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Dynamic polar climates in a greenhouse world: Evidence from clumped isotope thermometry of Early Cretaceous belemnites

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ABSTRACT

Sub-arctic Cretaceous (Berriasian–late Valanginian, ca. 145–134 Ma) marine temperatures obtained from fossil mollusks (belemnites) are determined using carbonate clumped isotope thermometry, an approach based on the "clumping" of ^{13}C and ^{18}O in the carbonate mineral lattice into bonds with each other. From our analyses we infer sub-arctic Early Cretaceous marine temperatures ranging from 10 °C to 20 °C. These possibly seasonally biased, warm sub-arctic temperatures are warmer than present mean summer water temperatures at 60–65°N and are therefore consistent with a warmer "greenhouse" world featuring a shallow (equable) latitudinal temperature gradient. Our combined temperature and $\delta^{18}O_{belemnite}$ data imply seawater $\delta^{18}O$ values that have a remarkably modern character in that they are similar to modern high-latitude seawater but more positive than modeled Cretaceous seawater. We identify a cooler late Valanginian interval (ca. 134 Ma) with temperatures consistent with polar regions a few degrees above freezing and also coincident with increased $\delta^{18}O$ seawater values. Thus we find evidence of intervals when polar ice was unlikely, and also when polar ice was plausible. Both scenarios support the view of generally warm but dynamic polar climates during greenhouse intervals that were punctuated by periods of ice growth.

INTRODUCTION

Although transient cool events within the Cretaceous have been suggested (Price and Nunn, 2010), data typically point to warm polar regions (Bice and Norris, 2002; Mutterlose et al. 2010; Littler et al., 2011) that were often warmer than general circulation models (GCMs) can reproduce (Spicer et al., 2008). Such warm polar temperatures challenge our understanding of how the ocean-atmosphere system operated in the past (Poulsen, 2004) and also have important implications for the prediction of future climates as they imply we may be underestimating climate change in such regions (Spicer et al., 2008). The oxygen isotope paleothermometry technique has proven to be a valuable tool to study past temperature variability and began with Urey et al. (1951), who proposed using the ^{18}O enrichment of fossil shell carbonate to reconstruct Mesozoic seawater temperatures. This approach formed a cornerstone of paleoclimate science during the ensuing six decades, but has been limited because the ^{18}O content of biogenic carbonate depends both on the ^{18}O content of water in which the carbonate formed, and on the temperature of the water itself. The recent advent of "clumped isotope" thermometry (Ghosh et al., 2006; Tripati et al. 2010; Dennis et al., 2011) addresses this problem because the approach simultaneously estimates temperature during shell biomineralization and provides $\delta^{18}O_{shell}$—independent of seawater $\delta^{18}O$. Furthermore, the temperature and $\delta^{18}O_{shell}$ can be used to calculate the $\delta^{18}O$ of ancient seawater. In this study, we use clumped isotope thermometry to determine marine temperatures and $\delta^{18}O_{seawater}$ of an Early Cretaceous polar region and test the veracity of GCM predictions.

MATERIAL AND METHODS

A total of 14 Berriasian–late Valanginian (ca. 145–134 Ma; Golbert et al., 1975; Price and Mutterlose, 2004) belemnite rostra were analyzed, derived from the Yatria River (64°7′51.45″N, 60°40′14.22″E), sub-polar Urals, Siberia (paleolatitude ~60–65°N; Smith et al., 1994) (Fig. 1). During the earliest Cretaceous, the Yatria River was located on the western margin of an epicontinental marine basin separated from the Moscow and Pechora Basins by the (paleo-) Urals and formed a southern extension of the Boreal–Arctic Sea, but without any direct connection with seaways towards
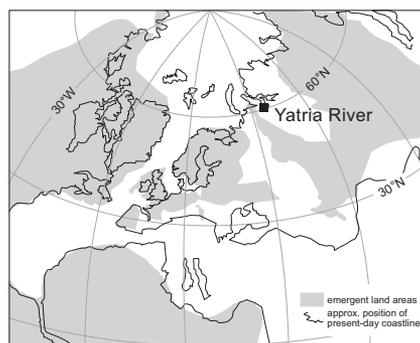

Figure 1. The paleogeographical setting of Europe and Western Siberia during the Early Cretaceous (Smith et al. 1994), and position of the Yatria River outcrop.

the Tethys in the south (Fig. 1). For each rostra, preservation was assessed via trace element geochemistry, backscattered scanning electron microscopy (BSEM), and carbonate staining (see Price and Mutterlose, 2004). Fragments were picked under a microscope to secure those judged to be best preserved, and were then analyzed for geochemistry (Fe, Mn) using a Varian 200 inductively coupled plasma–atomic emission spectrometer. Stable isotope measurements were conducted at Johns Hopkins University (JHU; Maryland, United States) using a Thermo MAT 253 mass spectrometer and a custom-built common acid bath carbonate device, following methods described by Passey et al. (2010). Clumped isotope data (Δ_{47}) were normalized to the "carbon dioxide equilibrium scale" (CDES) (Dennis et al. 2011) using a secondary transfer function approach described by Dennis et al. (2011, their section 2.2). Briefly, among analyses of unknowns (n = 43), we analyzed 15 aliquots of CO_2 gas heated in quartz tubes at 1000 °C ("heated gases"), and 18 samples of 5 different carbonate standards with Δ_{47} values that have been calibrated in the CDES reference frame. The heated gases were used to characterize instrument nonlinearity (a subtle dependence of observed Δ_{47} value on $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios of samples), and all data were accordingly corrected to remove this nonlinearity artifact. The nonlinearity-corrected Δ_{47} values were then converted to the CDES reference frame using a single, analytical session-specific secondary transfer function based on regression of nonlinearity-corrected Δ_{47} values of carbonate standards versus their calibrated (CDES) Δ_{47} values (see the calculations in Table DR1 in the GSA Data Repository[1]). A correction of +0.092‰ was applied to all data to normalize values to 25 °C phosphoric acid extractions (Henkes et al., 2013; see Tables DR1 and DR2).

Since the publication of the Ghosh et al. (2006) calibration, many more measurements have been made of inorganic calcite, foraminifera, and other carbonates having independently known growth temperatures. Although most

of these previous measurements are indistinguishable from the inorganic calibration line (Tripati et al., 2010), some recent calibrations differ (Dennis and Schrag, 2010; Guo et al., 2009), particularly at low temperatures. These calibration issues are critical to the application of clumped isotope thermometry. Here we use a mollusk- and brachiopod-specific calibration recently developed at JHU (Henkes et al., 2013) using analytical methods identical to those used in the present study. This calibration is similar to other calibrations (Dennis and Schrag, 2010; Guo et al., 2009), including a new mollusk-specific calibration generated in a different laboratory but using similar analytical methods as employed in our laboratory (Eagle et al., 2013). Use of the JHU equation, for example, results in calculated temperatures being nearly identical to those calculated using the theory-based calibration of Guo et al. (2009), ~2 °C lower than temperatures calculated using the experimental calibration of Dennis and Schrag (2010), and ~8 °C lower than temperatures calculated using the experimental calibration of Ghosh et al. (2006). Recently, Dennis et al. (2013) made measurements on modern cephalopods including cuttlefish and nautilus, and also identified an offset from the Ghosh et al. (2006) calibration. Although limited in number, the cuttlefish data of Dennis et al. (2013) are consistent with the calibration of Henkes et al. (2013). Hence, we prefer to use the JHU calibration (Henkes et al., 2013), without any further correction, because it is specific to the taxonomic group that we are studying, and it was generated in the same laboratory using the same methods.

RESULTS

The temperatures of carbonate growth, based on clumped isotope thermometry and the calculated $\delta^{18}O$ values of water in equilibrium with our samples at those apparent temperatures, are presented in Figures 2–4. The ^{13}C-^{18}O bond enrichment in these shells ranges between 0.71‰ and 0.74‰ (Δ_{47} relative to the CDES; Dennis et al., 2011) implying shell growth temperatures of 16 °C to 19 °C for the Berriasian, 13 °C for the early Valanginian, and 10 °C to 15 °C for the late Valanginian. Based on these temperatures and the measured shell carbonate $\delta^{18}O$ values, calculated seawater $\delta^{18}O$ values range from –1.1‰ to 0.1‰ (standard mean ocean water, SMOW) (average –0.7‰) for the Berriasian, –1.8‰ to –0.4‰ (SMOW) (average –1.0‰) for the early Valanginian, and –0.2‰ to 0.9‰ (SMOW) (average 0.4‰) for the late Valanginian. BSEM and carbonate staining (Price and Mutterlose, 2004) revealed minor diagenetic alteration around the rostrum margin and along the apical line, areas avoided during subsequent subsampling. Largely the rostra were composed of translucent calcite. Mn and Fe concentrations determined from each of the shells are low (<23 ppm for Mn, <18 ppm for Fe), also consistent with values for pristine shell calcite (e.g., Mutterlose et al., 2010; Table DR1). Four further samples were considered likely to have undergone some isotopic exchange registered by high Fe concentrations and/or prevalent opaque areas across the rostra. These samples show poor reproducibility and have been excluded from further analysis. Estimated maximum burial depth for all samples is less than 1200 m (Fig. DR1 in the Data Repository), translating to an estimated maximum burial temperature of ~60 °C (assuming a 30 °C/km geothermal gradient), well below the inferred temperature of ~100–200 °C above which self-diffusion can alter ^{13}C-^{18}O bonding distribution (Dennis and Schrag, 2010; Passey and Henkes 2012). Finally, the temperature (Δ_{47}), $\delta^{18}O_{belemnite}$, and $\delta^{18}O_{seawater}$ data are inconsistent with deep burial diagenesis or late diagenesis in ^{18}O-depleted meteoric waters, and there is no sign of closed-system ^{13}C-^{18}O reordering in a plot of Δ_{47} temperature versus calculated seawater $\delta^{18}O$ contoured for $\delta^{18}O_{belemnite}$; i.e., we do not see the clumped isotope temperatures increasing and the $\delta^{18}O_{belemnite}$ values staying the same (Fig. 3).

DISCUSSION

Because present mean annual (surface-water) temperatures at 60–65°N range from 0 °C to 10 °C (mean 6 °C) (Boyer et al., 2009), our data are consistent with a warm "greenhouse" world (Fig. 4). The warmest temperatures we observe are in the Berriasian (Fig. 2), and if extrapolated poleward using the present-day latitudinal temperature gradient, the estimated seawater temperatures at the poles are well above freezing. Because the Early Cretaceous latitudinal temperature gradient may have been shallower (e.g., Bice and Norris, 2002), polar temperatures were likely to be warmer than would be predicted using an extrapolation based on the present-day gradient. It is hence unlikely that ice was present at this time in the Arctic. Our temperatures for the Berriasian are also consistent with previously published TEX$_{86}$ data for the Early Cretaceous (Fig. 4). We cannot exclude the possibility that the belemnite growth temperatures are seasonally biased due to high shell accretion rates during the summer or migration from warmer-water regions. Today the warmest summer temperatures at 65°N in the northeast Atlantic Ocean and adjacent Arctic Ocean reach ~12 °C, although locally higher values can occur in shallow restricted settings (Boyer et al., 2009). An Early Cretaceous GCM simulation (Fluteau et al., 2007) provides warmer summer temperature estimates at a paleolatitude of 65°N (Fig. 4C) close to the cooler Valanginian estimates. Extrapolation of the coolest late Valanginian temperatures points to polar regions closer to freezing. This interpretation is consistent with dropstones and glendonites and
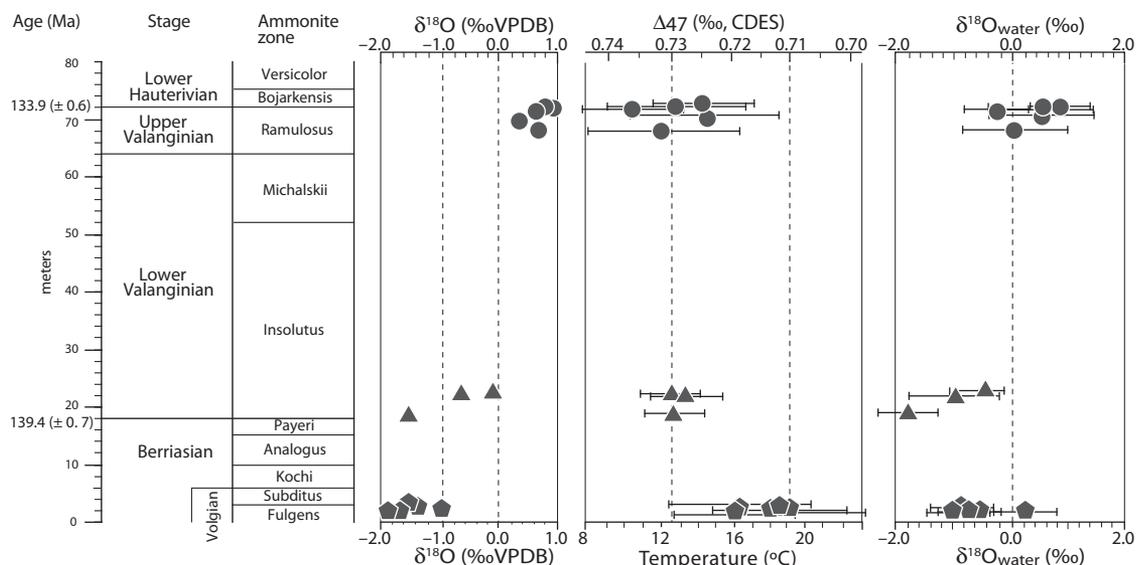

Figure 2. Yatria River (Siberia) stratigraphy, showing the $\delta^{18}O_{belemnite}$ (‰, Vienna Peedee belemnite [VPDB]) and clumped isotope (Δ_{47}, ‰) data and seawater $\delta^{18}O$ (from our combined temperature–$\delta^{18}O_{belemnite}$ data). Biostratigraphic data from Golbert et al. (1975). CDES—carbon dioxide equilibrium scale. Pentagon (e)—Berriasian; triangle (f)—early Valanginian; circle (g)—late Valanginian data. Details of how error bars were generated are given in Table DR1 (see footnote 1).
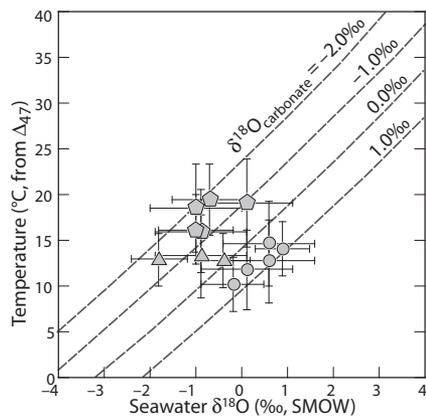
Figure 3. Inferred $\delta^{18}O_{seawater}$ versus temperature (calculated from Δ_{47} values using the calibration of Henkes et al. [2013]). Pentagons—Berriasian data; triangles—early Valanginian data; circles—late Valanginian data. SMOW—standard mean ocean water.

postulated transient cold episodes (Price and Nunn, 2010). A modest-sized ice sheet would have had to have been located on Antarctica, given its polar position and widespread areas of elevated terrain (DeConto and Pollard, 2003) as well as smaller ice sheets within Siberia, Canada, and Greenland. The variation in temperature seen does, on the other hand, contrast with the Cretaceous TEX_{86} records from the proto–North Atlantic (Littler et al., 2011), in particular Ocean Drilling Program Site 534, which shows a lack of temperature variation through the Valanginian. This may point to the inherent buffering of tropical regions to transient climate change (Littler et al., 2011). Projected cooling during the late Valanginian may therefore be restricted to higher latitudes, providing a steep gradient of temperature change.

Our combined temperature and $\delta^{18}O_{belemnite}$ data imply seawater $\delta^{18}O$ values of $-1.8‰$ to $0.9‰$ (average $-0.4‰$)(Figs. 2 and 4). If belemnite growth temperatures are seasonally biased, seawater $\delta^{18}O$ values must be viewed as maximum estimates. The range and average are similar to modern high-latitude seawater (LeGrande and Schmidt, 2006), yet only partially overlap with the low modeled seawater $\delta^{18}O$ distribution for the Cretaceous (Zhou et al., 2008), although the mean is similar to the inferred global average for Cretaceous seawater of $-1.0‰$ (Shackleton and Kennett, 1975). Cretaceous modeled values (Zhou et al., 2008) are less positive because the model was initialized to $-1.0‰$ (SMOW) in order to reflect the absence of ice sheets. Although extant relatives of belemnites (cuttlefish and *Spirula*) do not exhibit oxygen isotopic disequilibria with seawater (e.g., Price et al., 2009), it is possible that belemnite body fluid was in isotopic disequilibrium with seawater and this could contribute to the high

apparent seawater $\delta^{18}O$ values. However, given high rates of water turnover in marine organisms we estimate this effect to be no more than a few tenths per mil, and thus implied seawater values are still higher than those observed today.

We consider the seawater $\delta^{18}O$ values to be plausible and point to unexpected basin- or global-scale hydrologies. The depleted Berriasian seawater $\delta^{18}O$ values are associated with the warmest temperatures, whilst the coolest (late Valanginian) data are associated with more enriched (slightly more saline) seawater $\delta^{18}O$ values. Our findings are consistent with observations from the modern Arctic Ocean that show that warm conditions lead to the region having increased precipitation, input of riverine water, and melting of glacial ice, leading to the freshening of surface waters (e.g., Curry et al., 2003). Relatively fresh conditions characterizing the Arctic Ocean during warm intervals are also consistent with results from paleoclimate simulations, whereby greenhouse conditions induced an intensified hydrological

cycle with increases in precipitation at high latitudes (Poulsen et al., 2001).

The low temperatures of the late Valanginian are coincident with increased $\delta^{18}O$ seawater values. This may reflect a combination of factors including a decrease in precipitation and/or riverine input but also potentially an increase in the growth of ice (influencing both local and possibly global seawater $\delta^{18}O$ values). We envisage these mechanisms rather than an influx of relatively $\delta^{18}O$-enriched (saline) seawater transported from more southern oceans as we would expect to see these accompanied by increased temperatures also.

CONCLUSIONS

Our data implies a dynamic polar climate where changes in salinity occurred in the Early Cretaceous Arctic independently of major changes in ocean heat transport (as suggested also for the Eocene Arctic; Brinkhuis et al., 2006). Indeed the data presented here fit with an emerging picture of an unstable and variable
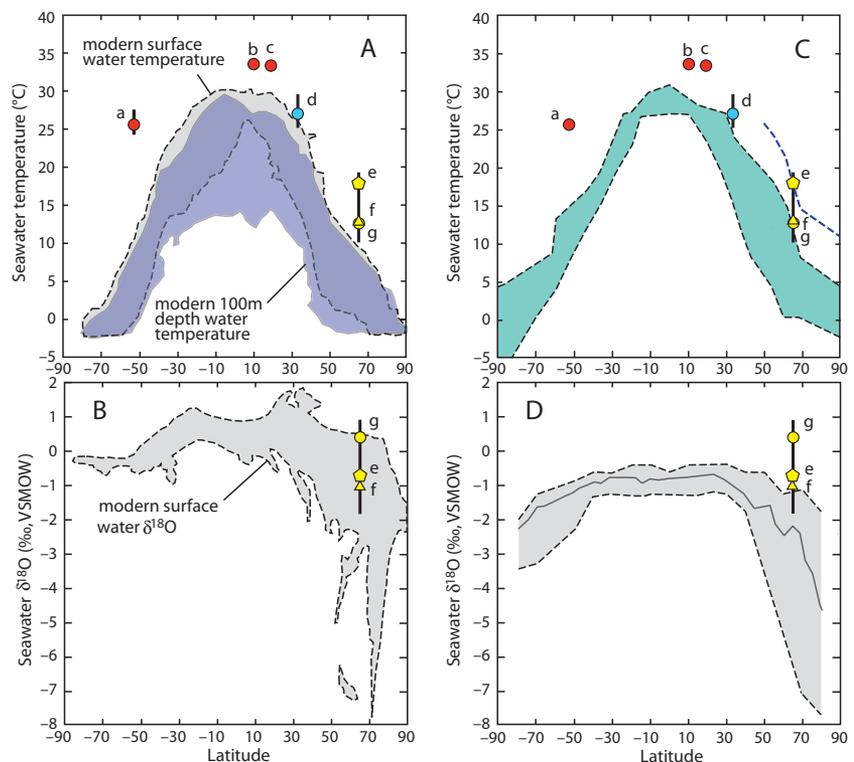

Figure 4. Meridional temperature and seawater $\delta^{18}O$ gradients. A: Mean annual temperature observations from the World Ocean Atlas (Boyer et al., 2009). B: Modern gridded mean annual $\delta^{18}O$ values from LeGrande and Schmidt (2006). C: General circulation model (GCM) simulation of Cretaceous (Aptian) sea-surface temperatures using $4 \times CO_2$ (Fluteau et al., 2007) plotted showing seasonal variations. Green shaded curve encompasses the winter (DJF—December, January, February) and summer (JJA—June, July, August) variation. Blue dashed line shows "extrapolated" poleward temperatures using profile of GCM model temperature. D: Mean annual zonal average $\delta^{18}O$ and range of seawater (Zhou et al., 2008). Red circles, a–c, represent Hauterivian TEX_{86} data (Littler et al., 2011), and blue circle, d, represents Barremian TEX_{86} data (Mutterlose et al., 2010); TEX_{86} temperature estimates are calibrated according to methodology of Kim et al. (2010). Yellow pentagon (e)—Berriasian; yellow triangle (f)—early Valanginian; yellow circle (g)—late Valanginian Δ_{47} data. VSMOW—Vienna standard mean ocean water.

Northern-Hemisphere climate during Paleocene and Eocene greenhouse climates including transient freezing or near-freezing sea-surface temperatures (e.g., Brinkhuis et al., 2006; Eldrett et al., 2007). The data also highlight the long-standing mismatch between GCM and high-latitude temperature proxies.

REFERENCES CITED

Bice, K.L., and Norris, R.D., 2002, Possible atmospheric CO_2 extremes of the Middle Cretaceous (late Albian–Turonian): Paleoceanography, v. 17, 1070, doi:10.1029/2002PA000778.

Boyer, T.P., Antonov, J.I., Baranova, O.K., Garcia, H.E., Johnson, D.R., Locarnini, R.A., Mishonov, A.V., Seidov, D., Smolyar, I.V., and Zweng, M.M., 2009, World ocean database 2009: Washington, D.C., U.S. Government Printing Office, NOAA Atlas NESDIS 66, 219 p.

Brinkhuis, H., and 22 others, 2006, Episodic fresh surface waters in the Eocene Arctic Ocean: Nature, v. 441, p. 606–609, doi:10.1038/nature04692.

Curry, R., Dickson, R.R., and Yashayaev, I., 2003, A change in the freshwater balance of the Atlantic Ocean over the past four decades: Nature, v. 426, p. 826–829, doi:10.1038/nature02206.

DeConto, R.M., and Pollard, D., 2003, Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2: Nature, v. 421, p. 245–249, doi:10.1038/nature01290.

Dennis, K.J., and Schrag, D.P., 2010, Clumped isotope thermometry of carbonatites as an indicator of diagenetic alteration: Geochimica et Cosmochimica Acta, v. 74, p. 4110–4122, doi:10.1016/j.gca.2010.04.005.

Dennis, K.J., Affek, H.P., Passey, B.H., Schrag, D.P., and Eiler, J.M., 2011, Defining an absolute reference frame for "clumped" isotope studies of CO_2: Geochimica et Cosmochimica Acta, v. 75, p. 7117–7131, doi:10.1016/j.gca.2011.09.025.

Dennis, K.J., Cochran, J.K., Landman, N.H., and Schrag, D.P., 2013, The climate of the Late Cretaceous: New insights from the application of the carbonate clumped isotope thermometer to Western Interior Seaway macrofossil: Earth and Planetary Science Letters, v. 362, p. 51–65, doi:10.1016/j.epsl.2012.11.036.

Eagle, R.A., and 12 others, 2013, The influence of temperature and seawater carbonate saturation state on ^{13}C–^{18}O bond ordering in bivalve mollusks: Biogeosciences Discussions, v. 10, p. 157–194, doi:10.5194/bgd-10-157-2013.

Eldrett, J.S., Harding, I.C., Wilson, P.A., Butler, E., and Roberts, A.P., 2007, Continental ice in Greenland during the Eocene and Oligocene: Nature, v. 446, p. 176–179, doi:10.1038/nature05591.

Fluteau, F., Ramstein, G., Besse, J., Guiraud, R., and Masse, J.P., 2007, Impacts of palaeogeography and sea level changes on Mid-Cretaceous climate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 247, p. 357–381, doi:10.1016/j.palaeo.2006.11.016.

Ghosh, P., Adkins, J., Affek, H., Balta, B., Guo, W., Schauble, E.A., Schrag, D., and Eiler, J.M., 2006, ^{13}C–^{18}O bonds in carbonate minerals: A new kind of paleothermometer: Geochimica et Cosmochimica Acta, v. 70, p. 1439–1456, doi:10.1016/j.gca.2005.11.014.

Golbert, A.V., Zakharov, V.A., Klimova, I.G., and Romanova, E.E., 1975, Yatria River, in Saks, V.N., ed., The Jurassic–Cretaceous Boundary and the Berriasian Stage in the Boreal Realm: Jerusalem, Keter, p. 56–65.

Guo, W.F., Mosenfelder, J.L., Goddard, W.A., and Eiler, J.M., 2009, Isotopic fractionations associated with phosphoric acid digestion of carbonate minerals: Insights from first-principles theoretical modeling and clumped isotope measurements: Geochimica et Cosmochimica Acta, v. 73, p. 7203–7225, doi:10.1016/j.gca.2009.05.071.

Henkes, G.A., Passey, B.H., Wanamaker, A.D., Grossman, E.L., Ambrose, W.G., and Carroll, M.L., 2013, Carbonate clumped isotope compositions of modern marine mollusk and brachiopod shells: Geochimica et Cosmochimica Acta, v. 106, p. 307–325, doi:10.1016/j.gca.2012.12.020.

Kim, J.-H., van der Meer, J., Schouten, S., Helmke, P., Willmott, V., Sangiorgi, F., Ko, N., Hopmans, E.C., and Sinninghe Damsté, J.S., 2010, New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: Implications for past sea surface temperature reconstructions: Geochimica et Cosmochimica Acta, v. 74, p. 4639–4654, doi:10.1016/j.gca.2010.05.027.

LeGrande, A.N., and Schmidt, G.A., 2006, Global gridded data set of the oxygen isotopic composition in seawater: Geophysical Research Letters, v. 33, L12604, doi:10.1029/2006GL026011.

Littler, K., Robinson, S.A., Bown, P.R., Nederbragt, A.J., and Pancost, R.D., 2011, High sea-surface temperatures during the Early Cretaceous Epoch: Nature Geoscience, v. 4, p. 169–172, doi:10.1038/ngeo1081.

Mutterlose, J., Malkoc, M., Schouten, S., Sinninghe Damsté, J.S., and Forster, A., 2010, TEX_{86} and stable ^{18}O paleothermometry of Early Cretaceous sediments: Implications for belemnite ecology and paleotemperature proxy application: Earth and Planetary Science Letters, v. 298, p. 286–298, doi:10.1016/j.epsl.2010.07.043.

Passey, B.H., and Henkes, G.A., 2012, Carbonate clumped isotope bond reordering and geospeedometry: Earth and Planetary Science Letters, v. 351–352, p. 223–236, doi:10.1016/j.epsl.2012.07.021.

Passey, B.H., Levin, N.E., Cerling, T.E., Brown, F.H., and Eiler, J.M., 2010, High-temperature environments of human evolution in East Africa based on bond ordering in paleosol carbonates: Proceedings of the National Academy of Sciences of the United States of America, v. 107, p. 11,245–11,249, doi:10.1073/pnas.1001824107.

Poulsen, C.J., 2004, A balmy Arctic: Nature, v. 432, p. 814–815, doi:10.1038/432814a.

Poulsen, C.J., Barron, E.J., Arthur, M.A., and Peterson, W.H., 2001, Response of the mid-Cretaceous global oceanic circulation to tectonic and CO_2 forcings: Paleoceanography, v. 16, p. 576–592.

Price, G.D., and Mutterlose, J., 2004, Isotopic signals from late Jurassic–early Cretaceous (Volgian–Valanginian) sub-Arctic belemnites, Yatria River, Western Siberia: Journal of the Geological Society, v. 161, p. 959–968, doi:10.1144/0016-764903-169.

Price, G.D., and Nunn, E.V., 2010, Valanginian isotope variation in glendonites and belemnites from Arctic Svalbard: Transient glacial temperatures during the Cretaceous greenhouse: Geology, v. 38, p. 251–254, doi:10.1130/G30593.1.

Price, G.D., Twitchett, R.J., Smale, C., and Marks, V., 2009, Isotopic analysis of the life history of the enigmatic squid Spirula spirula, with implications for studies of fossil cephalopods: Palaios, v. 24, p. 273–279, doi:10.2110/palo.2008.p08-067r.

Shackleton, N.J., and Kennett, J.P., 1975 Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation: Oxygen and carbon isotope analyses in DSDP Sites 277, 279, and 281, in Kennett, J.P., et al., eds., Initial Reports of the Deep Sea Drilling Project, Volume 29: Washington, D.C., U.S. Government Printing Office, p. 743–755.

Smith, A.G., Smith, D.G., and Funnell, B.M., 1994, Atlas of Mesozoic and Cenozoic Coastlines: Cambridge, UK, Cambridge University Press. 99 p.

Spicer, R.A., Ahlberg, A., Herman, A.B., Hofmann, C., Raikevich, M., Valdes, P.J., and Markwick, P.J., 2008, The Late Cretaceous continental interior of Siberia: A challenge for climate models: Earth and Planetary Science Letters, v. 267, p. 228–235, doi:10.1016/j.epsl.2007.11.049.

Tripati, A., Eagle, R., Thiagarajan, N., Gagnon, A., Bauch, H., Halloran, P., and Eiler, J., 2010, ^{13}C–^{18}O isotope signatures and 'clumped isotope' thermometry in foraminifera and coccoliths: Geochimica et Cosmochimica Acta, v. 74, p. 5697–5717, doi:10.1016/j.gca.2010.07.006.

Urey, H.C., Lowenstam, H.A., Epstein, S., and McKinney, C.R., 1951, Measurement of paleotemperatures and temperatures of the Upper Cretaceous of England, Denmark, and the southeastern United States: Geological Society of America Bulletin, v. 62, p. 399–416, doi:10.1130/0016-7606(1951)62[399:MOPATO]2.0.CO;2.

Zhou, J., Poulsen, C.J., Pollard, D., and White, T.S., 2008, Simulation of modern and middle Cretaceous marine $\delta^{18}O$ with an ocean-atmosphere general circulation model: Paleoceanography, v. 23, PA3223, doi:10.1029/2008PA001596.