Distinguishing base-level change and climate signals in a Cretaceous alluvial sequence

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ABSTRACT

We present the results of oxygen isotope and electron-microprobe analyses of sphaerosiderites obtained from Cretaceous paleosols in Iowa. The sphaerosiderite δ^{18}O values record Cretaceous meteoric groundwater chemistry and an overall waning of brackish groundwater inundation during alluvial-plain aggradation and soil genesis. We focus on horizons that precipitated from freshwater, in which δ^{18}O values ranging from −3.3‰ to −6.8‰ relative to the Peedee belemnite standard are interpreted to record variations in the Cretaceous atmospheric hydrologic cycle. During relative sea-level highstands, moisture was derived from the Cretaceous Western Interior Seaway, whereas during lowstands, when the seaway narrowed and occasionally withdrew from the Midcontinent, the dominance of hemispheric-scale atmospheric moisture transport initiated in the tropical Tethys Ocean led to decreased precipitation rates. These processes did not operate like a switch, but rather as a continuum of competing moisture sources and mechanisms of transport between the nearby epicontinental sea and the distant tropics. The sphaerosiderite data demonstrate (1) temporal variation in the intensity of hemispheric-scale atmospheric moisture transport and (2) long-term amplification of the global hydrologic cycle marked by extreme ^{18}O depletion at the Albian-Cenomanian boundary.

Keywords: Cretaceous, Dakota Formation, paleosols, sphaerosiderite, oxygen isotopes.

INTRODUCTION

Paleosols are useful paleoclimate proxies because they can contain a first-order record of atmospheric conditions during soil formation. For example, Ludvigson et al. (1998) demonstrated that sphaerosiderites in alluvial-plain gleysols contain a record of paleoprecipitation δ^{18}O chemistry, providing a powerful tool to reconstruct past atmospheric hydrologic cycles. However, given the emphasis of eustatic sea-level control on sedimentation, alluvial sequence development remains subject to considerable debate. Therefore, the task of reading the paleoclimate record from alluvial paleosols often involves first understanding other factors involved in paleosol formation.

A broad geographic distribution of middle Cretaceous sphaerosiderite-bearing paleosols has been documented for North America. In many places a paleosol exists within alluvial and coastal-plain deposits at the Albian-Cenomanian boundary (White et al., 2000). In coeval strata in the U.S. Midcontinent, Canada, and Delaware, a succession of paleosols is found. We focus on the Dakota Formation in Iowa because this region contains the largest number of amalgamated paleosols we have observed and sphaerosiderite preservation is pristine. This region provides an excellent opportunity to use sphaerosiderite δ^{18}O chemistry to assess (1) alluvial-plain evolution during globally high sea level and (2) variations in atmospheric hydrologic conditions during the middle Cretaceous greenhouse episode.

BACKGROUND

The mostly nonmarine Dakota Formation was deposited as fluvial, alluvial, and paralic sediments on a broad coastal plain. The formation consists of the lower sandstone-dominated Nishnabotna Member and the upper mudrock-dominated Woodbury Member. The Woodbury Member and coeval units of the U.S. Midwest often contain kaolinitic paleosols bearing millimeter-scale sphaerosiderites and varicolored mottles. The formation is divided into three sequences. The lower-upper Woodbury Member boundary marks the unconformity separating the second and third sequences and roughly coincides with the Albian-Cenomanian boundary (Brenner et al., 2000).

Coeval strata along the western margin of the Cretaceous Western Interior Seaway display stacking patterns similar to those of the eastern margin suggesting a common control on facies development. A simple mechanism for describing similar cross-basin stacking patterns is eustatic sea-level variation. This mechanism is attractive because the relative sea-level curve of the Cretaceous Western Interior Seaway correlates well with global eustatic events (Kauffman and Caldwell, 1993). Because positive covariant δ^{18}O and δ^{13}C trends in Dakota sphaerosiderites support independent evidence for marine influence (Ludvigson et al., 1995), an understanding of relative sea level during the time of formation of the Dakota Formation is critical to understanding the paleosol δ^{18}O record. However, various researchers have determined that the western margin Dakota Formation records climate cycles. Therefore a mechanism involving climate change also appears plausible to describe the Iowa paleosol δ^{18}O record.

METHODS

Outcrops in the Sioux City Brick Company clay pit and a series of cores within a quarter section on the company property, Woodbury County, Iowa, were described and sampled. Because horizontally bedded strata exist here, the core and pit descriptions were hung on elevation and used to construct a composite section (Figs. 1 and 2). The base of the section is ~65 m above the base of the Dakota Formation within the lower Woodbury Member.

We oriented and prepared 46 samples for transmitted light microscopy. A split of each sample was disaggregated in water and sieved to collect sphaerosiderites. The sphaerosiderites were embedded in epoxy, polished, and microdrilled for δ^{18}O and δ^{13}C analyses. A minimum of 10 microdrilled samples was analyzed for each horizon as outlined in Ludvigson et al. (1998). A pellet or thin section from each sample was polished for microprobe analyses. Each sample was carbon coated and analyzed for FeO, MnO, CaO, MgO, and SrO (as weight percent) at the U.S. Geological Survey JEOL JXA-8900R electron-microprobe laboratory in Reston, Virginia.

RESULTS

An inversely covariant relationship (r^2 = 0.972) exists between the $FeCO_3$ and $CaCO_3$ contents in the studied sphaerosiderites; the analyses show an overall stratigraphic trend of increasing $FeCO_3$ and decreasing $CaCO_3$ from the section base to 326.15 m above mean sea level (amsl) (Figs. 1A, 1B). The values for these parameters then remain approximately constant between 326.15 m amsl and the section top. The δ^{18}O values vary widely, although an overall upsection δ^{18}O decrease is visible (Fig. 1C).

Geochemical cycles, each consisting of closely spaced paleosols

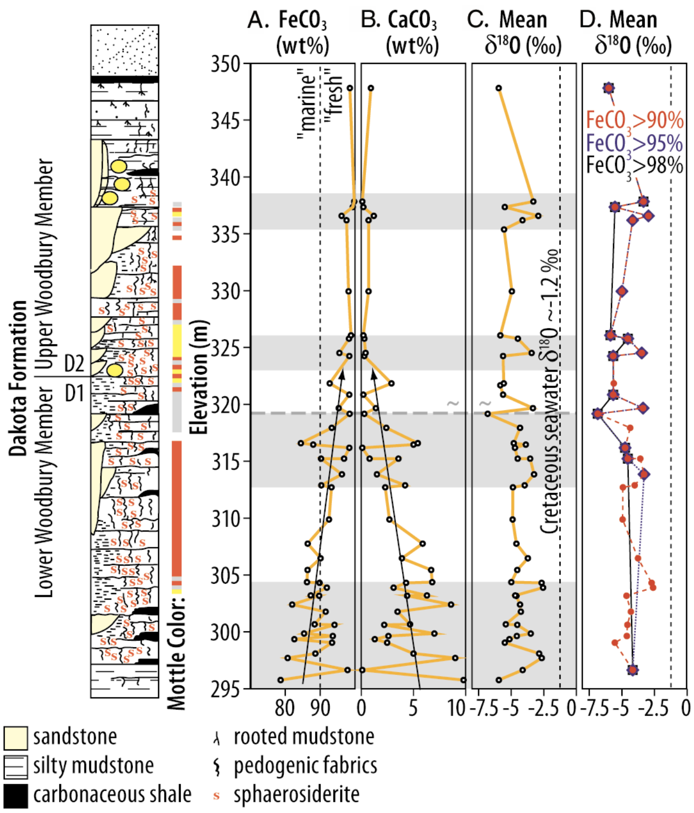

Figure 1. Composite stratigraphic and geochemical profiles for Albian–Cenomanian amalgamated paleosols in Woodbury County, Iowa. Note Albian-Cenomanian boundary at 319.2 m marked by horizontal dashed gray line and tildes. Grayed intervals delineate lowstand paleosol bundles. Large arrows on $FeCO_3$ (A) and $CaCO_3$ (B) plots show upsection shift toward freshwater environments of deposition. Profile D displays influence of $\delta^{18}O$ data filtering mechanism to discern subtle changes in marine influenced vs. freshwater derived siderite.

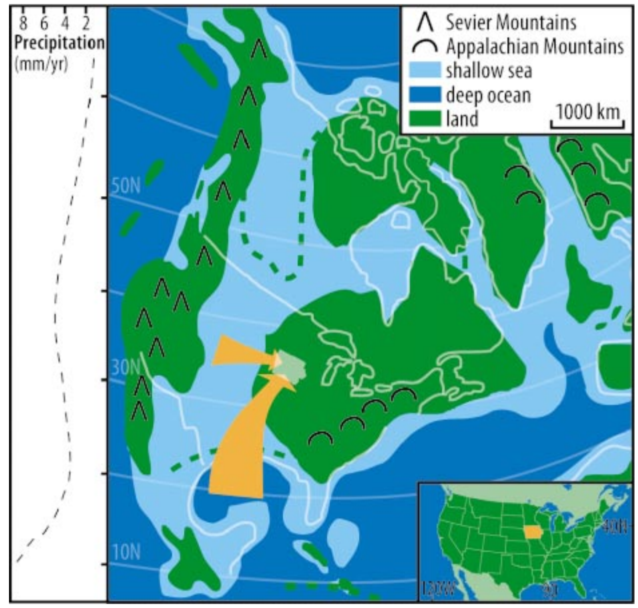

Figure 2. Paleogeographic reconstruction of North America during Albian-Cenomanian sea-level highstand (modified from White et al., 2001). Hudson Arm connection is based on interpretations of White et al. (2000) and Coniacian reconstruction of Ziegler and Rowley (1998). Paleolatitudinal precipitation gradient is from Poulsen (1999). Large orange arrow displays hemispheric-scale atmospheric moisture transport from subtropics to Western Interior Seaway, whereas small orange arrow shows vapor transport pathways from seaway. Dashed green lines mark extent of lowstand seaway, a setting in which atmospheric moisture transport is postulated to have occurred only from subtropics. Note that Iowa is shaded.

observable as high-frequency geochemical data variations, overlain by a zone of more widely spaced paleosols displaying little data variation, are superimposed on the general trend (Fig. 1). The closely spaced paleosols are characterized by red, yellow, and gray mottles and by microfabrics ranging from asepic to insepic interrupted by vosepic, masepic, lattisepic, or omnisepic horizons. The zones with fewer paleosols display insepic microfabrics and red mottles and are commonly lateral to channel sandstones.

ALLUVIAL AND COASTAL-PLAIN SEQUENCE STRATIGRAPHY

The simplest explanation for inversely covariant $FeCO_3$ and $CaCO_3$ values in the Sioux City Brick Company sphaerosiderites is based on differences in the principal cations present in Cretaceous waters. Siderite formed in freshwater is commonly very pure (>90 wt% $FeCO_3$) compared to marine siderite which is impure (Mozley, 1989). Because mixing marine and meteoric waters in a coastal phreatic system can result in complex variations in cation chemistry and because the Dakota Formation was at times in hydrologic communication with the sea, we interpret the inversely covariant relationship observed in the studied sphaerosiderites as a measure of shifts in the updip migration of brackish groundwater in the Dakota alluvial plain.

The Albian-Cenomanian boundary at the Sioux City Brick Company clay pit has been drawn at the top of the commonly red-mottled paleosol interval (D1-D2 sequence boundary; Brenner et al., 2000), a boundary pick that approximates the 319.2 m amsl paleosol displaying the lowest $\delta^{18}O$ value (−6.8‰), one of the highest $FeCO_3$ values (98%), one of the lowest $CaCO_3$ values (0%), and the cessation of the waning-in-marine-influence trend (Fig. 1). We interpret the 319.2 m amsl paleosol to be associated with the Albian–Cenomanian sea-level lowstand recognized throughout the Western Interior Basin (Kauffman and Caldwell, 1993) and globally (Immenhauser and Scott, 1999). The overall upsection shift from marine-influenced to nonmarine sphaerosiderites (Fig. 1) records waning marine influence during Dakota sedimentation, consistent with formation of the lower half of the paleosol succession along the late Albian Muddy Seaway (Witzke et al., 1999).

The characteristic bundling of paleosol spacing and micromorphology is instructive for further understanding base-level change on the Dakota alluvial plain. Amalgamated paleosol units in the Woodbury Member display a range of soil microfabrics and mottle colors; where fewer paleosols exist through a similar stratigraphic thickness, more homogeneous fabric and mottle characteristics are found. Because sepic-plasmic fabrics form by stresses in clayey soils during wetting and drying (FitzPatrick, 1993) and because fabric development can be considered as a mark of the duration and intensity of soil formation (Collins and Larney, 1983), the evolution from sequences characterized by many paleosols with variable drainage characteristics to fewer immature paleosols lateral to channel sandstones can be attributed to a decrease in avulsion frequency, as more fine-grained sediment was deposited between successive avulsions (Krause, 2002). The most likely cause of variation in avulsion frequency on the low-gradient, eastern ramp margin of the Cretaceous Western Interior Seaway—where tectonic subsidence was minimal (Brenner et al., 2000) and for which climate has been interpreted to have exhibited little if any seasonality (see discussion, White et al., 2001)—was sea-level change that directly affected base-level changes in the distal fluvial systems. This conclusion is supported by an abundant literature on sea-level effects on sediment stacking patterns in the Western Interior Basin (e.g., Kauffman and Caldwell, 1993). The interpretation that sea-level change was the cause of soil horizonation in Dakota paleosols in Nebraska (Joeckel, 1987) supports this assertion. Furthermore, the Dakota Formation paleosol-bearing sequence has been resolved at ~0.5–1 m.y. accuracy in the early Cenomanian and at ~1–2.5 m.y. in the late Albian (Brenner et al., 2000); each paleosol may record ~32–76 k.y. of deposition and soil formation. These time scales are suggestive of parasequences, and each paleosol bundle may be a parasequence set.

Prior to the Albian-Cenomanian boundary, fluvial facies and paleosols aggraded in the Sioux City region, whereas coeval estuarine facies in Nebraska episodically expanded eastward (Witzke et al., 1999). At the Sioux City Brick Company study site, the lowermost paleosol bundle (section base to ~304.4 m; Fig. 1) was deposited during a third- or fourth-order relative lowstand episode of floodplain instability marked by frequent avulsions, i.e., during the regressive limb of the Kiowa cycle of Kauffman and Caldwell (1993). This bundle was succeeded by less frequent paleosol development, whereas the floodplain and channels aggraded during highstands of relative sea level. The paleosol bundle from ~312.9 m to the Albian-Cenomanian boundary (319.2 m) formed during a second relative lowstand cycle that we attribute to development along the margins of the so-called Muddy Sea. Two third- or fourth-order relative highstand-lowstand paleosol cycles exist above the Albian-Cenomanian boundary (Fig. 1). Between ~323–326.15 and 335.4–338.5 m amsl, mottle characteristics and the geochemical data vary substantially. We consider these intervals as records of minor sea-level regressions superimposed on the overall transgressive limb of the Greenhorn cycle (see Kauffman and Caldwell, 1993). Farther upsection, marine palynomorphs are encountered, until paleosols are no longer observed. The top of the section consists of trough cross-stratified sandstone with marine burrows (Fig. 1) deposited as aggraded estuarine valley fill prior to the absolute Cretaceous Western Interior Seaway highstand.

ALBIAN-CENOMANIAN PRECIPITATION CHEMISTRY AND ATMOSPHERIC HYDROLOGY

Although we have used patterns of paleosol amalgamation and fabric development, as well as sphaerosiderite geochemistry, to unravel marine-influenced stratal stacking patterns in the continental Dakota Formation, the subtle nature of this record of marine influence must be stressed. Ufnar et al. (2004) developed isotope mass-balance models for fluid mixing in the Early Cretaceous Nanushuk Formation and showed that early diagenetic siderite precipitated from groundwater composed of <25% seawater. Because siderite growth is restricted to environments of zero sulfide activity, some Dakota sphaerosiderites likely precipitated from brackish groundwater in which sulfate reduction had progressed to completion. Microscopic pyrite inclusions at the core of some Dakota sphaerosiderites provide evidence of this process, although most are pyrite free and thus precipitated from freshwater.

To eliminate those sphaerosiderite-bearing horizons that were subjected to marine influence and thus attain a record of Cretaceous meteoric water chemistry, we filtered the $\delta^{18}O$ data set so that it only contained horizons with sphaerosiderites consisting of >90 wt% $FeCO_3$ (such values are considered to be characteristic of freshwater siderite; Mozley, 1989). We applied >95% and >98% filters to further enhance the reliability of the remaining $\delta^{18}O$ data (Fig. 1D). Several interesting results are worthy of discussion. First, although most of the data survived the 90% filter pass, supporting our observation that most of the paleosols formed in dominantly freshwater conditions, the 95% filter resulted in the loss of substantial late Albian data. This result is not altogether surprising because those sphaerosiderites were precipitated under the most marine-influenced conditions observed in the Sioux City Brick Company record. This observation indicates that the >90 wt% $FeCO_3$ marine to freshwater threshold (Mozley, 1989) should be considered as a "rule of thumb." Second, the overall pattern of variation in the geochemical data obtained from amalgamated lowstand paleosol bundles was retained after the 95% filter pass. The exception to this observation is the lowermost amalgamated paleosol unit, another casualty of late Albian marine influence. These observations are consistent with maximum meteoric influence during sea-level lowstand and suggest that sphaerosiderite $\delta^{18}O$ variation in lowstand deposits may provide the most reliable record of $\delta^{18}O$ variations in meteoric recharge. Third, the 319.2 m paleosol survived the 98% filter and remained the study sample most depleted in ^{18}O. With the exception of this Albian-Cenomanian boundary paleosol, an overall upsection ^{18}O depletion in the solely freshwater sphaerosiderite $\delta^{18}O$ record is observable from the Albian to the Cenomanian.

The $\delta^{18}O$ data from paleosol sphaerosiderites have been used to assess the paleoprecipitation regime of the middle Cretaceous greenhouse atmosphere. For example, middle Cretaceous precipitation rates along the Cretaceous Western Interior Seaway have been calculated to range from ~2500 to 4100 mm/yr (White et al., 2001) and from 2600 to 3300 mm/yr (Ufnar et al., 2002). Precipitation along the Albian-Cenomanian eastern margin of the Cretaceous Western Interior Seaway was at times dominated by rainfall originating from the seaway (White et al., 2001). In that model, equatorial Tethyan sea-surface currents drawn northward along the eastern seaway margin by estuarine-style circulation provided a warm moisture source to prevailing westerly winds, similar to the Gulf Stream effect on Europe today. However, that model, based on an assessment of the relative ^{18}O depletion between Cretaceous and modern precipitation caused by higher paleoprecipitation rates, was developed to describe late Albian precipitation and did not account for temporal $\delta^{18}O$ variations. The conceptual model we propose to describe variations in the record from the Sioux City Brick Company clay pit and vicinity relies on the notion that $\delta^{18}O$ values of precipitation can be affected by larger-scale atmospheric vapor transport.

The Cretaceous Western Interior Seaway was mostly a throughgoing seaway between the equatorial Tethys and arctic Boreal Oceans (Fig. 2). Occasionally the seaway partially withdrew from North America and existed as separate northern and southern embayments. At least one major regression occurred, near the Albian-Cenomanian boundary; therefore a precipitation model must consider alternate atmospheric moisture sources for those times when the seaway had withdrawn, wholly or mostly, from the Midcontinent. An obvious alternate moisture source is hemispheric-scale atmospheric transport: low-latitude tropical air masses were the dominant source for midlatitude precipitation in central North America during the Cretaceous Western Interior Seaway lowstand, and $\delta^{18}O$ variations in the wholly freshwater sphaerosiderite record represent a continuum of competing moisture sources and mechanisms of transport between the nearby epicontinental sea and the distant tropical Tethys Ocean (Fig. 2).

Model simulations indicate that middle Cretaceous midlatitude precipitation rates were lower during seaway lowstands than during highstands (Poulsen, 1999). The primary implication of these climate model results to our conceptual model is that the proximity of the epicontinental sea created an additional moisture source for precipitation along the seaway's eastern margin that was more effective and reliable than hemispheric-scale atmospheric vapor transport emanating from the distant tropics. This observation is important for the following reasons. First, ^{18}O enrichments and variation are visible in the lowstand data (Fig. 1D). The relative ^{18}O enrichments can be explained by decreased precipitation rates at lowstand associated with tropically derived moisture (i.e., a reduced amount effect without which values more depleted in ^{18}O would have been recorded). Variation in lowstand $\delta^{18}O$ data may record climate sensitivity and temporal variation in the intensity of hemispheric-scale atmospheric moisture transport. Relative ^{18}O enrichments may have been caused by an episodically subdued atmospheric hydrologic cycle reflecting times of overall tropical cooling, less tropical precipitation, and a decrease in the export of less isotopically evolved moisture through Hadley cell circulation. In this scenario, relative ^{18}O depletions within the lowstand paleosol bundles record times of relative warmth, hydrologic cycle intensification, greater tropical precipitation, and increased export of more isotopically evolved atmospheric moisture. Alternatively, considering the lowstand paleosol bundles as third- or fourth-order parasequence sets—implying that higher-frequency, lower-amplitude variations in relative sea level occurred during the overall lowstand—some of the $\delta^{18}O$ variation observed in lowstand data may be explained by competition between moisture sources as the seaway waxed and waned during overall shallower and narrower stages. The highstand seaway's dominating effect on climate, even when subject to higher-frequency narrowing during overall highstands, overwhelmed any signal possibly associated with moisture-source change; therefore very little variation is observed in the highstand data.

An overall ^{18}O depletion observable from late Albian to middle Cenomanian paleosols at the Sioux City Brick Company study site may suggest that as precipitation rates increased, the effect on precipitation increased along the more permanent Cenomanian throughgoing seaway, a setting subjected to fluctuations in sea level but never complete regression from the Midcontinent (i.e., a more stable, reliable, and warm moisture source that provided more rainfall). However, the observation that some of this trend exists within lowstand paleosols implies that a component of the overall ^{18}O depletion may have been caused by increased hemispheric-scale atmospheric moisture transport. Therefore the overall ^{18}O depletion may signal a long-term amplification of the global hydrologic cycle, an interpretation consistent with paleobotanically based observations of increasing global warmth through this time interval (e.g., Vakhrameev, 1981). A change from widely distributed Aptian–Albian Calcisols to Cenomanian Histosols in North America, interpreted to reflect a precipitation increase (Mack and James, 1992), supports both interpretations, and in either case, extreme ^{18}O depletion at the Albian-Cenomanian boundary marks maximum hydrologic-cycle amplification and global warmth.

CONCLUSIONS

Middle Cretaceous sphaerosiderites in Iowa paleosols record shifts in the updip migration of brackish groundwater along the eastern coastal plain of the Cretaceous Western Interior Seaway. Geochemical data and observations of bundling in paleosol spacing and micromorphology represent parasequence sets formed during third- or fourth-order relative sea-level change associated with Kiowa cycle regression and subsequent Greenhorn cycle transgression. A record of variation in the middle Cretaceous atmospheric hydrologic cycle is observable once the geochemical signature of base-level change has been defined. Higher seaway-derived mean annual precipitation occurred during sea-level highstand, whereas hemispheric-scale atmospheric moisture transport from the tropical Tethys Ocean led to reduced precipitation in Cretaceous Iowa at lowstand. The intensity of hemispheric-scale transport may have changed or competed with seaway moisture sources during transitional sea-level phases. The Albian-Cenomanian boundary is marked by extreme ^{18}O depletion, maximum hydrologic-cycle amplification, and global warmth.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation (grants EAR-96-28128 and ATM 03-10032) and the Petroleum Research Fund of the American Chemical Society (grants 32573-AC8 and 39503-AC8). The work could not have been accomplished without H. Belkin, S. Carpenter, L. González, and L. Young. Reviews by S. Driese and an anonymous reviewer were helpful.

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Manuscript received 14 July 2004
Revised manuscript received 27 September 2004
Manuscript accepted 1 October 2004

Printed in USA