 1996; Levin et al., 2006). Whereas enamel δ18O in obligate drinkers shows a first-order dependence on the δ18O of meteoric precipitation, drought-tolerant animals usually deviate to higher values because they obtain proportionally more water from leaves which are more affected by evaporative enrichment relative to surface water. Because evaporative enrichment is inversely proportional to relative humidity, Levin et al. (2006) proposed using the difference in δ18O

2. All isotope composition are expressed with the conventional δ notation in which the ratio R of heavy to light isotopes in a sample (e.g., 13C/12C or 18O/16O) is expressed as the parts per thousand or permil (‰) difference between the ratio in the sample (Rsample) and the ratio in a standard (Rstandard), normalized to Rsample: δ = [(Rsample/Rstandard) − 1] × 1000. In addition, all compositions are reported relative to the V-PDB (δ13C) and V-SMOW (δ18O) standards and all means are reported ± 1σ.
between obligate drinkers or “evaporation insensitive” (EI) taxa and drought tolerant or “evaporation sensitive” (ES) taxa as an index of terrestrial aridity.

In this study, we use the oxygen isotope composition of EI perissodactyls to reconstruct the composition of meteoric precipitation in Saskatchewan during the Eocene and Oligocene. Perissodactyls employ hind-gut fermentation, which is a relatively primitive feature that confers strong water-dependence (Kohn and Fremdt, 2007). Because of the additional factors that affect precipitation $\delta^{18}O$ besides MAT in any given location (e.g., air mass trajectory, isotope composition of moisture source regions), we do not use precipitation $\delta^{18}O$ to calculate changes in MAT across the EOT. However, we use enamel $\delta^{18}O$ zoning to estimate temperature seasonality for specific times. In this context, since teeth mineralize progressively from the occlusal surface towards the root over time scales of months to a few years, intra-tooth isotopic profiles composed of subsamples collected along the growth axis of a tooth provide an estimate of the seasonal variability in precipitation $\delta^{18}O$ which can be translated into temperature seasonality (Fricke et al., 1998; Zanazzi et al., 2007).

3. Materials and methods

3.1. Samples and study sites

A total of 19 teeth were analyzed in this study. These teeth belong to perissodactyls (horses and rhinos); some samples were identified only at the family level, others at the genus or species level. The teeth are from various fossil sites in the Cypress Hills Formation of southwestern Saskatchewan. These sites are within ~20 km from each other and are at an elevation of ~1100 m. The teeth from the Bud, Kealey Springs West (KSW), Parker Ranch/Alexander Ranch, Conglomerate Creek, Irish Springs and Calf Creek sites are late Eocene in age (Chadronian North American Land Mammal Age; NALMA), whereas the teeth from Fossil Bush and Anxiety Butte are early Oligocene in age (Orellan NALMA; Storer, 1996). The data from these teeth were compared with a more comprehensive dataset from the US Great Plains (Toadstool Park, Badlands National Park, and Torrington Quarry) and published in previous studies (Zanazzi et al., 2007; Zanazzi and Kohn, 2008). Fig. 1 shows the location of the Cypress Hills Formation and the sampling sites of Zanazzi et al. (2007) and Zanazzi and Kohn (2008).

The Cypress Hills Formation rests unconformably on rocks of the late Cretaceous Bearpaw Formation and Paleocene Ravenscrag Formation. The Cypress Hills Formation spans almost 30 Myr, from ~44 Ma (Eocene, Uinta NALMA) to ~16 Ma (Miocene, Hemingfordian NALMA). It is on average 38 m thick and consists mainly of conglomerates and sandstones deposited in a braided river plain in a semiarid climate with seasonal rainfall. These coarse sediments derived originally from the Rocky Mountains during the Laramide orogeny and were remobilized during post-orogenic unloading and rebound. Subsequent transport reflects uplift by the Eocene–Oligocene intrusions of the Sweetgrass Hills, the Bearpaw Mountains, and the Highwood Mountains in Northern Montana (Leckie and Cheel, 1989).

3.2. Sample preparation and isotope analyses

Teeth were sampled by removing 2–3 mm wide vertical strips of enamel with a slow speed diamond-wafering saw. The enamel strips

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Fig. 1. Map showing the sampling sites of this study in the Cypress Hills along with those of Zanazzi et al. (2007, 2009) and Zanazzi and Kohn (2008) in the US Great Plains (Toadstool Park, Nebraska; Badlands National Park, South Dakota; Torrington Quarry, Wyoming).
were sub-sampled perpendicular to the growth axis at intervals of 1.25 mm and the outer layer of enamel and adhering dentin were removed under a binocular microscope with a dental drill and a razor blade, respectively. Because of differences in tooth size and crown height, the number of analyzable subsamples varied among the analyzed teeth from 1 to 20. For the analyses of the carbonate component of enamel, powdered samples were treated with H₂O₂ to remove organically altered teeth from 1 to 20. For the analyses of the carbonate component height, the number of analyzable subsamples varied among the analyses of the carbonate component height.

### 4. Results

Summary descriptive statistics for the analyzed Cypress Hills teeth are reported in Table 1 (Eocene samples) and Table 2 (Oligocene samples). Both parametric (two-tailed heteroscedastic t-tests for central values and F-tests for variances) and non-parametric (two-tailed heteroscedastic t-tests for central values and F-tests for variances) statistical tests were performed on the data. Statistical significance is based on p < 0.05.

#### 4.1. Carbon isotopes

Fig. 2 shows box and whiskers plots for Eocene and Oligocene perissodactyl δ¹³C for the Cypress Hills and the US Great Plains. The δ¹³C values of Cypress Hills horses in the Eocene range from −9.7% to −8.3% and average −8.9 ± 0.4‰ whereas Eocene rhino δ¹³C values range from −9.2% to −8.2% and average −8.8 ± 0.3‰. Eocene average δ¹³C of horses vs. rhinos is not statistically different (p = 0.47 t-test; p = 0.49 Mann–Whitney test). With respect to Oligocene data, horse δ¹³C values range from −10.6% to −8.7%, and average −9.4 ± 0.6‰, rhino δ¹³C values range from −9.2% to −8.2%, and average −8.6 ± 0.2‰. Oligocene average δ¹³C of horses vs. rhinos is statistically different (p < 0.01 t-test and Mann–Whitney test). Oligocene average δ¹³C is statistically different for both horses and rhinos (p = 0.001 t-test; p = 0.002 Mann–Whitney test) and rhinos (p = 0.04 t-test; p = 0.01 Mann–Whitney test) separately. However, when horse and rhino data are pooled into perissodactyl datasets, average Eocene (−8.8 ± 0.3‰) and Oligocene (−9.0 ± 0.5‰) δ¹³C values are not statistically different (p = 0.15 t-test; p = 0.76 Mann–Whitney test). With respect to variability, intra-tooth isotope profiles generally show a very small δ¹³C range in both the Eocene and Oligocene (Figs. 3 and 4). However, variance in perissodactyl δ¹³C is probably higher in the Oligocene than in the Eocene (p < 0.001 F-test; p = 0.082 Levene test). When compared with data from Zanazzi et al. (2007) and Zanazzi and Kohn (2008), we generally find significantly higher perissodactyl average δ¹³C in the Cypress Hills than in the US Great Plains in both the Eocene (p < 0.001 t-test; p = 0.61 Mann–Whitney test) and Oligocene (p < 0.001 t-test and Mann–Whitney test). In addition, we find higher variability in perissodactyl δ¹³C in the US Great Plains relative to the Cypress Hills in both the Eocene and Oligocene (Fig. 2; p < 0.001, F-test and Levene test).

#### 4.2. Oxygen isotopes

Fig. 5 shows box and whiskers plots for Eocene and Oligocene perissodactyl δ¹⁸O in the Cypress Hills and the US Great Plains. The δ¹⁸O values of Cypress Hills horses in the Eocene range from 17.6% to 25.1% and average 21.3 ± 2.3‰; Eocene rhino δ¹⁸O values range from 16.1% to 21.1% and average 19.1 ± 1.3‰. Eocene average δ¹⁸O of horses vs. rhinos is statistically different (p = 0.001 t-test and Mann–Whitney test). With respect to Oligocene data, horse δ¹⁸O values range from 19.5% to 27.0% and average 23.7 ± 2.1‰; rhino δ¹⁸O values range from 14.4% to 21.6% and average 17.7 ± 2.0‰. Oligocene average δ¹⁸O of horses vs. rhinos is statistically different (p < 0.01 t-test and Mann–Whitney test). Similar to δ¹³C values, Eocene vs. Oligocene average δ¹⁸O is different for horses and rhinos separately (horses: p = 0.002 t-test and Mann–Whitney test; rhinos: p = 0.001 t-test and Mann–Whitney test) but not for the whole perissodactyl datasets (p = 0.61 t-test; p = 0.89 Mann–Whitney test). With respect to variability, intra-tooth profiles (Figs. 3 and 4) show a much higher range in δ¹⁸O than in δ¹³C and variance in the perissodactyl δ¹⁸O datasets is remarkably higher in the Oligocene (12.8%) than in the Eocene (3.9%); (p < 0.001 F-test and Levene test). Relative to the US Great Plains data,

### Table 1

Summary statistics of the carbon and oxygen isotope compositions of the Cypress Hills Eocene teeth analyzed in this study.

<table>
<thead>
<tr>
<th>Tooth ID</th>
<th>Taxon</th>
<th>Site</th>
<th>Tooth position</th>
<th>n subsamples</th>
<th>Mean δ¹³C (‰, V-PDB)</th>
<th>SD (‰)</th>
<th>Mean δ¹⁸O (‰, V-SMOW)</th>
<th>SD (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2787.1</td>
<td>Trigonias osborni</td>
<td>Bud</td>
<td>left M3</td>
<td>8</td>
<td>−8.6</td>
<td>0.2</td>
<td>18.2</td>
<td>1.1</td>
</tr>
<tr>
<td>P2551.29</td>
<td>Rhino</td>
<td>KSW</td>
<td>right p4</td>
<td>2</td>
<td>−8.7</td>
<td>0.0</td>
<td>20.8</td>
<td>0.4</td>
</tr>
<tr>
<td>P2551.29</td>
<td>Rhino</td>
<td>KSW</td>
<td>right p4</td>
<td>13</td>
<td>−8.6</td>
<td>0.1</td>
<td>20.2</td>
<td>0.8</td>
</tr>
<tr>
<td>CH 71-1</td>
<td>Rhino</td>
<td>Irish Springs</td>
<td>?</td>
<td>14</td>
<td>−9.1</td>
<td>0.1</td>
<td>18.2</td>
<td>0.6</td>
</tr>
<tr>
<td>P2595.5</td>
<td>Mesotherium</td>
<td>Parker Ranch/Alexander Ranch</td>
<td>right M1 or M2</td>
<td>3</td>
<td>−8.8</td>
<td>0.0</td>
<td>20.5</td>
<td>0.3</td>
</tr>
<tr>
<td>P2595.5</td>
<td>Mesotherium</td>
<td>Bud</td>
<td>right M1 or M2</td>
<td>3</td>
<td>−8.8</td>
<td>0.0</td>
<td>22.7</td>
<td>1.0</td>
</tr>
<tr>
<td>P2549.5</td>
<td>Mesotherium</td>
<td>Bud</td>
<td>left m1 or m2</td>
<td>2</td>
<td>−9.6</td>
<td>0.1</td>
<td>23.3</td>
<td>0.1</td>
</tr>
<tr>
<td>P2754.4</td>
<td>Mesotherium</td>
<td>Conglomerate Creek</td>
<td>right M1 or M2</td>
<td>3</td>
<td>−9.2</td>
<td>0.1</td>
<td>20.5</td>
<td>1.9</td>
</tr>
<tr>
<td>P1585.1542</td>
<td>Mesotherium propinquus</td>
<td>Calf Creek</td>
<td>left P4 or M7</td>
<td>4</td>
<td>−8.6</td>
<td>0.2</td>
<td>18.6</td>
<td>1.2</td>
</tr>
<tr>
<td>P1585.1546</td>
<td>Mesotherium propinquus</td>
<td>Calf Creek</td>
<td>right m2</td>
<td>3</td>
<td>−8.4</td>
<td>0.1</td>
<td>24.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### Table 2

Summary statistics of the carbon and oxygen isotope compositions of the Cypress Hills Oligocene teeth analyzed in this study.

<table>
<thead>
<tr>
<th>Tooth ID</th>
<th>Taxon</th>
<th>Site</th>
<th>Tooth position</th>
<th>n subsamples</th>
<th>Mean δ¹³C (‰, V-PDB)</th>
<th>SD (‰)</th>
<th>Mean δ¹⁸O (‰, V-SMOW)</th>
<th>SD (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2389.1</td>
<td>Rhino</td>
<td>Fossil Bush</td>
<td>right m1 or m2</td>
<td>20</td>
<td>−8.7</td>
<td>0.1</td>
<td>16.8</td>
<td>0.9</td>
</tr>
<tr>
<td>P2442.70</td>
<td>Rhino</td>
<td>Fossil Bush</td>
<td>right m1 or m2</td>
<td>10</td>
<td>−8.5</td>
<td>0.2</td>
<td>20.5</td>
<td>0.5</td>
</tr>
<tr>
<td>CH 31-2</td>
<td>Rhino</td>
<td>Fossil Bush</td>
<td>?</td>
<td>9</td>
<td>−8.8</td>
<td>0.2</td>
<td>17.0</td>
<td>2.1</td>
</tr>
<tr>
<td>P2707.18</td>
<td>Mesotherium</td>
<td>Fossil Bush</td>
<td>left p3 or p4</td>
<td>8</td>
<td>−9.5</td>
<td>0.2</td>
<td>25.0</td>
<td>1.1</td>
</tr>
<tr>
<td>P 1011.2</td>
<td>Mesotherium</td>
<td>Anxiety Butte</td>
<td>right m1 or m2</td>
<td>7</td>
<td>−9.8</td>
<td>0.6</td>
<td>23.9</td>
<td>2.0</td>
</tr>
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<td>P2442.26</td>
<td>Mesotherium</td>
<td>Fossil Bush</td>
<td>right m1 or m2</td>
<td>4</td>
<td>−8.8</td>
<td>0.1</td>
<td>22.2</td>
<td>2.0</td>
</tr>
<tr>
<td>ROM A575</td>
<td>Mesotherium</td>
<td>Fossil Bush</td>
<td>right P2</td>
<td>2</td>
<td>−10.1</td>
<td>0.3</td>
<td>21.1</td>
<td>0.8</td>
</tr>
<tr>
<td>P2360.1</td>
<td>Mesotherium</td>
<td>Anxiety Butte</td>
<td>right m1 or m2</td>
<td>3</td>
<td>−8.8</td>
<td>0.0</td>
<td>23.1</td>
<td>1.9</td>
</tr>
<tr>
<td>P2225.26</td>
<td>Mesotherium</td>
<td>Fossil Bush</td>
<td>right P1</td>
<td>1</td>
<td>−9.1</td>
<td>NA</td>
<td>27.0</td>
<td>NA</td>
</tr>
</tbody>
</table>
we find lower perissodactyl $\delta^{18}O$ in the Cypress Hills in both the Eocene and Oligocene ($p < 0.001$ t-test and Mann–Whitney test). The difference between the average perissodactyl $\delta^{13}C$ values in the Cypress Hills and in the US Great Plains is, however, similar for the Eocene ($5.1 \pm 2.4$‰) and Oligocene ($4.3 \pm 4.0$‰). Finally, we find higher perissodactyl $\delta^{13}C$ variability in the Cypress Hills than in the US Great Plains in both the Eocene and Oligocene ($p < 0.001$ F-test and Levene test).

5. Discussion

The changes in average $\delta^{13}C$ and $\delta^{18}O$ values across the EOT for horses and rhinos are opposite. More specifically, whereas horse average $\delta^{18}O$ increases across the EOT (from 21.3‰ to 23.7‰), rhino average value decreases (from 19.1‰ to 17.7‰). Similarly, whereas the average $\delta^{13}C$ of horses decreases from the Eocene (−8.9‰) to the Oligocene (−9.4‰), rhino average $\delta^{13}C$ increases, albeit only slightly (from −8.8‰ to −8.6‰). These opposite changes may be due to migration of the animals or simply to noise in the data, a feature found in other analogous datasets. For example, in an isotope study of fossil teeth in central Oregon (Kohn and Fremdt, 2007), small numbers of analyses for horses appear to bias data scatter and mean values relative to sympatric rhinos and similarly-sized oreodonts. A pooled dataset, however, gives more realistic values. Similarly, comparison of horses and rhinos at Toadstool Park fails to resolve a consistent isotopic offset, but rather indicates considerable scatter (Zanazzi et al., 2007; Zanazzi and Kohn, 2008; Boardman and Secord, 2013). As a consequence, to improve signal-to-noise, we pooled the data for horses and rhinos and discuss them in terms of perissodactyls datasets. Similar water dependencies of horses and rhinos (both are EI...
taxa; Levin et al., 2006) and similar habitat and diet (Zanazzi and Kohn, 2008) support this choice; the pooled datasets also provide the minimal number of samples required to accurately reconstruct palaeoclimates and palaeoenvironments (Hoppe et al., 2005).

5.1. Carbon isotopes

The δ13C data presented here are consistent with an expected pure C3 diet for the investigated perissodactyls. In C3 plants, δ13C values mainly reflect aridity and degree of vegetation openness. Therefore, the indistinguishable Eocene vs. Oligocene average perissodactyl δ13C in Saskatchewan suggests no major change in aridity across the EOT, confirming the results of Zanazzi et al. (2007) for the US Great Plains. In addition, high δ13C values are consistent with relatively dry environments in both the Eocene and Oligocene. The higher variability in Oligocene vs. Eocene perissodactyl δ13C values may indicate more variable precipitation and longer dry periods in the Oligocene than in the Eocene, although intra-tooth profiles show very small variability in both time periods. The higher average δ13C in Cypress Hills relative to the US Great Plains likely implies slightly drier condition at higher latitudes. Finally, the larger variability in perissodactyl δ13C in the US Great Plains relative to the Cypress Hills likely reflects the presence of a higher variety of ecosystems, given the larger spatial spread of the sampling sites in the US Great Plains.

The equation provided by Kohn (2010) can be rearranged (Kohn and McKay, 2012) to calculate MAP's based on enamel δ13C:

\[
\text{MAP (mm/yr)} = 10^{\frac{\delta^{13}C_{\text{fossil}} - 10.21}{0.0124 - \Delta \text{latitude} - \left(1.5 \times 10^{-6} \times \text{altitude}\right)}} - 300.
\]

Using a value of 14.6‰ for the enrichment in 13C between enamel and diet for the perissodactyls (Passey et al., 2005) and offsets of 2‰ (Eocene) and 1.9‰ (Oligocene) between the δ13C of modern and Eocene–Oligocene CO2 (Tiptle et al., 2010; i.e., δ13C_{fossil} = δ^{13}C_{\text{fossil}} - 14.6 - 2.0 and δ13C_{Eocene/Oligocene} = δ^{13}C_{\text{enamel}} - 14.6 - 1.9), a value of 49° for the absolute latitude and 1100 m for the altitude, we calculated MAP values of 127 mm/year in the Eocene and 130 mm/year in the Oligocene in the Cypress Hills. For the US Great Plains (latitude = 43°, altitude = 1370 m), we calculated MAP values of 215 mm/year and 230 mm/year for the Eocene and Oligocene, respectively. Although the uncertainties associated with these numbers are large (approximately half the calculated value; Kohn and McKay, 2012) these values are unrealistically low. Several possibilities might explain these low values, the most likely being an unknown diagenetic effect on enamel δ13C or an incorrect estimate of atmospheric CO2 δ13C from benthic fora- minifera. Further studies are required to resolve this issue.

5.2. Oxygen isotopes

As seen in the US Great Plains (Zanazzi et al., 2007; Zanazzi and Kohn, 2008; Boardman and Secord, 2013), the average enamel δ18O of the perissodactyls from the Cypress Hills does not change across the EOT, suggesting no change in local water composition. Because seawater δ18O increased by ~1‰ due to the ice volume effect across the transition (Katz et al., 2008), the δ18O of precipitation decreased by ~1‰ relative to seawater. This decrease might indicate either a small MAT decrease across the transition in Saskatchewan if aridity and atmospheric circulation did not change (which seems unlikely), or a larger decrease along with a shift in atmospheric circulation. Without independent knowledge of temperature (e.g., from an independent isotope proxy), moisture sources, air mass trajectories and aridity, δ18O shifts of tooth enamel or local water cannot be interpreted in terms of temperature change alone. This fact is well established in the literature. For example, shifting moisture patterns plus ice volume during the Last Glacial Maximum drove a ~1% increase in δ18O values of precipitation in Texas relative to today despite a ~4 °C lower MAT (Koch et al., 2004; Bracconnet et al., 2007; Kohn and McKay, 2010). Similarly, a decrease in MAT of 4–6 °C in England across the EOT produced no resolvable change to local water compositions (Hren et al., 2013). Thus, assertions that quasi-constant enamel isotope compositions from the Great Plains preclude large temperature changes across the EOT (e.g., Boardman and Secord, 2013) are unfounded.

With respect to seasonality, variability in Oligocene vs. Eocene perissodactyl δ18O values increased markedly, suggesting either a substantial increase in temperature seasonality across the EOT in Saskatchewan or a shift in seasonal moisture sources (i.e., proportions of moisture sources from the Gulf of Mexico vs. from the Pacific Ocean and from the continental polar/arctic regions). This increase in variability is much larger than that recorded in the US Great Plains, suggesting a larger sensitivity of higher latitudes to episodes of global climate change, at least with respect to seasonality. If the variation is ascribed solely to temperature seasonality, then the 5–95 percentile interval of an entire δ18O enamel dataset can be used to estimate intra-annual temperature variability. This interval can then be used, along with a temperature coefficient of seasonal variations in precipitation δ18O and a damping factor that accounts for the residence time of O2 in the animals, to estimate the MAT at a given location. These estimates carry large uncertainties, in part because they do not account for the damping effect of the enamel maturation process, for the averaging compositions in large water bodies (i.e., rivers and lakes), and for increased variation in leaf water δ18O in response to seasonal changes in humidity (Kohn, 1996). Nevertheless, using the perissodactyls 5–95 percentile interval for the Eocene (r = 6.1‰) and Oligocene (r = 10.5‰), a temperature coefficient for seasonal variation in precipitation δ18O (c) equal to 0.3‰/°C (Kohn and Welker, 2005), a damping factor (d) of 0.9 (Kohn et al., 2002), and a slope (m) for the line of modern perissodactyls δ18O vs. local water δ18O of 0.96 (this value is the average of horses and rhinos; Tütken et al., 2006 and Zanazzi et al., 2007), MART can be calculated using the following equation:

\[
\text{MART} \geq r \times m \times c \times d.
\]

MART values in Saskatchewan apparently increase from 21.7 °C (Eocene) to 37.3 °C (Oligocene). The Oligocene value is similar to the modern MART in Regina, SK (35 °C; NCDC, 2009). The apparent increase in MART across the transition in Saskatchewan far exceeds that recorded in the US Great Plains (from 21.9 °C to 25.8 °C; Zanazzi et al., 2007) and that calculated in coastal areas. For example, Eldrett et al. (2009) found an increase in MART of ~8 °C in Greenland whereas Ivany et al. (2000) found an increase of ~4 °C in the US Gulf coastal plain.

With respect to latitudinal gradients, the difference between the δ18O values in the US Great Plains vs. Saskatchewan (4–5‰) does not resolvable change from the Eocene to Oligocene. Gradients in modern local water δ18O in the mid-continents mainly reflect gradients in MAT, and if the same principles hold for the Eocene–Oligocene, our data suggest no change in latitudinal MAT gradients across the EOT in North America. This finding supports the CO2 hypothesis as a causal mechanism for the climate change across the EOT because model experiments predict uniform cooling at these latitudes with decreasing atmospheric CO2 levels (Rind, 1986).

We used here the relationship between rainwater δ18O and the δ18O of the carbonate component of enamel calculated for modern horses and rhinos to estimate a value for rainwater δ18O in Saskatchewan. The equation for horses is the following (Zanazzi et al., 2007):

\[
\delta^{18}O_{\text{water}} = 1.16 \delta^{18}O_{\text{enamel}} - 36.4
\]

whereas that for rhino is (Tütken et al., 2006):

\[
\delta^{18}O_{\text{water}} = 0.76 \delta^{18}O_{\text{enamel}} - 25.64.
\]
Using these equations, the average $\delta^{18}O$ value for horses (22.7‰) and rhinos (18.4‰), we found a value for local water $\delta^{18}O$ in Saskatchewan of $-10.1$‰ (horses) and $-11.7$‰ (rhinos). Taking an average of the two values ($-10.9$‰), and a value calculated for the US Great Plains ($-8.2$‰; Zanazzi et al., 2007) yields a latitudinal gradient in local water $\delta^{18}O$ of approximately 0.45‰/°lat. This gradient is slightly lower than the modern value for precipitation (0.6‰/°lat), is similar to values previously calculated for the Eocene (0.4‰/°lat; Fricke and Wing, 2004), and is higher than values calculated for the mid-Cretaceous greenhouse (−0.3‰/°lat; Suarez et al., 2012). These observations generally support the view that global cooling increases latitudinal temperature and isotopic gradients, at least at mid-latitudes.

6. Conclusions

New data are presented for the carbon and oxygen stable isotope composition of the carbonate component of enamel from rhino and horse teeth collected in the Eocene–Oligocene rocks of the Cypress Hills Formation (Saskatchewan, Canada) and compared with previously published data from the US Great Plains. Our data indicate that:

1) Average precipitation $\delta^{18}O$ did not change across the Eocene–Oligocene transition in Saskatchewan, similar to observations in the US Great Plains (Zanazzi et al., 2007). This result suggests that higher and lower latitudes in North America responded similarly to the climatic change associated with the transition with respect to average precipitation $\delta^{18}O$.

2) Latitudinal gradients in precipitation $\delta^{18}O$ in North America did not change across the Eocene–Oligocene transition. We calculate a value of 0.45‰/°lat for both the Eocene and Oligocene. This result supports the hypothesis that ascribes the climate cooling across the EOT to a drop in atmospheric pHCO2, as this mechanism is expected to produce uniform cooling at mid-latitudes.

3) Temperature seasonality increased greatly across the Eocene–Oligocene transition in Saskatchewan. This increase is much larger than that recorded in the US Great Plains, suggesting that temperature seasonality at higher latitudes responds more sensitively to major episodes of climate change.

4) Mean annual precipitation did not change substantially across the Eocene–Oligocene transition in both Saskatchewan and the US Great Plains. Precipitation was probably slightly lower in Saskatchewan in both the Eocene and Oligocene and values are characteristic of very dry ecosystems.

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References


