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Notes

Use of multiple oxygen isotope proxies for elucidating Arctic Cretaceous palaeo-hydrology

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Abstract: Stable oxygen isotope analysis of siderite and dinosaur tooth enamel phosphate from the Campanian–Maastrichtian Prince Creek Formation, Alaska, USA, are analysed to determine the palaeohydrology of the ancient Colville Basin north of the Ancestral Brooks Range. $\delta^{18}\text{O}$ of freshwater siderites relative to V-PDB ranges between -14.86 and -16.21% . Dinosaur tooth enamel $\delta^{18}\text{O}$ from three different sites (Kikak–Tegoseak, Peditomys Point, Liscomb) range between $+3.9\%$ and $+10.2\%$. $\delta^{18}\text{O}_{\text{meteoric water}}$ are calculated from $\delta^{18}\text{O}_{\text{siderite}}$ that formed at seasonal temperatures ranging from -2 to $14.5\text{ }^{\circ}\text{C}$, with a mean annual temperature of $6.3\text{ }^{\circ}\text{C}$. At $6.3\text{ }^{\circ}\text{C}$, the $\delta^{18}\text{O}_w$ calculated from siderite ranged between -22.23 and -20.89% V-SMOW. Ingested water compositions are estimated from dinosaur teeth assuming body temperatures of $37\text{ }^{\circ}\text{C}$ and local relative humidity of 77.5% , resulting in values ranging from -28.7 to -20.4% V-SMOW, suggesting consumption of meteoric water and orographically depleted runoff from the Brooks Range. The ranges in calculated $\delta^{18}\text{O}_{\text{meteoric water}}$ are compatible between the two proxies, and are mutually corroborating evidence of extremely ^{18}O -depleted precipitation at high latitudes during the Late Cretaceous relative to those generated using general circulation models. This depletion is proposed to result from increased rainout effects from an intensified hydrological cycle, which probably played a role in sustaining polar warmth.

Supplementary material: Parameters used for generation of equations compared to Kohn (1996) can be found at <http://www.geolsoc.org.uk/SUP18642>

Stable isotopic proxies are invaluable tools for understanding past and current climates. Pedogenic carbonates (siderite and calcite) are commonly used to determine the isotopic composition of meteoric water (Lohmann 1988; Hays & Grossman 1991; Ludvigson *et al.* 1998; Ufnar *et al.* 2004a; Suarez *et al.* 2011). When analysed over a range of latitudes, the resulting isotopic gradients can be used to determine global isotopic groundwater gradients. This gradient is related to the isotopic composition of the precipitation, which is itself related to temperature gradients, humidity and, in some instances, orographic effects.

Isotopic studies of the Cretaceous are of particular importance because future climatic conditions

(Kiehl 2011) are predicted to approach those ($p\text{CO}_2$, temperature) seen in the various greenhouse worlds of the Cretaceous. Several studies on the Cretaceous climate have revealed shallow equatorial-to-pole air and ocean temperature gradients (Wolfe & Upchurch 1987; Amiot *et al.* 2004; Jenkyns *et al.* 2004; Puc at *et al.* 2007), while others have indicated equator-to-pole precipitation $\delta^{18}\text{O}$ gradients that are steeper than the modern climate system (Ludvigson *et al.* 1998; Ufnar *et al.* 2002; Suarez *et al.* 2011). This steep gradient has been explained as resulting from increased rainout, thereby increasing latent heat transport from the equator to the poles during greenhouse conditions (Ufnar *et al.* 2004b). These conclusions are based on empirical

data, but general circulation models (GCMs) with isotopic capabilities have not been able to reproduce the steep isotopic gradient (Poulsen *et al.* 2007) at high latitudes. The inability of Earth system models to simulate empirically derived data has been explained by postulating local orographic effects as having confounded the high latitude data set. Consequently, additional studies of high-latitude regional climates are important for better understanding the disparity between GCM results and empirically derived data. Can the addition of vertebrate stable isotope proxies help to better understand regional palaeohydrology in the context of global climate change?

The sensitivity of the Arctic to climate changes makes it an ideal place to investigate past greenhouse states of the Earth. The Arctic preserves sediments deposited in greenhouse states, including the Palaeocene–Eocene thermal maximum (PETM) and the Cretaceous (the focus of this study) (Ufnar *et al.* 2004a; Pagani *et al.* 2006; Jahren *et al.* 2009). Investigation of these past climates suggests that during exceptional warmth, the Arctic was devoid of ice caps and sustained considerable biodiversity atypical of high latitudes today (e.g. lush deciduous forests in the middle Eocene (Jahren *et al.* 2010) and champsosaurs in the Cenomanian–Turonian (Tarduno *et al.* 1998; Vandermark *et al.* 2007)). The lack of ice caps, which decreases albedo, and the presence of dark-coloured vegetation, which increases insolation, acted as a positive feedback that helped sustain these warm climates of the Arctic (Hay & DeConto 1999). As current $p\text{CO}_2$ and temperatures increase, the not-too-distant future of the Arctic may become increasingly similar to the Arctic of the Cretaceous (Kiehl 2011).

The use of vertebrate remains as proxy data has some advantages over other palaeo proxies. Phosphate tends to be more resistant to diagenesis (Kolodny *et al.* 1996; Sharp *et al.* 2000) and may be a reliable proxy for water $\delta^{18}\text{O}$. Also, thermoregulating animals that grow their phosphate at a constant or near-constant body temperature can be analysed without having to determine temperature independently. As land-dwelling animals get their water from a variety of sources, they can also sample the full spectrum of freshwater isotopic compositions of a particular region (Barrick *et al.* 1999).

This study uses the vertebrate remains of dinosaurs from the Arctic Prince Creek Formation (PCF, late Campanian to early Maastrichtian) as an additional proxy for surface-water isotopic compositions to augment data from pedogenic siderites (Ufnar *et al.* 2004a). The $\delta^{18}\text{O}$ composition of phosphate from tooth enamel is used to calculate ingested surface water, and is compared to meteoric water values estimated from pedogenic siderite preserved in the PCF. The isotopic compositions

of vertebrates and pedogenic carbonates from other foreland basin settings have been used to identify local orographic effects (Suarez *et al.* 2012). Therefore, the comparison of vertebrate ingested water with local groundwater is carried out to determine the range in isotopic compositions of surface waters, and to determine if there is a significant orographic effect on meteoric water from the ancestral Brooks Range. Comparisons to estimates of the $\delta^{18}\text{O}$ of meteoric water from the underlying Nanushuk Formation (Albian–Cenomanian) are also made to determine whether the $\delta^{18}\text{O}$ of PCF meteoric waters are as depleted in ^{18}O during the slightly cooler Late Campanian–Early Maastrichtian interval, and from sampling sites much further removed from the ancestral Brooks Range than those initially studied by Ufnar *et al.* (2004a).

Stable isotopes in vertebrate bioapatite

The isotopic composition of continental vertebrates is primarily controlled by ingested surface water/living water and relative humidity (Kohn 1996). Offsets in $\delta^{18}\text{O}_w$ across the landscape can be recorded in bioapatites of the taxa that live in or consume it. As a result, the isotopic composition of vertebrate tooth enamel can be used to determine the range of the isotopic composition of surface water. Pedogenic calcite and siderite are known to record the average or slightly ^{18}O -enriched end-member (in the case of calcite) isotopic composition of meteoric water (Lohmann 1988; Cerling & Quade 1993; Cojan *et al.* 2003; Breecker *et al.* 2009; Suarez *et al.* 2009). Because pedogenic carbonates form in one location, they are less likely to record a wide range in the surface water isotopic composition, for example, from river water draining mountainous regions v. precipitation. Large-bodied thermoregulating terrestrial animals (non-aquatic) all demonstrate a similar relationship between ingested surface water and the $\delta^{18}\text{O}$ of tooth phosphate (Kohn 1996), with the dominant influences for $\delta^{18}\text{O}_p$ being surface water, diet and relative humidity. Terrestrial animal body water tends to be enriched compared to local drinking water as a result of water loss by panting or transcutaneous water loss (evaporative enrichment). This trend, however, is highly dependent on humidity. Herbivore enamel tends to be enriched relative to carnivores because of the consumption of isotopically ^{18}O -enriched plant leaves. Leaf water tends to be ^{18}O -enriched due to evaporation of water during photosynthesis, with the degree of enrichment again being highly dependent on relative humidity (low humidity = highly enriched leaf water). Source water can be significantly ^{18}O -depleted relative to local meteoric (rain) water if animals are

ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

consuming a significant portion of water from rivers sourced from high elevations where precipitation is depleted due to orographic rainout, cooler temperatures and/or melting snow (e.g. Dettman & Lohmann 2000). As a result, the analysis of land-dwelling vertebrates can be used to determine the range of regional hydrology, which is not available from the analysis of pedogenic carbonates. Thus, the combination of terrestrial vertebrate enamel and pedogenic siderites from the PCF is used to determine the range in palaeohydrology in the Campanian–Maastrichtian Arctic.

Geological/tectonic and palaeoclimatic setting

Geological and tectonic setting

The PCF is an alluvial succession deposited on a tidally influenced, high-latitude coastal plain in what is now known as the Colville Basin (Flaig *et al.* 2011). These sediments were shed during the rise of the ancestral Brooks Range (Fig. 1), which, during the Cretaceous, was a few hundred kilometres to the south (Fiorillo *et al.* 2010a). The ancestral Brooks Range was at least 1.5 km in elevation (Spicer 2003). Regionally, the PCF dips *c.* 3° to the north (Fiorillo *et al.* 2010a; Gangloff & Fiorillo 2010). It interfingers with the shallow marine Schrader Bluff Formation. Both formations are unconformably overlain by the Pliocene–Holocene Gubik Formation along the Colville River (Fiorillo *et al.* 2010a). The palaeo-latitude of Cretaceous rocks in this area is thought to be between 82° and 85°N (Witte *et al.* 1987; Besse & Courtillot 1991; Rich *et al.* 2002; Spicer & Herman 2010). Ash layers in the vicinity of the Liscomb Bonebed returned weighted mean K–Ar and ⁴⁰Ar/³⁹Ar ages of 69.1 ± 0.3 Ma (Conrad *et al.* 1990) and 69.2 ± 0.5 Ma (Flaig 2010), which is consistent with an Early Maastrichtian age (Maastrichtian = 70.6–65.5 Ma, ICS 2010 Geologic Time Scale) suggested by palynological data (Frederiksen 1990; Fiorillo *et al.* 2010a, b; Flaig *et al.* 2013).

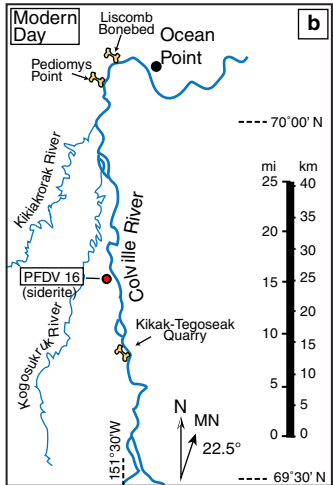
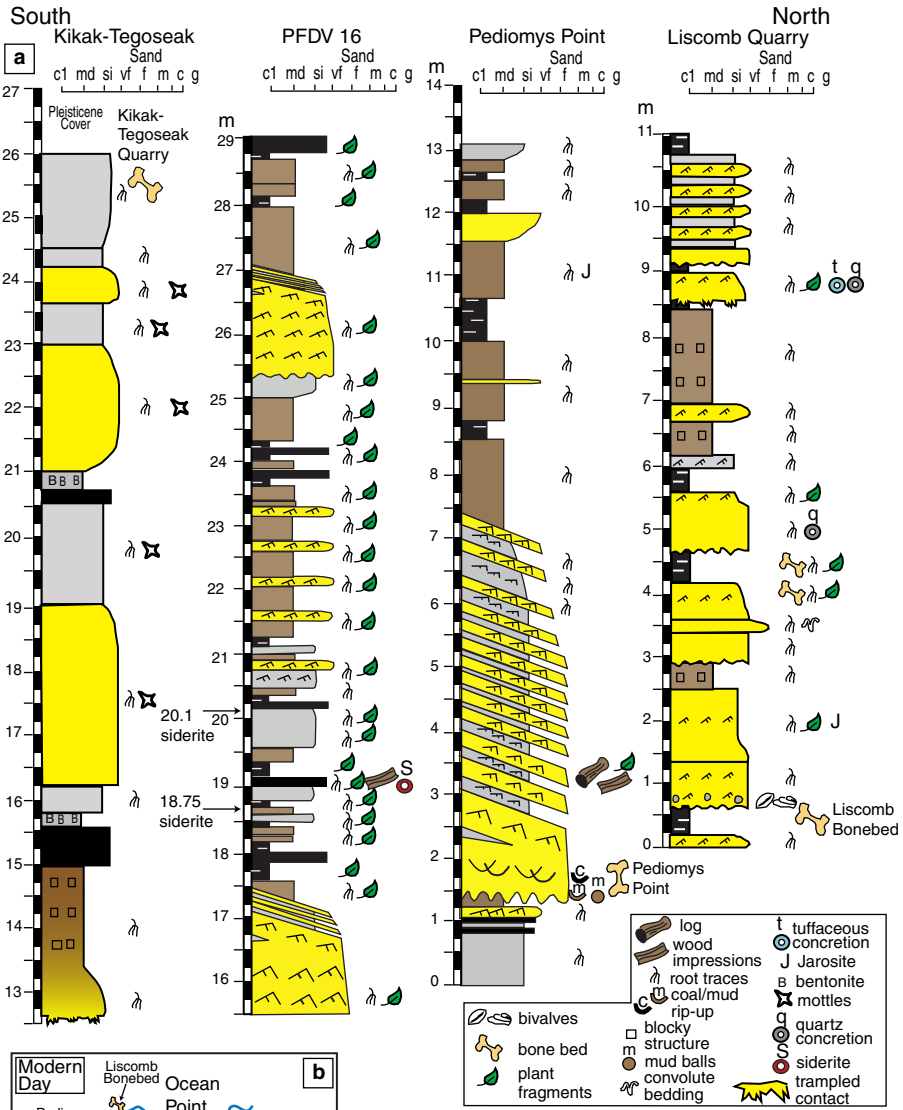
The PCF was deposited on a high-latitude Arctic coastal plain (Flaig *et al.* 2011). Occasional marine transgression and marine influence on sedimentation is evidenced by the tidal influence in fluvial deposits and the presence of jarosite, pyrite and gypsum (as a pyrite weathering product), all of which increase in abundance up-section near the contact between the PCF and the overlying Schrader Bluff Formation (Flaig 2010; Flaig *et al.* 2011). PCF palaeoenvironments include meandering trunk channels, meandering and fixed distributary channels, crevasse splays, levees, swamps, small lakes and ponds, and poorly developed palaeosols with

redoxomorphic features (Fiorillo *et al.* 2010a; Flaig 2010; Flaig *et al.* 2011). Trunk channel are 13+ m-thick, fining-upward successions containing basal lags with trough cross-bedded sandstones, inclined heterolithic stratification (IHS), convolute bedding, isolated bone fragments, logs, wood impressions and plant fragments (Flaig *et al.* 2011). Meandering distributary channels are thinner (2–6 m thick) and finer-grained, but also contain IHS. Third-order fixed distributary channels are the thinnest channel-form deposits (1.5–3.0 m thick) and lack prominent lateral accretion surfaces, containing only rare IHS. Crevasse splays are thinner interbedded siltstone and mudstone deposits. Levees are characterized by tabular sandstones up to 1 m thick overlain by successive intervals of olive-grey to dark brown siltstone and sandy siltstone. Abundant root traces, plant fragments, bioturbation and ferruginous nodules suggest weak soil development on splays and levees. Organic-rich floodplain deposits include organic-rich siltstone, carbonaceous shale, mudstone and coal, recording deposition in floodplain lakes, ponds, swamps and weak palaeosol development. The majority of bone beds are found encased in crevasse splays or overbank flood facies (Fiorillo *et al.* 2010a, b; Flaig 2010; Flaig *et al.* 2011).

Palaeosols of the PCF are similar to modern entisols, inceptisols and potential acid sulphate soils (Flaig *et al.* 2011). Palaeosols show redoximorphic features that are characteristic of alternating waterlogged and well-drained periods (Fiorillo *et al.* 2010a).

The majority of vertebrate remains analysed in this study come from three dinosaur quarries (Fig. 1): Kikak–Tegoseak, Liscomb Bonebed and Pediomys Point. Based on a regional dip of 3° to the north, the site furthest to the south, Kikak–Tegoseak is the oldest site and separated by hundreds of metres from the next stratigraphically higher site, Pediomys Point, which is separated by hundreds of metres from the uppermost site, Liscomb Bonebed. Unfortunately, incomplete, semi-continuous exposures along the Colville River do not allow for direct correlation of the stratigraphy between the three sites.

The Kikak–Tegoseak quarry contains floodplain facies including rooted very fine sandstone and siltstone. Bones show no signs of significant abrasion or weathering (no higher than weathering level 2), but do show some root etching and borings reminiscent of dermestid beetles. The majority of the remains from Kikak–Tegoseak are from the centrosaurine ceratopsian *Pachyrhinosaurus* (Fiorillo *et al.* 2010a, b). The large size of the associated bones and fine-grained matrix suggests that whole or partial carcasses floated into the site carried by relatively low-energy currents.



ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

Pediomys Point contains fine- to medium-grained sandstone, siltstone and mudstone deposited in meandering distributary channels, mud-filled abandoned channels and interdistributary environments that include crevasse splays, small lakes or ponds, swamps, floodplain palaeosols and ashfall deposits (Flaig 2010). Abundant jarosite (altered pyrite) and rare brackish-water clams and gastropods suggest a marine influence and a distal coastal plain setting. Fossils from Pediomys Point include the teeth of osteichthyans, dromaeosaurs, hypsilophodonts, pachycephalosaurs, hadrosaurids and mammals.

The Liscomb Bonebed contains organics (6.8–10.5% total organic content, TOC) sandy, argillaceous tuffaceous siltstone and mudstone. Most clays are smectitic and the presence of pyrite and jarosite indicates that it was close to the marine interface. Taphonomic study of the site suggests it was a mass mortality of sub-adult to juvenile *Edmontosaurus*, which were deposited by overbank floods (Gangloff & Fiorillo 2010). Nearby ashes indicate an approximate age of 69.1 ± 0.3 Ma for sediments (Conrad *et al.* 1990; Flaig 2010).

Palaeoclimatic, palaeoenvironmental setting and fauna

Palaeo-temperatures, based on plant remains, suggest the Campanian–Maastrichtian North Slope of Alaska ranged from a cold month mean no colder than -2°C to a warm month mean of 14.5°C , and averaged $6.3 \pm 2.2^\circ\text{C}$ (based on the CLAMP and TEX₈₆ analysis of Spicer & Herrman (2010)), which is in general agreement with earlier leaf physiognomy work (Spicer & Parrish 1990). Precipitation estimates for the PCF ranged between 500 to 1500 mm/yr (Spicer & Parrish 1990). Globally, there is evidence for two warming events in the Maastrichtian (Li & Keller 1998; Barrera & Savin 1999; Nordt *et al.* 2003; Wilf *et al.* 2003) that may overlap with the timing of the PCF deposition. The older of these two warming events occurred between 69.5 and 68.5 Ma and is associated with increases in atmospheric $p\text{CO}_2$ concentrations of 1000–1200 ppmv (Nordt *et al.* 2003). This increase in $p\text{CO}_2$ may have caused global mean annual temperatures to be $c. 22^\circ\text{C}$ and is correlated with an increase in ocean temperatures of $c. 3^\circ\text{C}$ and associated with the initiation of increased volcanic activity in the Indian Deccan traps (Hofman *et al.* 2000). This $p\text{CO}_2$ and temperature peak is also correlated

to the mid-Maastrichtian Event, in which a minor extinction occurred prior to the more extreme late Maastrichtian extinction event (Frank & Arthur 1999; Keller 2001; Bralower *et al.* 2002). Although the 69 Ma global warming event increased temperatures relative to the Santonian, mean annual temperatures (MATs) during PCF deposition were not as high as in the Aptian–Albian global warming event, when the MAT during deposition of the Nanushuk Formation was $c. 11^\circ\text{C}$ (Wolfe & Upchurch 1987; Spicer & Corfield 1992) or during deposition of the Turonian–Coniacian Tuluvak Formation, which may have been even warmer with a MAT of $c. 13^\circ\text{C}$ (Parrish *et al.* 1987; Spicer & Parrish 1990). This is also evidenced by the lack of turtle or crocodile remains in the PCF (Fiorillo *et al.* 2010a; Gangloff & Fiorillo 2010). Turtles and crocodiles are present in the Nanushuk and Tuluvak formations (Gangloff & Fiorillo 2010); they do not live in areas with prolonged near-freezing seasons (Markwick 1998).

The PCF is characterized by a high quantity of low-diversity vertebrate fauna, with the majority of vertebrate fauna being dinosaurian (Fiorillo *et al.* 2010a, b; Gangloff & Fiorillo 2010). Of the dinosaurian fauna, the majority of herbivores are either *Pachyrhinosaurus* or *Edmontosaurus*, with some remains of hypsilophodont and other unidentified hadrosaurs. Carnivorous species include tyrannosaurids such as *Albertosaurus*, as well as smaller maniraptorans such as *Troodon* and the dromaeosaurid *Sauronitholestes* (Phillips 2003; Fiorillo *et al.* 2010a, b). Some mammalian remains such as the marsupial *Pediomys* have also been discovered, as well as unidentified osteichthyes fish and chondrichthyes remains (Gangloff & Fiorillo 2010). Flora included coniferous forests on coastal plains, with broad-leaved deciduous flora in the riparian areas and an understorey of ferns and angiosperms (Spicer & Herrman 2010; Flaig 2010).

Materials and methods

Materials

Tooth samples were provided by the Museum of Nature and Science, Dallas, Texas, USA. Samples include the teeth attributable to *Troodon*, *Dromaeosaurus* and a tyrannosaurid, as well as teeth attributable to *Pachyrhinosaurus*, *Edmontosaurus* and unidentified hypsilophodontids, hadrosaurids and ornithomorphs. Material came from three main sites

Fig. 1. Location and stratigraphy. (a) Representative stratigraphic sections of bonebed sites and siderite localities from south to north. (b) Locations of sites for modern-day geography. (c) Palaeogeographic reconstruction for $c. 65$ Ma. (Modified from Google Earth Paleogeography Gallery, Blakey 2011.)

(from oldest to youngest): Kikak–Tegoseak, Pedionys Point and Liscomb Bonebed. Additionally, one tooth, found as float along the Colville River, was added to the analysis, and data for several large theropod (probably tyrannosaurid) teeth from Fricke & Rogers (2000) were added to the data set. Crocodile and turtle remains have not been recovered from the PCF and were not included in this study. *Edmontosaurus*, hadrosaurid, ornithomids and hypsilophontid teeth were grouped together as ‘non-ceratopsian herbivores’. Primary siderite cement and sphaerosiderites were analysed from two different stratigraphic levels in the PFDV-16 (Fig. 1b) measured section. Eight samples from 18.75 m above the Colville River datum and ten samples from 20.10 m above the Colville River datum were micromilled for isotopic analysis.

Analytical methods and equations

When possible, at least 10 individuals per taxa were analysed in attempts to determine the range in seasonal variability (Clementz & Koch 2001; Levin *et al.* 2006; Kohn & Dettman 2007). When 10 individuals could not be sampled, at least 3–5 serially sampled teeth were analysed, as required to resolve the seasonal variability and range in $\delta^{18}\text{O}_p$ of a particular taxa per stratigraphic level (Clementz & Koch 2001; Levin *et al.* 2006; Kohn & Dettman 2007). This is also the minimum number required to obtain an error of *c.* 1.3‰, which is the average standard deviation of $\delta^{18}\text{O}_{\text{enamel}}$ (Levin *et al.* 2006). Approximately 200–500 μg of enamel powder was milled using a hand-held slow-speed drill. Phosphate samples were converted to silver phosphate following the method of O’Neil *et al.* (1994), as modified by Bassett *et al.* (2007). Silver phosphate samples were analysed at the W. M. Keck Paleo-environmental and Environmental Stable Isotope Laboratory at the University of Kansas, Department of Geology, on a Thermo high-temperature conversion elemental analyser (TC/EA) connected to a ThermoFinnigan MAT 253 continuous-flow mass spectrometer, and at the Stable Isotope Laboratory at the University of California, Santa Cruz, on a TC/EA connected to a ThermoFinnigan Delta Plus XP. Phosphate $\delta^{18}\text{O}$ is reported in parts per thousand (‰) relative to V-SMOW. Samples were calibrated with a combination of organic standards (e.g. IAEA-601) and calibrated phosphate standards (e.g. Acros Ag_3PO_4 and NIST 120c). NIST 120c was monitored as a quality control standard and is better than $\pm 0.3\%$ V-SMOW, producing an average value of $22.5 \pm 0.3\%$. This is higher than the most recently accepted value for NIST 120c of *c.* 21.7‰ (Lécuyer 2004; Lécuyer *et al.* 2007; Halas *et al.* 2011). There has been

some ambiguity as to the correct NIST 120c value because of variations depending on both the analysis method (conventional fluorination, reaction with graphite in sealed silica tubes, or high-temperature reduction using a TC/EA) and preparation method (slow precipitation method *v.* rapid precipitation or BiPO_4 method *v.* Ag_3PO_4 method), as pointed out by several workers (O’Neil *et al.* 1994; Vennemann *et al.* 2002; Lécuyer 2004). A value of 22.5‰ was suggested for Ag_3PO_4 analysis by Vennemann *et al.* (2002); however, recent papers by other authors as well as Vennemann suggest a value of 21.7‰ (Lécuyer 2004; Lécuyer *et al.* 2007; Halas *et al.* 2011; Vennemann 2012). In order to make values comparable to the most recently accepted NIST 120c values, we subtracted 0.8‰ from all samples (our average NIST-120c value (22.5‰) minus the currently accepted value of 21.7‰).

Siderite samples from the PCF were analysed for O-isotopic composition. Samples were thin-sectioned for petrographic analysis and facing billets were used to sample pedogenic carbonates. Approximately 60–180 μg of siderite from two levels of the PCF were micromilled and vacuum-roasted at 200 °C to remove volatiles. All samples were then analysed by reaction with 100% H_3PO_4 at 75 °C and using the siderite-acid fractionation factor from Carothers *et al.* (1988) using a Kiel III carbonate reaction device interfaced to the inlet of a ThermoFinnigan MAT 253 dual inlet mass spectrometer. Siderite isotope data are reported relative to V-PDB. Precision was monitored through the daily analysis of NBS-18 and NBS-19 and was better than 0.10‰ for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$.

Dinosaur ingested water was estimated using modified biological parameters for herbivorous birds, as presented by Kohn (1996). Kohn (1996) creates a mass balance equation accounting for input O moles and isotopic composition and output O moles, and modifies each for various animal physiologies. For herbivorous dinosaurs, the Kohn (1996) bird equation was modified to account for a sustained body temperature of 37 °C, *v.* the 38 °C suggested by Amiot *et al.* (2006), a much larger body size (*c.* 200 kg *v.* 0.15 kg for herbivorous birds in the Kohn model), which alters the food input requirements and respiratory O_2 requirements as well as output of O moles, slightly lower digestibility for food (from 0.9 to 0.7 – coniferous forest food *v.* deciduous leaves), and equal amounts of water loss from skin and mouth (see Supplementary Material for comparison to Kohn 1996). An additional correction to the equation was made because the theoretical model was generated with data generated by converting animal phosphate to BiPO_4 . Oxygen isotopic compositions generated via conversion to BiPO_4 analysis have been shown to be *c.* 1.0‰ lower than apatite conversion to

ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

Ag_3PO_4 (O'Neil 1994; Chenery *et al.* 2010). As such, the phosphate-body water fractionation of Kohn (1996) was altered from 17.5 to 18.5 (see Supplementary Material), resulting in the following equation for ingested water by herbivorous birds:

$$\delta^{18}\text{O}_w = 1.41\delta^{18}\text{O}_p + 20.1h - 49.69 \quad (1)$$

This modified herbivorous bird equation was then altered for increased input of O from protein and fat (Kohn 1996), resulting in the following equation for water ingested by carnivorous dinosaurs:

$$\delta^{18}\text{O}_w = 1.43\delta^{18}\text{O}_p + 7.3h - 40.69 \quad (2)$$

Humidity was estimated using an empirically derived data set – the model for the Aptian–Albian from Suarez *et al.* (2011). In modelling water $\delta^{18}\text{O}$ -palaeo-latitude gradients as calculated from 2°S–75°N using Albian pedogenic carbonates, a modelled humidity of *c.* 77.5% was attained using a zonal MAT estimated from leaf physiognomy for the underlying Nanushuk Formation palaeo-latitude at 75°N with a MAT of 11.7 °C (Wolfe & Upchurch 1987; Spicer & Corfield 1992). The MAT for the PCF is 6.3 °C at a palaeo-latitude of *c.* 82 to 95°N (Spicer & Parrish 1990; Spicer & Herman 2010). Although this is lower than the MAT and palaeo-latitude during the Aptian–Albian, it is the best estimate available as no $\delta^{18}\text{O}$ -palaeo-latitude gradients have been developed for the Campanian–Maastrichtian.

The isotopic composition of siderite converted to V-SMOW was used to calculate the water from which it precipitated. The temperature-dependent fractionation factor determined by Carothers *et al.* (1988) was used to calculate the isotopic composition of meteoric water:

$$1000 \ln \alpha = 3.13 \times (10^6/T^2) - 3.5 \quad (3)$$

$$\delta^{18}\text{O}_w - \text{V-SMOW} = (\delta^{18}\text{O}_{\text{sid}} + 1000)/\delta - 1000 \quad (4)$$

Water was calculated at minimum, average and maximum temperatures of –2 °C, 6.3 °C and 14.5 °C, respectively (Spicer & Herman 2010).

Results

The isotopic composition of dinosaurian phosphate (Table 1, Fig. 2a) ranges from a minimum of 3.9‰ V-SMOW for hadrosaurid teeth from Pediomys Point to a maximum of 10.2‰ for *Troodon* at Liscomb Bonebed and from a tyrannosaurid also from Liscomb Bonebed (10.2‰). Data from the three sites were supplemented with data from

large theropod teeth from Fricke & Rogers (2000) (9.4‰) and from analysis of a tyrannosaur tooth that was found as float along the Colville River (8.1‰). The isotopic compositions of the siderite range between –14.86‰ and –16.21‰ V-PDB and are summarized in Table 2 and Figure 2b.

There are several trends that can be observed in the phosphate and siderite data, including the following.

- The isotopic compositions of siderite from the two levels are not significantly different from one other.
- The isotopic composition of carnivores tends to be more enriched than that of the herbivorous dinosaurs at each site, including the float Colville River tyrannosaurid tooth and the large theropod tooth from Fricke & Rogers (2000), except when compared to ceratopsians at Kikak–Tegoseak.
- Pediomys Point non-ceratopsian remains are lighter in isotopic composition than remains from Kikak–Tegoseak and Liscomb Bonebed.
- Liscomb Bonebed remains are heavier in isotopic composition than Kikak–Tegoseak and Pediomys Point remains.

The isotopic composition of water from siderite depends on the temperature at which it precipitated (Table 3, Fig. 3). At a minimum temperature (cold month mean) of –2 °C (Spicer & Herman 2010), water values ranged from –24.66‰ V-SMOW to –23.33‰ V-SMOW. At a maximum temperature (warm month mean) of 14.5 °C (Spicer & Herman 2010) they ranged from –20.03‰ to –18.68‰, and at an average temperature of 6.3 °C they ranged from –22.23‰ to –20.89‰.

The isotopic composition of ingested water for the different dinosaurs was similar to that of siderite (Table 3, Fig. 4). The values for *Pachyrhinosaurus* ranged from –25.9‰ at Kikak–Tegoseak to –23.4‰, also at Kikak–Tegoseak. The isotopic composition of non-ceratopsian herbivores (*Edmontosaurus* and hypsilophodontids) ranges between –28.7‰ at Pediomys Point to –22.8‰ at Liscomb Bonebed. In comparison, the isotopic composition of carnivores ranged from a minimum of –26.1‰ from a large theropod tooth from Kikak–Tegoseak to –20.4‰ for a *Troodon* tooth at Liscomb Bonebed. The float Tyrannosaurid tooth from the Colville River averaged –23.4‰, and the large theropod tooth analysed by Fricke & Rogers (2000) averaged –21.7‰.

There are several apparent trends in the calculated water values.

- The range for meteoric water calculated for siderite from –2 to 14.5 °C overlaps the range for water values calculated from dinosaurs, at minimum and average temperatures.

Table 1. $\delta^{18}O_p$ of vertebrate remains relative to V-SMOW

Sample	Taxa	Locality	$\delta^{18}O_p$ V-SMOW	Laboratory
DMNH-22881-a	<i>Edmontosaurus</i>	Liscomb	8.0	UCSC
-bc			7.0	KPESIL
DMNH-21031-ab	Tyrannosauridae	Liscomb	8.0	KPESIL
-c			8.2	KPESIL
-d			10.2	UCSC
DMNH-21047-a	Hadrosauridae	Liscomb	8.6	UCSC
-b			7.7	UCSC
-c			7.6	UCSC
-d			6.9	UCSC
-e			7.5	UCSC
DMNH-22336b	<i>Troodon formosus</i>	Liscomb	7.5	KPESIL
-c			10.2	KPESIL
DMNH-22478-ab	Tyrannosauridae	Liscomb	7.9	KPESIL
-c			7.9	KPESIL
DMNH-22846-1	Hadrosauridae	Pediomys	4.1	KPESIL
-b			3.9	KPESIL
DMNH-22846-2			3.9	KPESIL
-b			4.1	KPESIL
DMNH-22846-3			3.9	KPESIL
-b			4.2	KPESIL
DMNH-22840-ac	Hypsilophodontidae	Pediomys Point	6.9	KPESIL
-b			6.2	KPESIL
-d			7.1	KPESIL
DMNH-22842-ab	Dromaeosauridae	Pediomys Point	7.3	KPESIL
-d			7.7	KPESIL
-e			7.9	KPESIL
DMNH-22841b	Hypsilophodontidae	Pediomys Point	6.6	KPESIL
DMNH-22532b	<i>Pachyrhinosaurus</i>	Pediomys Point	6.9	KPESIL
DMNH-22493-a	<i>Pachyrhinosaurus</i>	Kikak–Tegoseak	7.5	UCSC
-b			7.3	UCSC
-c			7.6	UCSC
-d			6.6	UCSC
-e			7.3	UCSC
DMNH-22484-a	Ornithischian	Kikak–Tegoseak	6.1	UCSC
-b			5.5	UCSC
-c			5.5	UCSC
DMNH-22482-a	<i>Pachyrhinosaurus</i>	Kikak–Tegoseak	5.9	UCSC
-b			7.0	UCSC
-c			6.6	UCSC
-d			6.7	UCSC
-e			6.5	UCSC
DMNH-22150-a	<i>Pachyrhinosaurus</i>	Kikak–Tegoseak	6.7	UCSC
-b			6.3	UCSC
-c			6.1	UCSC
DMNH-22379-a	Theropod	Kikak–Tegoseak	6.3	KPESIL
-b			8.1	UCSC
-c			6.4	KPESIL
-d			6.4	KPESIL
-e			6.4	KPESIL
DMNH-22200-a	Tyrannosauridae	Colville River (float)	8.2	UCSC
-b			8.1	UCSC
-c			8.0	UCSC
-d			8.5	UCSC
-e			7.8	UCSC
Theropod-1	Large theropod	Fricke & Rogers (2000)	9.4	KPESIL
Theropod-2	Large theropod	Fricke & Rogers (2000)	9.0	KPESIL
Theropod-3	Large theropod	Fricke & Rogers (2000)	9.6	KPESIL
Theropod-4	Large theropod	Fricke & Rogers (2000)	9.4	KPESIL

ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

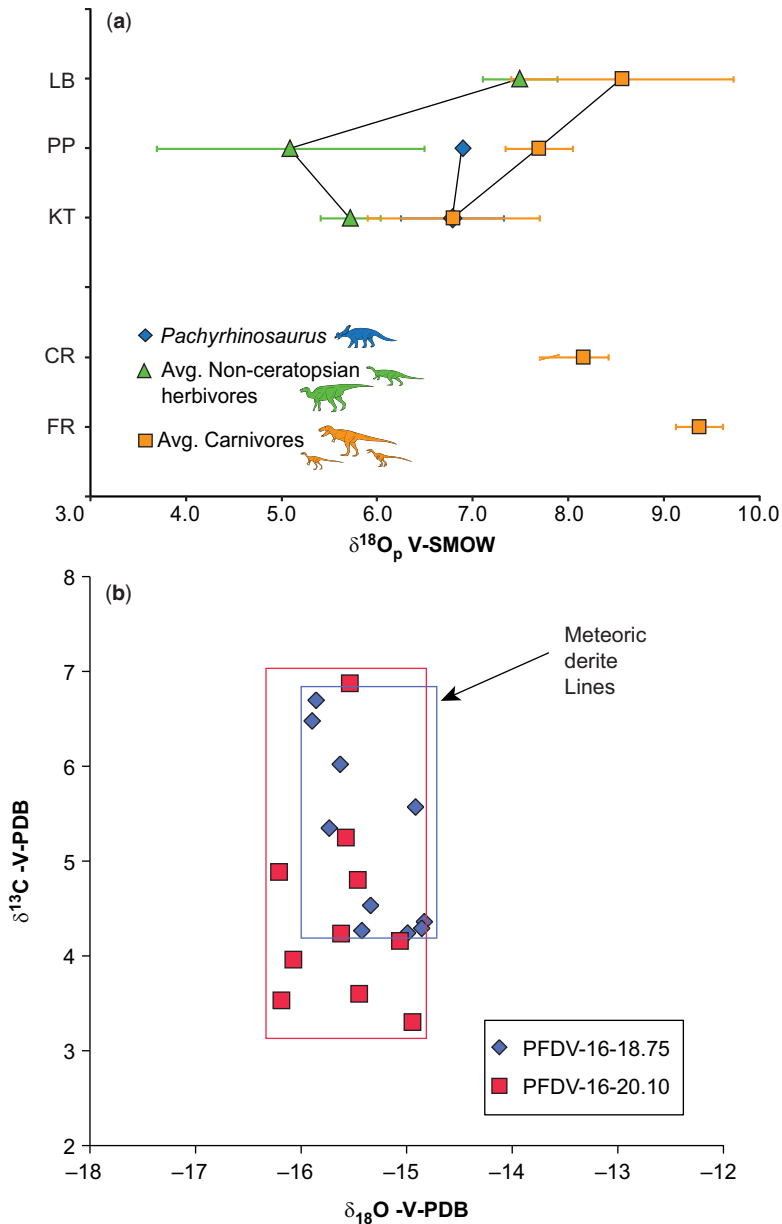


Fig. 2. Results of isotopic analysis. (a) O-isotopic composition of phosphate relative to V-SMOW. Sites are organized stratigraphically and are connected by lines. The Colville River tyrannosaurid tooth (CR) and the theropod teeth from the study of Fricke & Rogers (2000) (FR) have unknown stratigraphic affiliation and so are not connected to sites whose stratigraphic relationship is known. (b) C- and O-isotope cross-plot relative to V-PDB of siderite from the section PFDV-16, at 18.75 m and 20.10 m above the lower datum. Boxes define meteoric siderite lines characterized by $\delta^{13}C$ variability greater than $\delta^{18}O$ variability. LB, Liscomb Bonebed; PP, Pedimys Point; KT, Kikak–Tegoseak; CR, Colville River; FR, Fricke & Rogers (2000). Error bars, one standard deviation.

- Water ingested by most carnivores tends to be more enriched in ^{18}O than for herbivorous dinosaurs.
- Water ingested by *Pachyrhinosaurus* is more enriched in ^{18}O than for other herbivorous dinosaurs.

Table 2. Oxygen-isotopic composition of siderite relative to V-SMOW

Sample	Level	$\delta^{18}\text{O}_{\text{sid}}$ (‰ – VSMOW)	Average	1 σ
PFDV-16-18.75 c	18.75	–14.86	–15.40	0.43
PFDV-16-18.75 d	18.75	–15.63		
PFDV-16-18.75 e	18.75	–15.86		
PFDV-16-18.75 f	18.75	–14.92		
PFDV-16-18.75 g	18.75	–15.34		
PFDV-16-18.75 h	18.75	–14.99		
PFDV-16-18.75 i	18.75	–15.89		
PFDV-16-18.75 j	18.75	–15.73		
PFDV-16-20.1 a	20.10	–15.54		
PFDV-16-20.1 b	20.10	–15.58		
PFDV-16-20.1 c	20.10	–15.45	–15.61	0.43
PFDV-16-20.1 d	20.10	–14.94		
PFDV-16-20.1 e	20.10	–15.46		
PFDV-16-20.1 f	20.10	–15.06		
PFDV-16-20.1 g	20.10	–16.18		
PFDV-16-20.1 h	20.10	–16.21		
PFDV-16-20.1 i	20.10	–16.07		
PFDV-16-20.1 j	20.10	–15.62		

- Liscomb Bonebed records have the highest $\delta^{18}\text{O}_{\text{w}}$ values.

Discussion

We analysed the more diagenetically resistant bioapatite, enamel. Enamel has larger crystal sizes than bone apatite as well as decreased organic content (<10%), resulting in a low surface area available for isotopic exchange (Kolodny *et al.* 1996; Glimcher 2006). Inorganic isotopic exchange tends to occur to bone carbonate (Zazzo *et al.* 2004) rather than phosphate. The phosphate molecule is significantly more resistant to diagenesis than the easily exchangeable carbonate molecule (Kolodny *et al.* 1996; Sharp *et al.* 2000). However, some researchers have demonstrated isotopic exchange via microbial alteration to phosphate (Blake *et al.* 1998; Zazzo *et al.* 2004). Other studies have used the *c.* 9‰ offset between $\delta^{18}\text{O}_{\text{p}}$ and $\delta^{18}\text{O}_{\text{egg CO}_3}$ when precipitated at equilibrium from the same body water to suggest the primary O-isotopic composition of phosphate (Iacumin *et al.* 1996; Bojar *et al.* 2010). The separation of $\delta^{18}\text{O}$ values of vertebrate remains along physiological and dietary lines (e.g. carnivores v. herbivores) has also been used to indicate the preservation of original biogenic signals (Lécuyer *et al.* 2003; Fricke *et al.* 2008; Amiot *et al.* 2009). For example, Lécuyer *et al.* (2003) analysed a wide diversity of Late Cretaceous taxa from the Laño locality of northern Spain and reported $\delta^{18}\text{O}_{\text{p}}$ values for crocodile teeth (19.2‰), an *Iguanodon* tooth (19.3‰), an *Ankylosaurus* tooth (19.3‰), a fish scale (19.7‰), a turtle shell

(19.5‰), alligator teeth (19.5‰), a *Titanosaurus* tooth (19.4‰), a theropod tooth (19.1‰), a shark tooth (19.4‰) and a ray tooth (18.7‰) with no more than 1.0‰ difference between taxa, suggesting poor preservation of the original biological information. There are clear differences in phosphate values along dietary and physiological lines for the PCF data. For example, at all sites, theropod $\delta^{18}\text{O}_{\text{p}}$ is significantly greater than in herbivores, with the exception of *Pachyrhinosaurus* at Kikak–Tegoseak (Fig. 2, Table 1). *Pachyrhinosaurus* tends to be significantly enriched in ^{18}O relative to other herbivores both at Pediomys Point and Kikak–Tegoseak Quarry (Fig. 2, Table 1).

Siderite values also preserve original material. Thin-section analysis revealed that the analysed materials were microcrystalline siderites (Fig. 5). Additionally, the cross-plots of C and O (Fig. 2b) reveal a meteoric siderite line characterized by an O-isotopic variation that is less than the C-isotopic variation. This is typical of original soil carbonates (Ludvigson *et al.* 1998; Suarez *et al.* 2010).

PCF palaeohydrology

The calculated stable isotopic compositions of $\delta^{18}\text{O}_{\text{w}}$ from dinosaurs and pedogenic siderite can be used to describe the regional palaeohydrology of the PCF (Figs 3 & 4). First, when compared broadly to siderite, the calculated dinosaur-ingested water isotopic compositions are similar to those calculated from siderite, suggesting the majority of water consumed by dinosaurs was in the same compositional range as meteoric water estimated

ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

Table 3. Calculated $\delta^{18}\text{O}$ of meteoric water from siderite and $\delta^{18}\text{O}$ ingested water from dinosaurs

Sample	Taxa/material	Location	Temperature (°C)	$\delta^{18}\text{O}_w$	1σ
PFDV-16-18.75	Siderite	18.75 m	-2	-23.86	0.43
PFDV-16-18.75	Siderite	18.75 m	6.3	-21.43	0.43
PFDV-16-18.75	Siderite	18.75 m	14.5	-19.22	0.43
PFDV-16-20.10	Siderite	20.10 m	-2	-24.07	0.43
PFDV-16-20.10	Siderite	20.10 m	6.3	-21.64	0.43
PFDV-16-20.10	Siderite	20.10 m	14.5	-19.43	0.43
DMNH-22881	<i>Edmontosaurus</i>	Liscomb	37	-23.6	1.1
DMNH-21047	Hadrosauridae	Liscomb	37	-23.6	0.4
DMNH-21031	Tyrannosauridae	Liscomb	37	-22.5	1.8
DMNH-22478	Tyrannosauridae	Liscomb	37	-23.8	0.1
DMNH-22336	<i>Troodon</i>	Liscomb	37	-22.4	2.8
Avg carnivores		Liscomb	37	-22.8	1.7
Avg non-ceratopsian herbivores		Liscomb	37	-23.6	0.6
DMNH-22846-1	Hadrosauridae	Pediomys Point	37	-28.5	0.1
DMNH-22846-2	Hadrosauridae	Pediomys Point	37	-28.6	0.2
DMNH-22846-3	Hadrosauridae	Pediomys Point	37	-28.5	0.4
DMNH-22840	Hypsilophodontidae	Pediomys Point	37	-25.0	0.5
DMNH-22841	Hypsilophodontidae	Pediomys Point	37	-24.9	0.0
DMNH-22532	<i>Pachyrhinosaurus</i>	Pediomys Point	37	-24.4	0.0
DMNH-22842	Dromaeosauridae	Pediomys Point	37	-24.1	0.5
Avg. carnivores		Pediomys Point	37	-24.1	0.5
Avg. non-ceratopsian herbivores		Pediomys Point	37	-27.1	2.0
Avg. ceratopsian		Pediomys Point	37	-24.4	0.0
DMNH-22484	Ornithischian	Kikak-Tegoseak	37	-26.1	0.4
DMNH-22493	<i>Pachyrhinosaurus</i>	Kikak-Tegoseak	37	-23.9	0.6
DMNH-22482	<i>Pachyrhinosaurus</i>	Kikak-Tegoseak	37	-24.9	0.6
DMNH-22150	<i>Pachyrhinosaurus</i>	Kikak-Tegoseak	37	-25.2	0.5
DMNH-22379	Large theropod	Kikak-Tegoseak	37	-25.4	1.1
Avg. carnivores		Kikak-Tegoseak	37	-25.4	1.1
Avg. non-ceratopsian herbivores		Kikak-Tegoseak	37	-26.1	0.4
Avg. ceratopsian		Kikak-Tegoseak	37	-22.8	0.8
DMNH-22200	Tyrannosauridae	Colville River	37	-23.4	0.4
Theropod-1	Large theropod	F&R 2000	37	-21.6	
Theropod-2	Large theropod		37	-22.2	
Theropod-3	Large theropod		37	-21.3	
Theropod-4	Large theropod		37	-21.6	
Avg. large theropod			37	-21.7	0.4

by siderite (Fig. 4). Small variations within the dinosaur-ingested water values can help to tease out regional differences within the PCF. For example, non-ceratopsian herbivores document $\delta^{18}\text{O}_w$ values as low as -28.7‰ , up to 9.5‰ lower than the $\delta^{18}\text{O}_w$ calculated from siderite at maximum temperatures from 18.75 m in PFDV-16 (Figs 3 & 4). This value may be the result of orographically depleted water or snowmelt water from the Brooks Range. It is well documented that local rivers are more depleted in ^{18}O than local meteoric water due to the catchment effect (Dettman & Lohmann 2000; Dutton *et al.* 2005; Suarez *et al.*

2011). Assuming a river water isotope gradient (lapse rate) of $-4.2\text{‰}/\text{km}$ decrease in $\delta^{18}\text{O}$ (Dutton *et al.* 2005) and a meteoric water lapse rate of $2.8\text{‰}/\text{km}$, where the isotopic composition of meteoric water is *c.* -19.2‰ , that of river water is -20.6‰ . If the minimum $\delta^{18}\text{O}_w$ calculated from non-ceratopsian enamel is -28.7‰ , resulting in a 8.1‰ decrease in $\delta^{18}\text{O}$, non-ceratopsian dinosaurs would have consumed river water sourced from as much as 1.9 km of elevation higher than the elevation at which siderite formed. This is a reasonable estimate for the area as the Brooks Range palaeo-elevation is placed conservatively

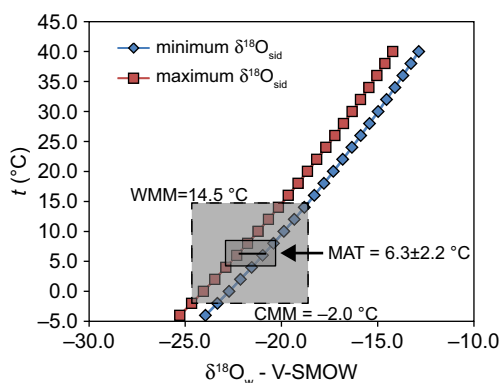


Fig. 3. Isotopic composition of meteoric water derived from Prince Creek Formation siderites based on the temperature-dependent fractionation equation of Carothers *et al.* (1988). The two lines represent water values from the maximum (red squares) and minimum (blue diamonds) siderite $\delta^{18}\text{O}$ values plotted at various temperatures. The solid box represents the range of water compositions at a MAT of $6.3 \pm 2.2 \text{ }^\circ\text{C}$ (line) $\pm 2.2 \text{ }^\circ\text{C}$ (solid box) and the dashed box represents ranges of water isotopic compositions at a warm month mean (WMM) of $14.5 \text{ }^\circ\text{C}$ and cold month mean (CMM) of $-2 \text{ }^\circ\text{C}$ based on temperatures determined from CLAMP analysis of Spicer & Herman (2010).

at 1.5 km (Spicer 2003) and as high as 4 km (Vogl *et al.* 2002; Poulsen *et al.* 2007). PEDIOMYS POINT documents the lightest $\delta^{18}\text{O}_w$ of the three sites, despite the fact that Kikak-Tegoseak was closest to the Brooks Range. One might expect that sites closest to the mountains would capture the most ^{18}O -depleted water compositions. However, the light $\delta^{18}\text{O}_w$ documented at PEDIOMYS POINT might result from a taphonomic bias. Remains were deposited in a coarse-grained lag at the base of a fine- to medium-grained sandstone with cross-bedding and ripples, and although the presence of jarosite and brackish-water clams suggest possible marine influences found in the deposit, it is possible that the remains came from much closer to the mountains, where the animals might have consumed much lighter water, and then their remains were transported downstream to the coastal plain.

LISCOMB BONEBED, on the other hand, documents the highest $\delta^{18}\text{O}_w$ (maximum of -22.4‰). It is also the site that is furthest to the north. Palaeogeographic reconstruction (Fig. 1c) suggests that it would have been very close to the coast and the presence of jarosite in the overlying beds suggest the influence of marine or mixed waters (Flaig 2010; Flaig *et al.* 2011). The combination of siderite and dinosaurian data suggest that the PCF regional palaeohydrology consisted of meteoric water that averaged *c.* -21‰ with an orographically

influenced $\delta^{18}\text{O}_w$ composition of *c.* -28‰ and near-coastal precipitation of *c.* -19‰ .

PCF dinosaur palaeoecology

Relative to one another, the different taxa from the PCF show some unique groupings. The most evident is the ^{18}O -enriched nature of carnivore phosphate and calculated ingested water (Figs 2b & 4). Theoretical modelling and some observations suggest carnivores should be depleted relative to herbivores due to herbivore consumption of evaporatively ^{18}O -enriched plant leaves (Kohn 1996; Levin *et al.* 2006). However, PCF carnivores are more enriched than the herbivores. Without additional modern data it is difficult to explain this offset; however, carnivore data from the Pleistocene Natural Trap Cave, Wyoming, USA, also show an ^{18}O -enriched carnivore O-isotopic composition relative to herbivores (McKay 2008). McKay (2008) explains that this enrichment may be due to changes in the proportion of drinking water relative to food water with high protein content, high vapour output or other unknown physiological differences not accounted for in the carnivorous models of Kohn (1996). Additional error for the estimated carnivorous bird equation used for theropods, such as whether or not they excreted urea or urinated, may also add to the calculated enrichment of carnivorous dinosaur phosphate. *Pachyrhinosaurus* teeth tend to be more enriched relative to other herbivorous dinosaurs such as *Edmontosaurus* and unidentified hypsilophodonts. This is probably due to differences in drinking water source and/or consumed food water. Non-ceratopsians that have lower $\delta^{18}\text{O}_p$ values relative to ceratopsians (*Pachyrhinosaurus*) may have relied heavily on the river water that drained the Brooks Range, which was ^{18}O -depleted due to orographic effects (Dettman & Lohmann 2000; Suarez *et al.* 2012). The ^{18}O -depleted nature of non-ceratopsian teeth does not necessarily suggest migration to uplands, as has been relied on by other authors (e.g. Fricke *et al.* 2008, 2011). A more parsimonious explanation is that the rivers drained isotopically depleted water from higher in the catchment basin. Some authors have suggested PCF dinosaurs may have migrated to the coast during the dark winter season to consume aquatic plants such as seagrass (Brinkman *et al.* 1998; Gangloff & Fiorillo 2010). The isotopic data reported here do not support this. Seagrass should have $\delta^{18}\text{O}_w$ values similar to sea water, which in the Cretaceous was *c.* -1.2‰ (Poulsen *et al.* 2007; Suarez *et al.* 2011). *Pachyrhinosaurus* have the highest $\delta^{18}\text{O}_p$ values relative to other herbivores. If *Pachyrhinosaurus* consumed seagrass for a significant portion of the year, their $\delta^{18}\text{O}_p$ and calculated $\delta^{18}\text{O}_w$ would be higher

ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

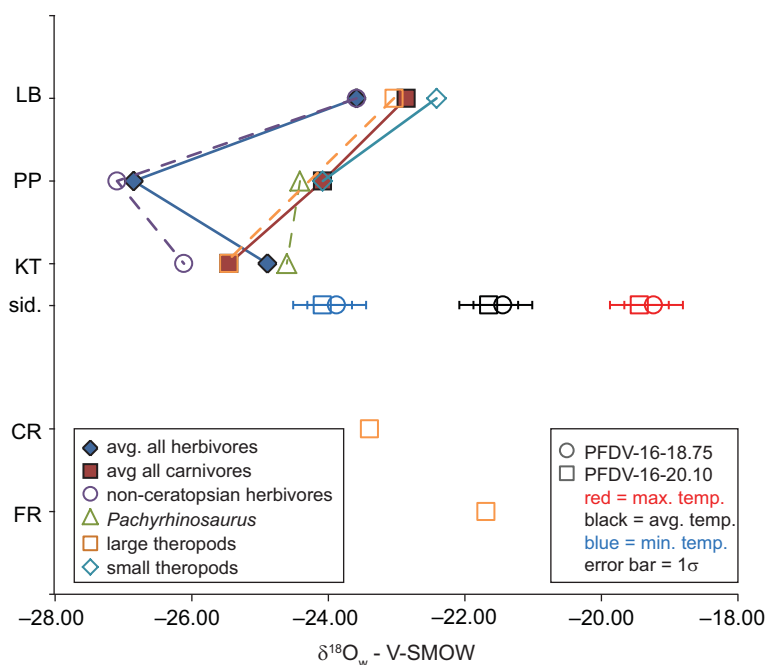


Fig. 4. Oxygen isotopic composition of PCF water relative to V-SMOW calculated from dinosaur tooth enamel and siderite at minimum (blue), MAT (black) and maximum (red) temperatures, as suggested by Spicer & Herman (2010). Note that the range in water calculated from dinosaur tooth enamel encompasses the range of water values calculated from siderite. LB, Liscomb Bonebed; PP, Pedomys Point; KT, Kikak–Tegoseak; sid., siderite; CR, Colville River tyrannosaur; FR, Fricke & Rogers (2000).

relative to meteoric water, calculated from the PCF. More probably, *Pachyrhinosaurus* may have foraged for food in the coniferous forests of the coastal floodplains away from riparian areas. Non-ceratopsian herbivores may have foraged for food in the riparian areas where the $\delta^{18}\text{O}$ of river water and $\delta^{18}\text{O}$ of plant water offsets are minimal. Further analysis of a much larger data set as well as the addition of C-isotopic composition analysis of tooth enamel may be helpful to clearly define PCF dinosaur palaeoecology.

Arctic palaeoclimate in the Cretaceous

The similarity of $\delta^{18}\text{O}_w$ values calculated from enamel and siderite is an independent corroboration for the light $\delta^{18}\text{O}$ of meteoric water at high latitudes documented by other authors (Ludvigson *et al.* 1998; Ufnar *et al.* 2002, 2004a, b; Suarez *et al.* 2011). The range in $\delta^{18}\text{O}$ of dinosaur-ingested water suggests the orographically ^{18}O -depleted endmember of snowmelt was *c.* -28‰ . Siderite values at MAT are much more restricted, ranging between -21.23‰ and -20.89‰ , indicating they were not depleted by orographic processes as suggested by Poulsen *et al.* (2007). Additionally,

when compared to the $\delta^{18}\text{O}_w$ values calculated from siderites of the underlying Nanushuk Formation (-20.57‰ to -21.07‰), when the Arctic MAT was closer to 11 °C (Parrish & Spicer 1988; Ufnar *et al.* 2004a; Suarez *et al.* 2011), values for the PCF are virtually identical (-21.23‰ to -20.89‰). From the Albian–Cenomanian time (Nanushuk Formation) to the Campanian–Maastrichtian time (PCF), the formation of siderite went from a more proximal position relative to the Brooks Range to a more distal position (along the coastal plain). This distance should result in an increase in $\delta^{18}\text{O}_w$; however, there is a decrease. This decrease is not solely a result of formation at colder temperatures, because dinosaurs, which were thermoregulating to some degree (Amiot *et al.* 2006), document similar $\delta^{18}\text{O}_w$ values. We suggest that the low $\delta^{18}\text{O}$ of meteoric water from the PCF was the result of increased rainout effects due to an intensified hydrological cycle that enhanced latent heat transport, as suggested for the Aptian–Albian by Ludvigson *et al.* (1998), Ufnar *et al.* (2004b) and Suarez *et al.* (2011). The increased latent heat transport may be due to a short-term global warming event (middle Maastrichtian event), as documented by several authors (Frank & Arthur

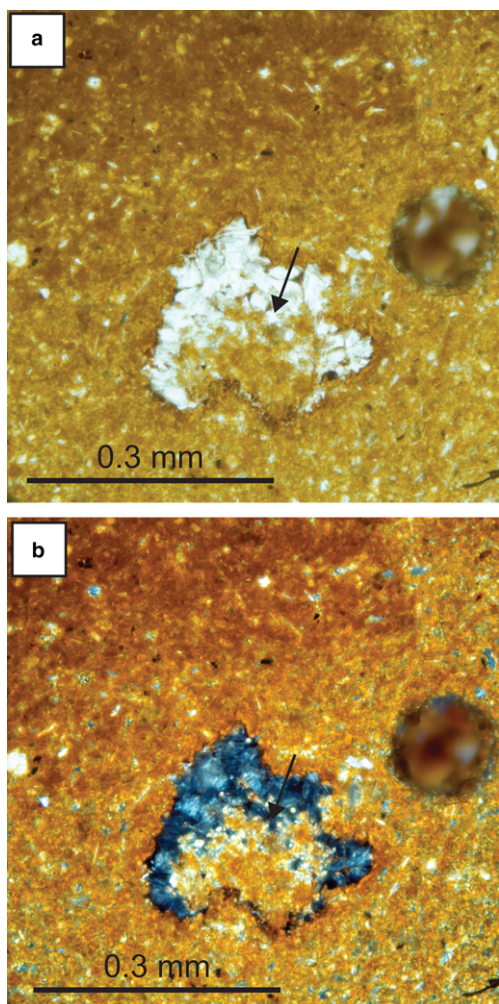


Fig. 5. Photomicrograph of microcrystalline siderite in (a) plain polarized light and (b) cross-polarized light. The arrow points to clusters of microcrystalline crystals of siderite contained within a zeolite-filled vug. Siderite is pervasive throughout the matrix.

1999; Keller 2001; Bralower *et al.* 2002; Nordt *et al.* 2003). The depleted nature of meteoric water (compared to the Nanushuk Formation) may also be due to the potential increase in palaeo-latitude from *c.* 70° to 75°N during the Nanushuk Formation to 82° to 85°N during the Maastrichtian (Parrish & Spicer 1988; Spicer & Herman 2010).

Implications for modern Arctic climate

This work serves as a case study of warm-period Arctic climate research. The increase in latent heat transport suggested by this and other workers (Ludvigson *et al.* 1998; Ufnar *et al.* 2004*b*; Suarez

et al. 2011) suggests increased transfer of heat to the poles via the hydrological cycle. This has important implications for current polar warming and the Arctic amplification phenomenon documented by Graversen *et al.* (2008). Arctic amplification refers to the accelerated industrial-age warming at Arctic latitudes. Hypotheses for the cause of this warming focus on everything from snow–ice albedo decreases and changes in oceanic–atmospheric circulation, to changes in cloud cover. The rapid feedbacks of Arctic amplification as well as significant warming at higher levels of the atmosphere suggest that atmospheric heat transport is an important cause of recent Arctic warming. These trends can be tracked with stable isotopic proxies, and palaeo-hydrological research of other warm Arctic worlds in Earth history may help provide answers to the causes of modern Arctic amplification.

Cretaceous warm worlds suggest an increase in rainout due to enhanced latent heat transport based on sediments containing extremely ^{18}O -depleted meteoric water proxies at high latitudes, such as those seen in this study. However, other warm Arctic worlds such as that documented in the Paleocene–Eocene suggest an increase in $\delta^{18}\text{O}$ and δD of meteoric water relative to modern-day Arctic meteoric water (Pagani *et al.* 2006; Jahren *et al.* 2009). This may be due to decreased meridional and/or vertical temperature gradients resulting in warmer polar temperatures. This decreased temperature gradient would decrease the fractionation due to rainout effects (Pagani *et al.* 2006). Alternatively, meteoric water transport may have been vastly different from today, originating somewhere other than the tropics (Jahren *et al.* 2009). Clearly, significant research endeavours with detailed proxy data and coupled modelling needs to be conducted in the future to understand the underlying factors that cause amplified Arctic warming and positive feedbacks associated with Arctic warming.

Conclusions

Stable isotopic analysis of terrestrial vertebrate phosphate is a valuable tool to elucidate regional palaeohydrology, which is not attainable exclusively by means of analysis of soil carbonates. However, it adds potential complications to interpretation (e.g. differences in migration *v.* multiple local water sources), although it may also offer insights into the range of local water reservoirs. For this study, the addition of vertebrate phosphate as a proxy material both validates the ^{18}O -depleted nature of meteoric water in high latitudes (PCF as low as *c.* -24‰) and also adds additional information

ARCTIC PALAEOHYDROLOGY OF THE CRETACEOUS

regarding the range in isotopic composition of the various water reservoirs found in the regional palaeohydrology of the PCF (i.e. Brooks Range runoff and coastal precipitation). For the PCF, snowmelt runoff was as high as c. 6‰ lower (or depleted) than in local meteoric water (−22.23‰ to −20.89‰ at a MAT of 6.3 °C). Based on the isotopic composition of vertebrate phosphate from the Liscomb Bonebed, which was at a distal location relative to the orogenic belt and near the coast, near-shoreline precipitation was as heavy as −20.4‰.

Of all the dinosaurs, carnivores tend to record the highest $\delta^{18}\text{O}_w$ values. This can be attributed to physiological fractionations not being accurately modelled in our equation (e.g. increased proportion of metabolic water as opposed to drinking surface water; urea excretion v. urination) or the consumption of food/water that was enriched relative to local meteoric water (Kohn 1996; McKay 2008). Relative to other herbivores, *Pachyrhinosaurus* is enriched in ^{18}O , suggesting consumption of enriched food sources (e.g. plants outside riparian areas). There is no evidence of migration and consumption of shoreline plants as suggested by Brinkman *et al.* (1998) and Gangloff & Fiorillo (2010). The depleted nature of non-ceratopsians may suggest water dependence and the consumption of isotopically depleted river water draining the Brooks Range, or the consumption of plants from riparian areas.

The overlap in the $\delta^{18}\text{O}$ of dinosaur-ingested water and meteoric water from siderite corroborates ^{18}O -depleted high-latitude precipitation in a warmer Arctic than today (c. −19.0 at a MAT of −12 °C) (IAEA 1992). This depleted meteoric water was probably a result of increased rainout linked to an intensified hydrological cycle that increased latent heat transport to the poles (Ludvigson *et al.* 1998; Ufnar *et al.* 2004b; Suarez *et al.* 2011). This intensified hydrological cycle may have contributed to the amplified warming of Arctic temperatures, and may be analogous to modern observation of amplified Arctic temperatures relative to those that are modelled for the modern climate system (Graversen *et al.* 2008). An intensive research effort to study the palaeoclimate of the Arctic over geological time is needed to understand the unique climate dynamics of the Arctic and to understand what factors contribute to Arctic thermal variations.

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