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Water-column stability, residence times, and anoxia in the Cretaceous North American seaway

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ABSTRACT

Output from a one-dimensional, mixed-layer ocean model and a general circulation model suggests a consistent relation between surface-water residence times, large vertical salinity gradients, and anoxic bottom water during transgressive periods in the Cretaceous North American seaway. Model results show that severe storms over the seaway were not effective in mixing oxygen to the sediment-water interface when vertical salinity gradients exceeded 1‰–2‰ and depths were >300 m. At precipitation − evaporation + river runoff ($P - E + R$) rates calculated from the general circulation model (up to 300 cm/yr), conditions favorable to the maintenance of anoxic bottom water would be established within a matter of months. Large vertical salinity gradients at these $P - E + R$ values would form in time periods as short as 1–2 yr. This is considerably shorter than seaway residence times calculated from the Sverdrup relation and from wind-stress curl calculations of atmospheric general circulation models.

INTRODUCTION

Continental interior seaways of the Mesozoic represent a geologic environment with no modern analogues. One of the most thoroughly studied and documented of these seaways existed in the continental interior of North America during the middle to Late Cretaceous. This interval of geologic time is believed to have had a warm global climate, elevated atmospheric CO_2, and high sea level. The Cretaceous North American seaway was characterized by a series of transgressive-regressive cycles with distinctive biota, sediments, and geochemistry. Foremost among these features were transitions between an oxygenated and anoxic water column that appeared during the late Cenomanian to Turonian transgressions, when the seaway attained its maximum depth (Kauffman, 1984). The oxygenated-anoxic transitions are believed to have resulted from climatic forcings (Barron et al., 1985). Anoxic conditions are manifested by lack of benthic fauna and relatively high amounts of organic carbon and siliciclastic sediment. Sediments deposited under oxygenated bottom conditions generally show bioturbation and high carbonate concentrations (Pratt, 1984).

Formation of anoxic bottom water has been attributed to the development of an influx of fresh water that limited vertical mixing of the water column (Pratt, 1984; Barron et al., 1985). Density stratification in a relatively wet climate is believed to have been caused by elevated precipitation and associated river inflow from the surrounding highlands (Fig. 1). High precipitation rates over the seaway are suggested by general circulation model studies of the middle Cretaceous (Barron and Washington, 1982). Oxygen isotope data from carbonates suggest that surface water in the seaway consisted of ~20% fresh water (Arthur et al., 1985; Glancy et al., 1991). This brackish-water model has been criticized on the basis of foraminifera biofacies reconstructions, which suggest that water of normal salinity was present at most times in the seaway (Eicher and Diner, 1985). These studies suggest that anoxic water in the seaway is related to the intrusion of oxygen-minimum water from the open ocean.

Wind is a critical factor in any analysis of the Cretaceous North American seaway. Strong winds are capable of homogenizing water-column salinity and mixing oxygen to the seaway bottom as well as transporting water in and out of the seaway. Cenomanian-Turonian winter simulations by Glancy (1992) show weak zonal wind gradients over the seaway during maximum solar insolation and moderate gradients during minimum solar insolation (Fig. 2). Summer simulations suggest a somewhat chaotic wind pattern over the seaway for both minimum and maximum insolation. Applying the atmospheric general circulation model over the North American seaway (Ericksen and Slingerland, 1990; Glancy, 1992) yields smaller (<7 m/s) magnitudes for winter and summer winds than for those in much of the modern ocean (Hellerman and Rosenstein, 1983). Steady-state ocean simulations of the Albian seaway clearly show a wind-driven, subtropical gyre south of lat 50°N (Ericksen and Slingerland, 1990, Fig. 6c) as a result of the winter zonal wind gradient. During the Cenomanian-Turonian, this gyre would encompass most of what is now the interior of the United States including the well-documented, Cenomanian-Turonian, limestone–

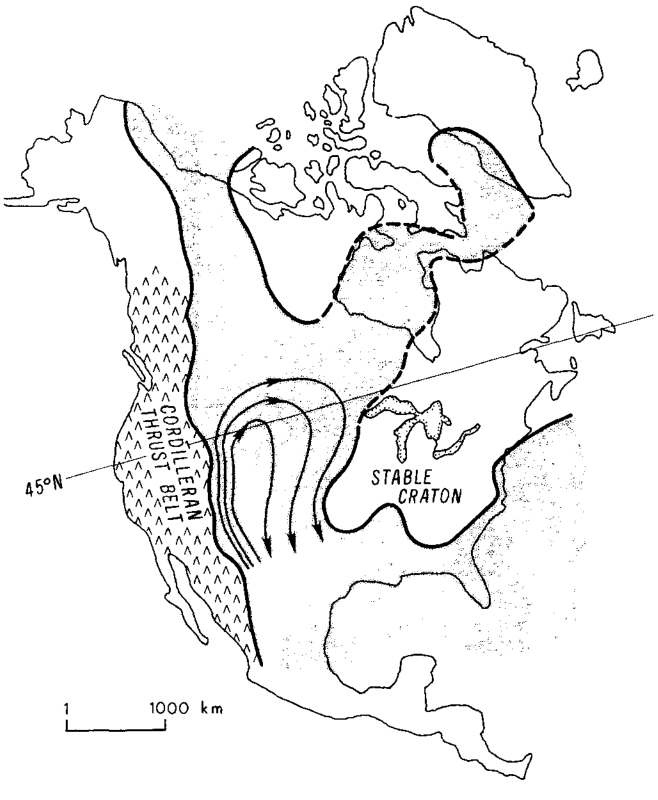

Figure 1. Generalized paleogeography of North America during late Cenomanian–Turonian after Kauffman (1984) and Eaton and Nations (1991). Shaded area represents extent of seaway. Arrows show generalized flow of subtropical gyre suggested by previous numerical model of seaway (Ericksen and Slingerland, 1990).

black shale couplets in Colorado, Nebraska, and Kansas (Pratt, 1984; Barron et al., 1985; Eicher and Diner, 1985) (Fig. 1).

Relatively few quantitative studies have addressed questions of ocean circulation in the Cretaceous seaway. Barron and Peterson (1990) used an oceanic general circulation model to study fundamental aspects of the Cretaceous ocean, yet the 5° by 5° resolution of their model did not permit detailed resolution of seaway processes. Ericksen and Slingerland (1990) used a three-dimensional, mesoscale circulation model to examine the presence of storm deposits in the sedimentary record during Albian time. Their model specifically did not include water-column stratification, however.

In this paper, I use simple hydrodynamic models to examine two specific questions related to vertical stratification of water in the Cenomanian-Turonian North American seaway: (1) the role that wind stress played in maintaining bottom-water oxygen conditions and (2) the precipitation − evaporation + runoff ($P - E + R$) values necessary to produce vertical salinity gradients suggested by isotopic and paleontological data. Results of the one-dimensional simulations are then used in conjunction with simple geophysical fluid-dynamic considerations of the proposed subtropical gyre to examine water residence times in light of the numerical model results and existing theories of seaway hydrography.

HYDRODYNAMIC MODELS OF SALINITY AND OXYGEN

Although one-dimensional models do not reproduce horizontal circulation and mass transport, they have the advantage of performing sensitivity analyses of different variables in a rapid and efficient manner. Furthermore, they allow important questions of seaway dynamics and chemistry (e.g., the importance of viable biogeochemical models) to be addressed prior to running more expensive and computer-intensive three-dimensional models. The one-dimensional, mixed-layer model used in this study has a proven record of accurately simulating vertical profiles of hydrographic and geochemical data in lakes and open-ocean settings (see Mellor and Durbin [1975], Klein and Coste [1984], and Jewell [1992] for details of model development and implementation).

Numerical experiments were performed to examine the relations among vertical salinity gradients, winter storms, seaway depth, $P - E + R$ values, and bottom-water oxygen concentrations. Initial vertical salinity gradients ranged from 1‰ to 7‰. A seasonal surface heat flux with an amplitude of 50 W/m^2 was applied. This produced a seasonal sea-surface temperature fluctuation of 7–8 °C, close to that observed in the mid-latitudes of the modern ocean. After 200 d of each simulation, surface-wind stress representing a severe storm was applied for 3 d. At all other times, a climatic wind of 7 m/s was applied. Initial dissolved-oxygen concentrations were 0 μmol/L except at the surface where oxygen was saturated with respect to the atmosphere. In this manner, it was possible to determine the amount of oxygen that was mixed downward by the winds. A constant $P - E + R$ of 100 cm/yr was applied throughout the simulations.

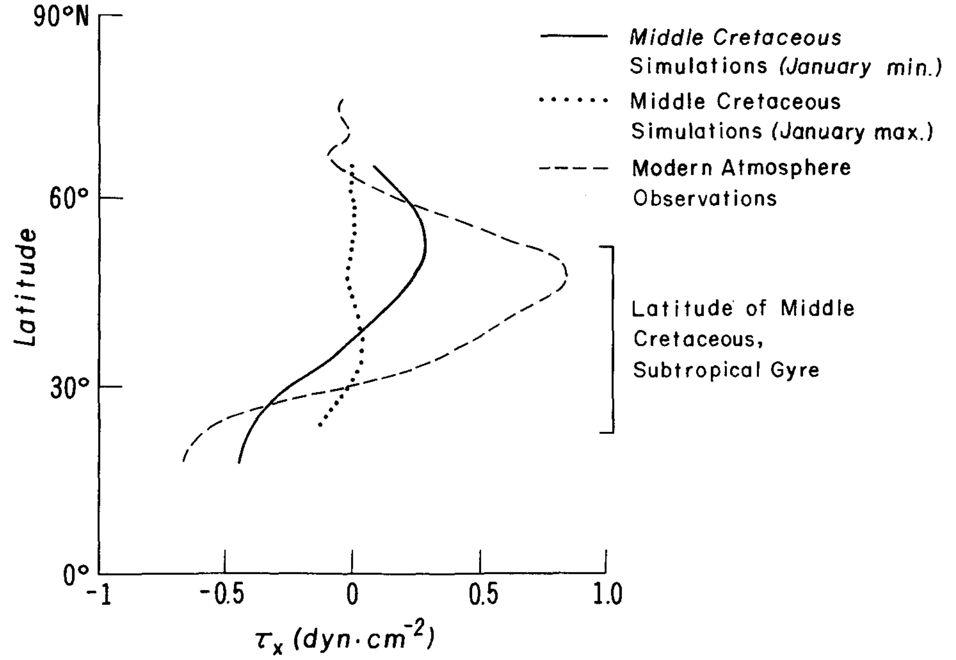

Figure 2. East-west wind-shear stress patterns (in dyn/cm^2) for Cretaceous atmosphere (Glancy, 1992) and modern atmosphere (Hellerman and Rosenstein, 1983). January minimum and January maximum refer to amount of solar insolation applied during Cretaceous winter general circulation model simulations. Cretaceous wind stress is average of values over seaway; modern value is zonal average of world atmosphere.

A simple biogeochemical model was employed in which surface productivity was specified at 100 $g \cdot m^{-2} \cdot yr^{-1}$ of carbon (Pratt, 1985) and carbon remineralization was calculated according to the relation of Betzer et al. (1984). Organic carbon remineralization was converted to oxygen depletion by using the well-known Redfield ratio (Redfield et al., 1963). Sensitivity analyses showed that surface productivity values of 50–150 $g \cdot m^{-2} \cdot yr^{-1}$ of carbon had only minor influence on bottom-water oxygen in comparison to physical parameters such as vertical salinity gradients and wind-shear stress.

Winter Storms

Simulations of bottom-water oxygen concentrations were conducted for various depths, vertical salinity gradients, and storm severity (Fig. 3). A 20–40 m/s storm would be typical during a Cretaceous winter (Ericksen and Slingerland, 1990). Hurricane velocities are commonly between 50 and 100 m/s, although these storms do not encompass as much area as a typical winter storm and would therefore not be as effective at mixing waters throughout the entire seaway area.

Seaway depths of >300 m show negligible increases in bottom oxygen concentration for initial salinity gradients greater than 1‰–2‰ in all but the most severe storm conditions. For a 60 m/s storm lasting 3 d, mixing of oxygen to the bottom would occur in modestly deep seaways (300–400 m) with vertical salinity gradients of <2‰. It is unlikely that a storm of this magnitude would uniformly influence a seaway with dimensions as great as 1000 by 4000 km. Winter storms with wind velocities of 20–40 m/s would be much more common and areally extensive.

Precipitation–Evaporation–River Runoff

The degree of freshwater input into the Cenomanian-Turonian seaway would determine the vertical salinity gradient of the seaway. As shown above, modest salinity gradients are capable of maintaining bottom-water anoxia during likely winter storms over the seaway. Much higher vertical salinity gradients (up to 20% dilution by fresh water) are suggested by stable isotope analyses of limestones deposited beneath the seaway (Arthur et al., 1985).

General circulation model simulations of the Cretaceous suggest that the mid-latitudes of the North American continent were characterized by very high precipitation-minus-evaporation rates (~200 cm/yr) (Barron and Washington, 1982). The degree of river runoff is unknown. The ratio of river runoff to precipitation rates has been summarized for several modern river basins (Holland, 1978). In high-precipitation areas, the ratio generally ranges between 0.2 and 0.5. Land east and west of the transgressive Cenomanian-Turonian seaway occupied considerably less area than the seaway itself (Fig. 1). $P - E + R$ values could therefore be as great as 300 cm/yr, although smaller values would have been more likely.

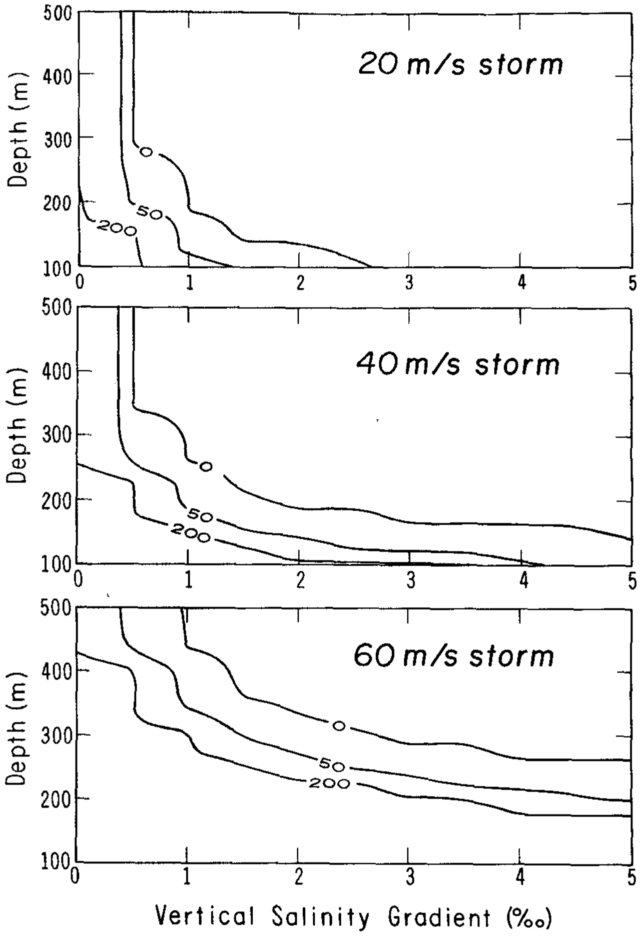

Figure 3. Bottom-water oxygen concentrations (μmol/L) plotted as function of initial water-column salinity gradient (‰) and depth (m) for 20 m/s, 40 m/s, and 60 m/s storms. Duration of all storms modeled was 3 d.

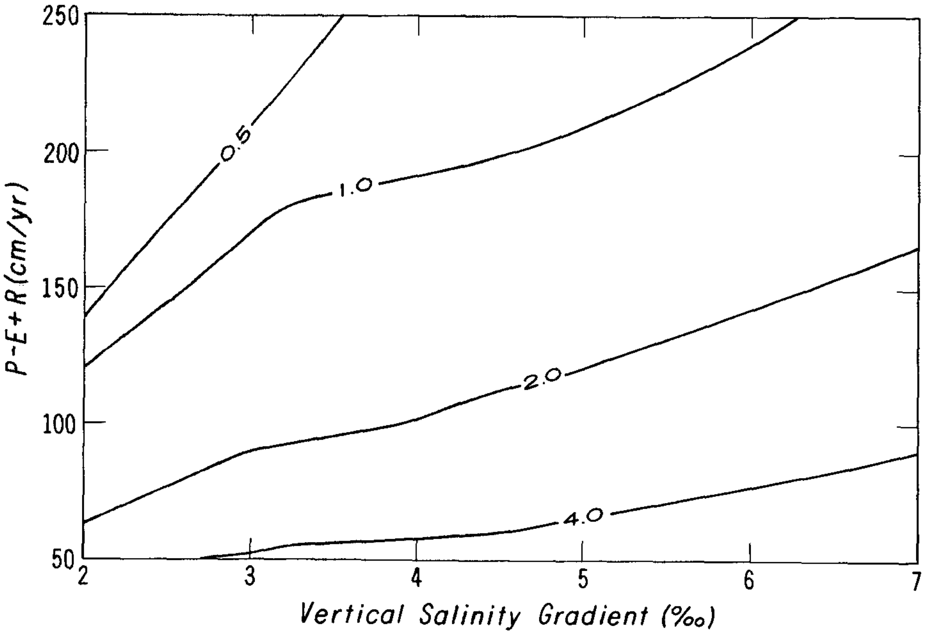

Figure 4. Time (in yr) required to establish a given water-column salinity gradient as function of precipitation − evaporation + river runoff ($P - E + R$) in cm/yr.

The hydrodynamic model described above was run for several $P - E + R$ values. In all simulations, a single winter storm of 20 m/s velocity and a duration of 3 d was applied. All other boundary conditions were equal to those described above. Vertical salinity gradients of 7‰ were established within 1 yr for the $P - E + R$ rates suggested by general circulation model studies (Fig. 4). Salinity gradients capable of maintaining bottom-water anoxia (1‰–2‰) were established within a matter of months at these very high $P - E + R$ rates.

Surface-water Residence Times

The next logical question regarding circulation in the seaway is, What was the typical residence time of water in the seaway? Wind-driven circulation within a semienclosed body of water such as the Cretaceous seaway of the Western Interior determines the surface-water residence time. Assuming that water entering the seaway had normal marine salinity, then long surface-water residence times allow freshwater input to exert considerable influence on the vertical salinity gradients. Short residence times would favor normal-marine salinities.

If a wind-driven, subtropical gyre was operative during the Cenomanian-Turonian winters (Fig. 2), fresh water coming from the western highlands would be swept northward by the western boundary current of the gyre and then southward out of the seaway by broader eastern boundary currents (Fig. 1). The variable summer winds over the seaway might not have permitted development of a wind-driven gyre, although the small magnitude of these winds argues against wholesale removal of water during the summer. To a first approximation, the vertical salinity gradient would be determined by the amount of time surface water spent in the gyre relative to the rate of freshwater input.

Surface-water residence times can be crudely calculated with the aid of the Sverdrup relation, which relates the mass-transport stream function, ψ, to the curl of the wind stress (Hellerman and Rosenstein, 1983; Pedlosky, 1982):

$$\psi = \int \frac{\nabla \times \tau}{\beta}\, dx + \text{constant.}$$

In this equation, τ is wind-shear stress, and β is the north-south gradient of the

Coriolis parameter. The constant of integration is determined by applying the boundary condition of zero mass transport at land boundaries.

In the modern Atlantic Ocean, the wind-driven subtropical gyre has a transport of $\sim$30 sverdrups (1 Sv = 10^6 m^3/s) (Pond and Pickard, 1983). The narrower Cenomanian-Turonian seaway (Fig. 1) and weaker north-south wind-stress gradients (Fig. 2) suggest that water transport in this setting was considerably less. Sverdrup calculations performed with the general circulation model surface-wind data of Glancy (1992) suggest transports of 0.2–2 Sv, depending on the time of year and the seasonal amplitude of solar insolation.

If one assumes that the horizontal dimensions of the subtropical gyre in the Cenomanian-Turonian seaway were approximately 1000 by 2000 km (Fig. 1) and that the wind-driven surface layer was 100 m deep, then the total volume of surface water was $\sim 2 \times 10^{14}$ m^3. Transports of 0.2–2 Sv suggest surface-water residence times of 6–60 yr within the seaway. Obviously, short-term events such as winter storms or hurricanes would cause water to move in and out of the seaway at a faster rate. Even so, these calculated residence times are more than sufficient to accumulate a significant brackish-water lid at $P - E + R$ rates of 100 cm/yr or less (Fig. 4).

CONCLUSIONS

The numerical and analytical results presented here are idealized and neglect many of the details that would be revealed by a three-dimensional dynamic model. Nevertheless, several conclusions can be drawn about Cenomanian-Turonian North American seaway dynamics. (1) Typical winter storms are ineffective in mixing oxygen from the surface waters to the bottom of the transgressive Cenomanian-Turonian North American seaway. (2) Atmospheric general circulation model studies suggest that surface-water residence times of the seaway were on the order of several years to several decades. These relatively long residence times are largely the result of weak winds and zonal wind-stress gradients over the seaway (Fig. 2). (3) As a result of this sluggish, wind-driven circulation in the seaway, modestly high $P - E + R$ values could have produced very high vertical salinity gradients. This point is particularly critical to the interpretation of isotope data presented by Arthur et al. (1985) and Glancy et al. (1993). These studies document pelagic limestone δ^{18}O values of approximately −5‰. If the surface of the seaway were diluted by 20% fresh water, then freshwater δ^{18}O values would be approximately −20‰. Oxygen isotope values between −8‰ and −21‰ from freshwater bivalves collected west of the seaway were reported by Glancy et al. (1991). These lower values imply that freshwater dilution in the Cenomanian-Turonian seaway could have been >20%. The numerical results presented here suggest that dilutions of >20% during periods of high precipitation over the seaway would have been the rule rather than the exception.

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