Middle Cretaceous greenhouse hydrologic cycle of North America

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ABSTRACT

We present a paleolatitudinal precipitation reconstruction for the greenhouse setting of mid-latitude North America based on the oxygen isotopic composition of sphaerosiderites found in middle Cretaceous wetland paleosols. Our reconstructed middle Cretaceous $\delta^{18}O$ values of precipitation are ~4‰ less than values from comparable modern low-elevation coastal settings free of monsoons. The data fit a conceptual model in which the precipitation source for the eastern margin of the Cretaceous Western Interior Seaway of North America is an ^{18}O-enriched oceanic coastal jet. In this subtropical-tropical setting, mid-Cretaceous precipitation rates are interpreted to range from ~2500 to ~4100 mm/yr.

Keywords: Cretaceous, North America, Dakota Formation, sphaerosiderites, hydrologic cycle, precipitation rates.

INTRODUCTION

A warmer planet should have an intensified hydrologic cycle because evaporation is a strong nonlinear function of temperature. Model-predicted future global mean evaporation and precipitation display increases ranging from 3% to 15% due to increased atmospheric CO_2 concentrations (Mitchell et al., 1990). However, observations of past precipitation have been limited and/or problematic, and the distribution of precipitation is difficult to simulate when using numerical climate models because of the scale and complexity of the hydrologic cycle. Here we use an oxygen isotope-based precipitation proxy to help address these uncertainties. Today, variations in $\delta^{18}O$ values of precipitation are attributed to latitude, temperature, continentality, altitude, seasonality, and amount effect (Dansgaard, 1964; Rozanski et al., 1993). In this paper the role of these effects is addressed for middle Cretaceous precipitation.

The middle Cretaceous (Albian, Cenomanian, and Turonian ages, ca. 112–92 Ma) climate was warmer than today. Although the nature of this warmth is debatable, higher middle Cretaceous atmospheric CO_2 concentrations (Berner, 1994) are hypothesized to have resulted in globally averaged temperatures to 8 °C higher than present (Caldeira and Rampino, 1991). Barron et al. (1989) suggested that the presence of four times present-day atmospheric CO_2 concentrations increased middle Cretaceous globally averaged precipitation rates by 25%. More recent atmospheric general circulation model simulations using GENESIS (Global Environmental and Ecological Simulation of Interactive Systems) hindcast precipitation rates of ~1500 mm/yr for a middle Cretaceous mid-latitude lowstand setting of the Western Interior Seaway of North America, and ~2200 mm/yr for a highstand (Poulsen, 1999). These middle Cretaceous precipitation rates are elevated relative to modern values, and are supported by the globally widespread distribution of coeval laterites (Sigleo and Reinhardt, 1988), because laterites form under precipitation rates >1000 mm/yr (Bardossy, 1982).

Many North American middle Cretaceous lateritic paleosols (Fig. 1) contain sphaerosiderites (White et al., 2000), i.e., millimeter-scale spherulitic siderite precipitated in saturated wetlands at shallow-groundwater mean annual temperatures; the carbon and oxygen isotope compositions of sphaerosiderites record the isotope chemistry of ancient meteoric water (Ludvigson et al., 1998).

METHODS AND RESULTS

Albian-Cenomanian sphaerosiderites were collected from North American outcrops and cores (Fig. 1). The Albian-Cenomanian boundary is commonly a sequence boundary formed at eustatic sea-level lowstand (Immenhauser and Scott, 1999) and provides a chronostratigraphic marker for correlation between the outcrops and cores. We collected samples with a microdrill from 10 sphaerosiderites from each paleosol of late Albian age and analyzed them for carbon and oxygen isotope composition as outlined in Ludvigson et al. (1998).

Latitudinal paleoprecipitation $\delta^{18}O$ values were calculated from the sphaerosiderite $\delta^{18}O$ values. This derivation requires knowledge of the temperature at which the siderite formed. The meridional cross section of surface air temperatures along the eastern margin of the Western Interior Seaway (Fig. 2) was derived from a late Albian simulation by using the GENESIS version 2.0 atmospheric general

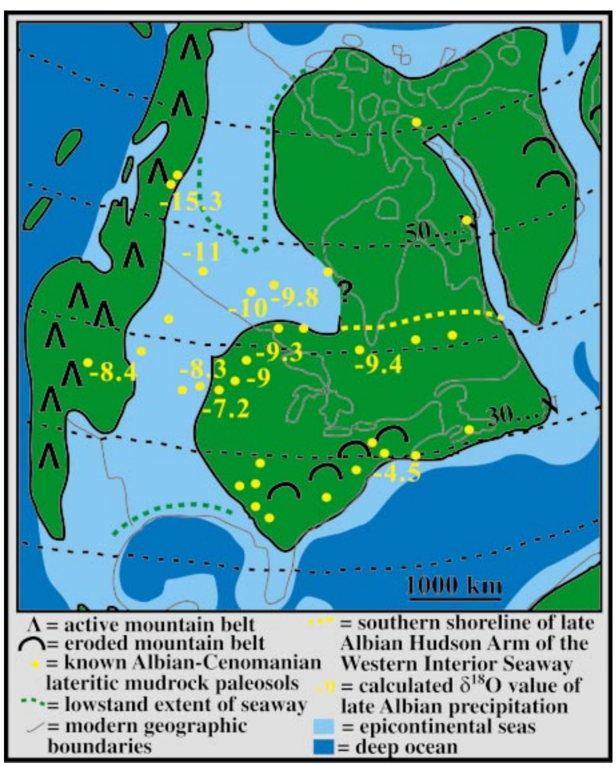

Figure 1. Middle to late Albian highstand paleogeography of North America (Kiowa-Skull Creek cycle; 98–106 Ma) showing distribution of known localities of Albian-Cenomanian kaolinitic mudrock paleosols and calculated $\delta^{18}O$ values for late Albian precipitation. Data presented here are mean values for 10 data points acquired from each sphaerosiderite-bearing horizon. Note that only $\delta^{18}O$ values for late Albian precipitation from eastern margin of Western Interior Seaway are considered in this paper. Base map is adapted from Scotese (1991), Scotese et al. (1988), and references in White et al. (2000).

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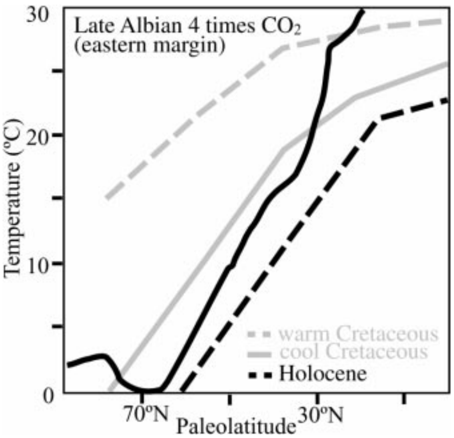

Figure 2. Late Albian mean annual surface-temperature gradient from eastern margin of Western Interior Seaway calculated from Poulsen (1999) compared to earlier estimates for mid-Cretaceous and Holocene Earth (Barron, 1983).

circulation model. Boundary conditions include the late Albian continental reconstruction of Barron (1987) and four times present-day CO_2 concentrations (1380 ppm). Orbital parameters were set to present-day values. A more detailed description of the boundary conditions was summarized in Poulsen (1999).

GENESIS simulates late Albian Western Interior Seaway temperatures to 5 °C higher than at present and a weaker Cretaceous equator-to-pole gradient (Fig. 2). The model-derived mean annual temperatures were used to assign a temperature-dependent, siderite-water fractionation factor (Carothers et al., 1988) for each site. If it is assumed that sphaerosiderites formed in shallow groundwater, then the sphaerosiderite-derived $\delta^{18}O$ values (relative to SMOW [standard mean ocean water]) record mean annual late Albian precipitation $\delta^{18}O$ values (Ludvigson et al., 1998). The distribution of late Albian precipitation $\delta^{18}O$ estimates (Fig. 1) was used to derive relationships between late Albian paleotemperature and paleolatitude, as well as the relationship of paleoprecipitation $\delta^{18}O$ to paleolatitude and paleotemperature (Figs. 3, 4, and 5).

DISCUSSION

The potential error sources in this model-based approach are not trivial. First, we assumed that the temperature-dependent, siderite-water fractionation factor relationship is linear at Earth surface temperatures, even though experimental and theoretical siderite-water fractionations may differ by 2‰ at low temperatures (Carothers et al., 1988). Second, although the standard deviations of our calculated $\delta^{18}O$ means are mostly low ($<$0.1‰), several horizons have standard deviations to 0.5‰. Third, our temperature estimates are based on the assumptions that model-derived temperatures are accurate and that sphaerosiderites formed at mean annual temperatures of shallow groundwater. In fact, discrepancies between paleotemperature proxy data and general circulation model results suggest that the models do not accurately simulate heat transport to or from the continents. For example, a North American middle Cretaceous paleotemperature reconstruction predicted a mean annual temperature range of 21–24 °C (Wolfe and Upchurch, 1987), whereas GENESIS simulations for that time ranged from 0 to 30 °C (Barron et al., 1995). In addition, the depth of invariable tropical soil temperature is 10 m, whereas shallower temperatures may vary seasonally by 1–3 °C (Chang, 1957). Kappelmeyer (1961) showed that shallow groundwater and soil temperatures match and covary seasonally; therefore, the temperature of sphaerosiderite formation may have varied somewhat. To assess our potential error, we recalculated the fractionation factors by using a data standard deviation of 0.5‰ and a temperature range of $\pm$5 °C. This assessment suggests that potential errors in our calculations may range from 0.6‰ to 2.6‰ (or 9%–26%). Assuming that the maximum potential error is evenly distributed through our latitudinal profile, then the error could account for 65% of the ^{18}O depletion discussed subsequently.

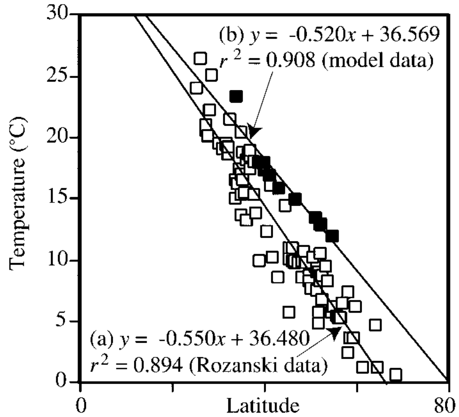

Figure 3. Temperature vs. latitude for (a) our modern filtered data (open squares; Rozanski et al., 1993) and (b) late Albian model output (filled squares) from atmospheric general circulation model GENESIS (Poulsen, 1999).

Nonetheless, the controls of altitude, continentality, seasonality, temperature, latitude, and amount effect on the study interval were assessed to better understand the latitudinal $\delta^{18}O$ gradient of middle Cretaceous precipitation. Our samples are from alluvial to coastal plain depositional settings with no mountains along the Western Interior Seaway cratonic margin, so orography cannot be a control on sphaerosiderite $\delta^{18}O$ values. Furthermore, all of the strata were deposited within ~200 km of the paleoshoreline (White et al., 2000), so any continental effect is considered minimal.

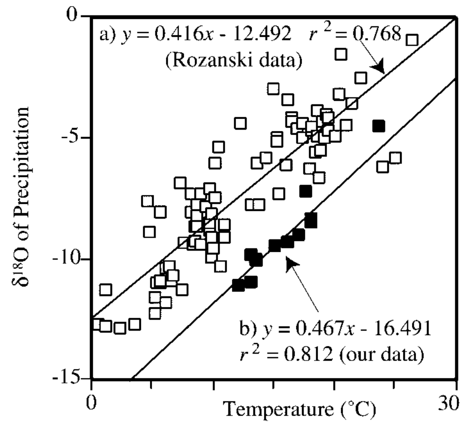

Figure 4. Precipitation $\delta^{18}O$ vs. temperature for (a) our modern filtered data set (open squares; Rozanski et al., 1993) and (b) a late Albian sphaerosiderite data set (filled squares) for Cretaceous Western Interior Seaway eastern margin.

Although seasonal temperature and evapotranspiration changes along the Western Interior Seaway are conceivable, model and empirical data suggest that seasonal effects were minor. For example, palynological studies of the Dakota Formation in the southwestern United States indicate that the climate was probably subtropical to tropical (e.g., am Ende, 1991), and middle to Late Cretaceous North American paleobotanical evidence indicates that rainfall was distributed evenly throughout the year (Wolfe and Upchurch, 1987). The close association of lignites and sphaerosiderites formed in saturated wetlands is suggestive of humid paleoclimates during sphaerosiderite formation. Paleoclimate model simulations suggest that North American Cen-

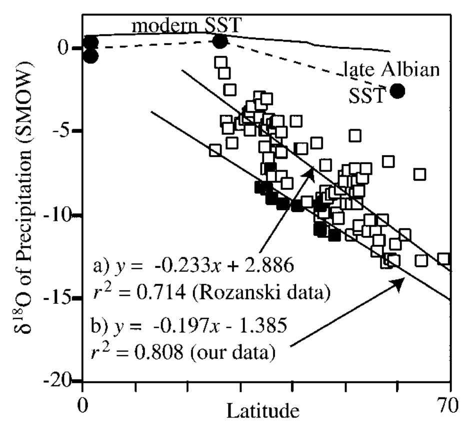

Figure 5. Precipitation $\delta^{18}O$ vs. latitude for (a) our modern filtered data (open squares; Rozanski et al., 1993) and (b) late Albian sphaerosiderite data set (filled squares) for Cretaceous Western Interior Seaway eastern margin. Curved solid line is modern sea-surface $\delta^{18}O$ profile and dashed line connecting solid circles is our calculated late Albian sea-surface $\delta^{18}O$ profile discussed in text. SST—sea-surface temperature; SMOW—standard mean ocean water.

omanian coals formed in areas with a moist climate throughout the year (Valdes et al., 1996), and there is little seasonality in GENESIS-generated Western Interior Seaway precipitation (Poulsen, 1999). Therefore, the sphaerosiderite-derived $\delta^{18}O$ values are unlikely to record seasonal temperature or evapotranspiration changes.

To understand the effects of temperature, latitude, and 'amount effect,' the late Albian data were compared to filtered modern precipitation $\delta^{18}O$ values. The data of Rozanski et al. (1993) were filtered by removing all stations with elevations of >300 m (orographic effects), with precipitation rates of >1700 mm/yr (monsoonal effects), and with locations >250 km from coastlines (continental effect) and/or outside of the latitude 25°–70° range. In this manner, modern relationships were established for settings most comparable to the late Albian sphaerosiderite-bearing paleoenvironments. A strong positive relationship exists between latitude and mean annual temperature in the modern filtered data and in the late Albian model data (Fig. 3). A good positive relationship exists between modern and late Albian mean annual $\delta^{18}O$ values of precipitation, and mean annual temperature (Fig. 4) and latitude (Fig. 5).

The slope of the late Albian precipitation $\delta^{18}O$ versus paleotemperature line for the eastern margin of the Western Interior Seaway ($y = 0.467x - 16.491$, $r^2 = 0.812$) resembles that of the modern filtered data (slope = 0.416, $r^2 = 0.768$), although a 4‰ depletion exists between the modern and Albian lines (Fig. 4). Similar observations can be made for late Albian precipitation $\delta^{18}O$ values versus paleolatitude (Fig. 5); i.e., the slope of the eastern margin of the Western Interior Seaway line ($y = -0.197x - 1.385$) approximates the slope of the modern line, but shows a 4.3‰ depletion relative to modern values. These observations suggest that the late Albian atmospheric setting along the eastern margin of the seaway was comparable to modern low elevation coastal settings free of monsoons.

Our analysis has not explained the relative ^{18}O depletion between Albian and modern precipitation $\delta^{18}O$ values. At first glance, the depletion is perplexing because relatively warmer conditions should lead to a relative enrichment in precipitation $\delta^{18}O$ values. Therefore, lower $\delta^{18}O$ values should be associated with icehouse conditions rather than middle Cretaceous greenhouse conditions.

The ^{18}O depletion recorded in our middle Cretaceous sphaerosiderite $\delta^{18}O$ is unlikely to be the result of ocean-water ^{18}O depletion at a subtropical source. A global-ocean $\delta^{18}O$ estimate of −1.2‰ for an ice-free Earth has been applied to Western Interior Seaway isotopic studies. If a substantial part of the atmospheric water vapor over the seaway's eastern margin was derived from subtropical regions of increased evaporation, then it is reasonable to consider these atmospheric vapors to have been reduced at least 1.2‰ relative to modern values. However, a latitudinal sea-surface salinity difference probably has persisted through time (e.g., Huber et al., 1995). We constructed a late Albian sea-surface $\delta^{18}O$ profile by using foraminiferal isotopic data (Huber et al., 1995; Norris and Wilson, 1998), modeled paleotemperatures (Poulsen, 1999), and an empirical equation relating foraminiferal oxygen isotope data to aqueous oxygen isotope composition and temperature (Erez and Luz, 1983). Our late Albian profile resembles a modern sea-surface $\delta^{18}O$ versus latitude profile (Fig. 5), and our calculated late Albian subtropical sea-surface $\delta^{18}O$ value (~0.7‰ relative to SMOW) is supported by observations of ^{18}O-enriched mid-Cretaceous subtropical surface waters relative to average Cretaceous seawater (Woo et al., 1992).

Valdes et al. (1996) showed that the Western Interior Seaway had an ameliorating effect on the North American climate by warm, moist, air advection. In general, this atmospheric regime is supported by other model results (e.g., Glancy et al., 1993; Poulsen, 1999), and by the observation that large epicontinental water masses may provide most of the moisture over continents. Because reduced sea-surface $\delta^{18}O$ values have been postulated for the seaway's western margin (e.g., Glancy et al., 1993), they could account for the depletion in sphaerosiderite ^{18}O if the western waters were an atmospheric water-vapor source to the eastern margin. This scenario is unlikely for the following reasons. First, Western Interior Seaway circulation-modeling results describe a north-flowing coastal jet along the eastern margin that drew Tethyan waters into the seaway and a western-margin south-flowing jet that drew in northern Boreal waters (Slingerland et al., 1996). Calcareous nannofossil temperature reconstructions (Watkins, 1986) indicate that Tethyan-derived eastern water was likely warmer than western Boreal-influenced water. The warmer eastern water likely had a greater evaporative capacity than the cooler western water, because evaporation rates are strongly surface-temperature dependent. Second, we suggest that the Sevier Mountains weakened zonal jetstream flow and increased meridional flow by inducing downstream troughs over the seaway. Storms tend to develop east of jetstream troughs and flow in a northeasterly direction toward the next downstream ridge; therefore, we infer that storms were initiated in the central Western Interior Seaway from where they flowed toward the eastern margin. In addition, a subtropical high southeast of the seaway was postulated to steer hurricanes into it (PSUCLIM 2, 1999). Because hurricanes dissipate over cool water, we suggest that both tropical and extratropical storms tended to migrate toward the eastern margin.

Ocean models indicate that the source of the water in the southeastern Western Interior Seaway was the subtropics (Poulsen, 1999); therefore, we consider waters drawn into the seaway's eastern coastal jet to have been ^{18}O enriched by net evaporation at the source. Model-derived early Turonian steady-state surface salinity in the central part of the seaway attained values of 37.0 practical salinity units (Slingerland et al., 1996), the equivalent of $\delta^{18}O$ values being >1‰ in the modern Atlantic and Pacific Oceans. If the Cretaceous global ocean was depleted by −1.2‰ relative to modern values, then the central part of the seaway may have had $\delta^{18}O$ values >0. Tethyan subtropical waters that swept the seaway's eastern margin appear to have had higher $\delta^{18}O$ compositions relative to the global ocean. Therefore, we conclude that the isotopic composition of the seaway's eastern-margin water-vapor sources cannot account for the depleted sphaerosiderite values.

The only remaining effect on the $\delta^{18}O$ value of precipitation that we have not assessed is the amount of monthly precipitation, or the amount effect. Dansgaard (1964) noted low precipitation $\delta^{18}O$ values during rainy months, and generally higher values during periods with less precipitation. He described the $\delta^{18}O$ decrease through ^{18}O fractionation as the total amount of condensate from a water vapor mass increased, and the remaining vapor became progressively more depleted. This amount effect is most pronounced in regions displaying little temperature fluctuation throughout the year, and is therefore strongest in the tropics, seasonally important in temperate latitudes, and never occurs at the poles (Dansgaard, 1964; Rozanski et al., 1993).

A relationship between modern precipitation amount and precipitation $\delta^{18}O$ values has been established. Dansgaard (1964) reported precipitation $\delta^{18}O$ values ranging from −1.2‰ to −3.6‰ per 100 mm of rainfall per month in all settings, −1.6‰ per 100 mm per month for islands, and −2‰ per 100 mm per month for coastal settings. For modern islands where no relationship can be established between precipitation $\delta^{18}O$ values and other factors controlling them, a 4‰ reduction in precipitation $\delta^{18}O$ represents ~250 mm of rainfall per month (Rozanski et al., 1993). These values can account for late Albian precipitation rates ranging from 3200 mm/yr (4.3‰ reduction in a tropical island setting) to 1300 mm/yr (4‰ reduction in a continental setting). We consider the coastal values (2‰

per 100 mm per month) as most analogous to the late Albian Western Interior Seaway eastern margin, so late Albian precipitation rates ranging from ~2400 (4‰ reduction) to ~2600 (4.3‰ reduction) mm/yr are reasonable.

This precipitation estimate is based solely on the observed decrease in late Albian precipitation $\delta^{18}O$ values relative to modern precipitation $\delta^{18}O$ values for similar latitudinal and temperature settings. If the late Albian relative ^{18}O depletion was caused by above-average precipitation rates for comparable modern settings, then late Albian precipitation rates along the eastern margin of the Western Interior Seaway may have been ~150–1500 mm/yr (Rozanski et al., 1993) higher than our earlier estimates. This observation suggests that mean annual precipitation rates for parts of the eastern margin of the late Albian seaway may have been as high as 4100 mm/yr. These estimates could increase if the values of $\delta^{18}O$ of the seaway's eastern-margin water-vapor sources were >0‰.

CONCLUSIONS

The $\delta^{18}O$ values obtained from sphaerosiderites formed in saturated wetland paleosols can be combined with paleotemperature estimates (model-derived paleotemperatures in this paper) to estimate paleoprecipitation $\delta^{18}O$ values. Paleoprecipitation $\delta^{18}O$ values versus paleolatitudinal gradients can be reconstructed by applying these estimates to analyses of ancient hydrologic cycles. We conclude that orographic, seasonal, and continental effects played minor roles in the late Albian atmospheric hydrologic cycle along the eastern margin of the Cretaceous Western Interior Seaway of North America. Furthermore, we conclude that subtropical waters that swept the seaway's eastern margin (1) were the primary source of water vapor to the eastern margin, (2) were enriched in ^{18}O relative to the global ocean, and (3) cannot account for the depleted ^{18}O sphaerosiderite values presented in this paper. The relative reduction of ~4‰–4.3‰ between estimated $\delta^{18}O$ values for late Albian precipitation and modern values is a function of an amount effect. We conclude that the late Albian seaway's eastern margin was subject to average precipitation rates ranging from ~2500 to 4100 mm/yr.

ACKNOWLEDGMENTS

These investigations were funded by the Center for Global and Regional Environmental Research at the University of Iowa, the National Science Foundation (grant EAR-96-28128), and the Petroleum Research Fund of the American Chemical Society (grant 32573-AC8). We acknowledge critical reviews by Mike Arthur, Eric Barron, Walt Dean, and an anonymous reader, but remain responsible for the data and interpretations presented in the paper.

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Manuscript received July 19, 2000
Revised manuscript received December 11, 2000
Manuscript accepted December 21, 2000

Printed in USA