Estuarine circulation in the Turonian Western Interior seaway of North America

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ABSTRACT

To understand the patterns of lithofacies, marine faunas, organic-carbon enrichment, isotopes, and trace elements deposited in the early Turonian Western Interior seaway, we conducted circulation experiments using a three-dimensional, turbulent flow, coastal ocean model driven by GENESIS, a climate model developed at the National Center for Atmospheric Research (NCAR). Circulation and chemical evolution of the seaway waters are computed under the following initial and boundary conditions: (1) paleobathymetry according to a new interpretation of the lithostratigraphy and biostratigraphy; (2) temperatures and salinities of the Boreal and Tethys oceans and adjacent drainage basins based on isotopic data, atmospheric temperatures, and precipitation-evaporation magnitudes computed by GENESIS; and (3) mean annual wind stresses over the seaway computed by GENESIS. Results show that the seaway exported freshened water much like Hudson Bay today. Runoff from eastern drainages exited the seaway as a northern coastal jet; runoff from western drainages exited as a southern coastal jet. Both jets simultaneously drew in surface Tethyan and Boreal waters, creating a strong counterclockwise gyre occupying the entire north-south extent of the seaway. The curious stratal and faunal variations of the early Turonian deposits arise from this gyre and its associated water masses.

INTRODUCTION

Strata deposited in the Western Interior seaway of North American at the peak of the Cenomanian–Turonian transgressive-regressive (Greenhorn) cycle exhibit a complex pattern of lithofacies, marine faunas, organic-carbon enrichment, isotopes, and trace elements. Those who study the Western Interior seaway have proposed four principal hypotheses for these stratal and faunal variations: (1) incursion of Tethyan and/or Boreal water masses of differing properties, (2) caballing, (3) enhanced vertical stratification in the seaway due to a fresh-water lid, and (4) wind-driven upwelling. Each has its difficulty, however. The idea of incursion of Tethys oceanic waters is popular (Eicher and Worstell, 1970; Frush and Eicher, 1975; Kauffman, 1985; Pratt, 1985; Eicher and Diner, 1985; Hay et al., 1993) but somewhat ad hoc because the physical oceanographic mechanism that would have driven it is not known. Rising sea level is thought to have in some way allowed warmer and more saline waters from Tethys to spread northward, displacing cooler, less saline waters derived from the Boreal ocean to the north. Some authors believe that the Tethyan waters were denser (Watkins et al., 1993, p. 524), whereas others (e.g., Kauffman, 1988, p. 630) believe that Tethyan waters wedged over denser Boreal waters. Some authors have concluded that the resulting circulation in the seaway was clockwise (Gordon, 1973), whereas others have concluded it was counterclockwise (Kent, 1968, for the Mancos Shale; Scott and Taylor, 1977), or even throughflowing (Lloyd, 1982). The second hypothesis, caballing (Fisher, 1991; Hay et al., 1993), is the mixing of two water masses to produce a denser third water that sinks. It was introduced originally by Hay, who thought that in the Western Interior seaway, surface waters of differing salinities and temperatures would enter from the north and south, evolve to acquire roughly equal densities, mix along a front, and flow out as bottom currents. The front was thought to mark the northern limit of Tethyan faunas. Hay also thought that entrained plankton might introduce large amounts of organic carbon into bottom waters, thus making them dysoxic. Paradoxically, this is contrary to the process in modern seas, such as the Sea of Japan, where caballing actually ventilates the bottom. The fresh-water lid hypothesis and its variants (Kauffman, 1975; Pratt, 1981, 1984, 1985; Barron et al., 1985; Hattin, 1985; ROCC Group, 1986; Watkins, 1986; Kauffman, 1988; Glancy et al., 1993; Kyser et al., 1993; Pratt et al., 1993; Jewell, 1993; Sethi and Leithold, 1994) postulate that the precipitation minus evaporation (P – E) balance over the seaway and adjacent drainage basins created a surface layer of lower-salinity water. This surface layer stratified the basin by density, thereby creating oxygen-deficient bottom waters which controlled the distribution of faunas and organic carbon burial. Never discussed, however, is how a freshened surface layer is maintained in the face of wind- and temperature-driven circulation. A freshened surface layer also would seem to be inconsistent with the diverse foraminiferal faunas deposited in the center of the seaway at highstand (Eicher and Diner, 1985). Parrish et al. (1984), using an analog climate model applied to a similar basin configuration, predicted that Ekman transport out of the seaway in the presence of arid adjacent uplands would promote upwelling along the United Sates–Canada border, thereby leading to high productivity there and enhanced organic

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carbon burial. As shown below, this prediction is not borne out for the early Turonian.

Here we propose a fifth hypothesis that we call EST, which is short for estuarine. We conclude from atmospheric and oceanic circulation modeling that despite its two entrances, the Western Interior seaway during the Greenhorn cycle acted like a large estuary wherein fresh-water runoff from its eastern and western shores exited the seaway as coastal jets while simultaneously drawing in Tethyan and Boreal waters, much as laterally inhomogeneous estuaries do today. Circulation resulting from the Cretaceous mean annual wind field and meridional temperature gradient only accentuated a strong counterclockwise circulation in the seaway.

METHODOLOGY

Our approach has been to compute the Turonian climate over North America using GENESIS, a global climate model developed by Pollard and Thompson (1992) at the National Center for Atmospheric Research (NCAR), and then use that climate to drive a coastal ocean model (see Barron et al., 1993, for details on using GENESIS in Cretaceous paleoclimate simulations). GENESIS consists of an atmospheric general circulation model (GCM) coupled to surface models of soil, snow, sea ice, and a slab ocean, and includes a land-surface-transfer model that computes near-surface fluxes of heat, moisture, and momentum in the presence of vegetation. The atmospheric GCM is an extensively modified version of the NCAR Community Climate Model version 1 (CCM1). As an example of the accuracy of GENESIS, one can compare today's runoff to the predicted precipitation minus evaporation (P – E) over North America. The observed runoff is 5.5×10^{12} m^3/yr. If one assumes that P – E equals runoff, then GENESIS predicts a value of 6.4×10^{12} m^3/yr, which is ≈116% of the observed.

The initial and boundary conditions for the Turonian climate simulation are given in Table 1. Although most conditions are self explanatory, soil moisture, soil color, vegetation type, and orbital parameters deserve comment. The soil model in GENESIS is used to describe the moisture and heat conditions in the upper few metres of soil. Soils are classified into 1 of 12 textures, ranging from sand to clay, which describe a soil's hydraulic properties, and into 1 of 8 color classes ranging from dark to light, which describe a soil's albedo. In this simulation, we specify intermediate values everywhere. GENESIS also considers two vegetation layers (canopy and grass) at each grid point for computing radiative and turbulent surface fluxes. Vegetation attributes such as leaf area index and solar transmittance/reflectance are combined into 12 different vegetation types. We have chosen an intermediate value, such that the Earth was everywhere covered with a mixed canopy and a ground cover. The orbital parameters are held constant at present-day values. The sensitivity of the modeled climate to changes in the Earth's orbital configurations was investigated by carrying out another simulation with the obliquity and precession set to maximize the seasonal contrast in the Northern Hemisphere. Although substantial differences were observed elsewhere, neither temperature nor precipitation within the seaway was significantly changed. Winter temperatures and winter and summer precipitation-evaporation balances were essentially unchanged, and summer temperatures were only 2–4 °C warmer. The land surface of North America was more sensitive to the orbital changes, exhibiting larger increases in temperature, precipitation, and evaporation. Runoff from the western and southeast sides of the seaway was reduced while runoff from the northeast increased. Thus, although the geographical distribution of runoff sources to the seaway was affected by the change in orbital configuration, the change in net input to the seaway was small.

To compute the circulation, stratification, and water properties of the seaway as it responded to the atmospheric winds, moisture fluxes, and heat balance predicted by GENESIS, we used CIRC, a three-dimensional formulation of turbulent flows in coastal seas by Leendertse and Liu (1977), which has been modified by Keen and Slingerland (1992) and this study to account for thickening of the wind mixed layer and constituent transport. Initial and boundary conditions for the CIRC simulation are given in Table 2. Paleogeography of the seaway (Fig. 1) was developed from the literature for a time slice at maximum highstand of the Green-

TABLE 1. GENESIS BOUNDARY CONDITIONS FOR THE TURONIAN CLIMATE EXPERIMENT, WESTERN INTERIOR SEAWAY

Boundary Condition	Value
Solar constant	Held constant at present-day average of 1370 Wm^{-2}
Orbital parameters: eccentricity, precession, obliquity	Held constant at present-day values
Ozone mixing ratios	Held constant at present-day values
Soil texture	Intermediate value (6)
Soil color	Intermediate value (5)
Vegetation type	Mixed canopy and groundcover everywhere (savannah, 6)
Land-sea distribution	From Barron (1987), Scotese and Golonka (1992), Ziegler et al. (1983)
Topography	From Scotese and Golonka (1992), Ziegler et al. (1983)
Atmospheric CO_2	Four times present value of 340 ppm (after Berner et al. 1983, Arthur et al. 1991)
Oceanic poleward heat flux	0.15x Carissmo et al. (1985) observations

TABLE 2. CIRC BOUNDARY CONDITIONS FOR TURONIAN CIRCULATION EXPERIMENT, WESTERN INTERIOR SEAWAY

Boundary Condition	Value
Basin bathymetry and planform	Sageman and Arthur (1994)
Wind speed and direction at each surface node	Mean annual wind field computed by GENESIS under conditions listed in Table 1
Initial water temperatures at each node	Steady state values pre-computed by CIRC when driven solely by mean annual atmospheric temperature field from GENESIS; values range from 6 °C in north to 25 °C in south
Initial salinities at each node	32 psu in the Boreal ocean; 36 psu in Tethys
Bed friction factors	Manning's *n* everywhere 0.06 $m^{1/2}$/s
River discharges at boundary nodes	18 rivers spaced equally every 450 km along the seaway's east and west shorelines. River discharges into the seaway are set equal to the P – E for each river's drainage basin.
Evaporation or precipitation fluxes off the seaway surface	Fresh water added or subtracted from the upper layer of the seaway in proportion to the net precipitation hindcast at each node by GENESIS.

Notes: CIRC is a three-dimensional formulation of turbulent flows in coastal seas developed by Leendertse and Liu (1977. GENESIS is a climate model developed at the National Center for Atmospheric Research.

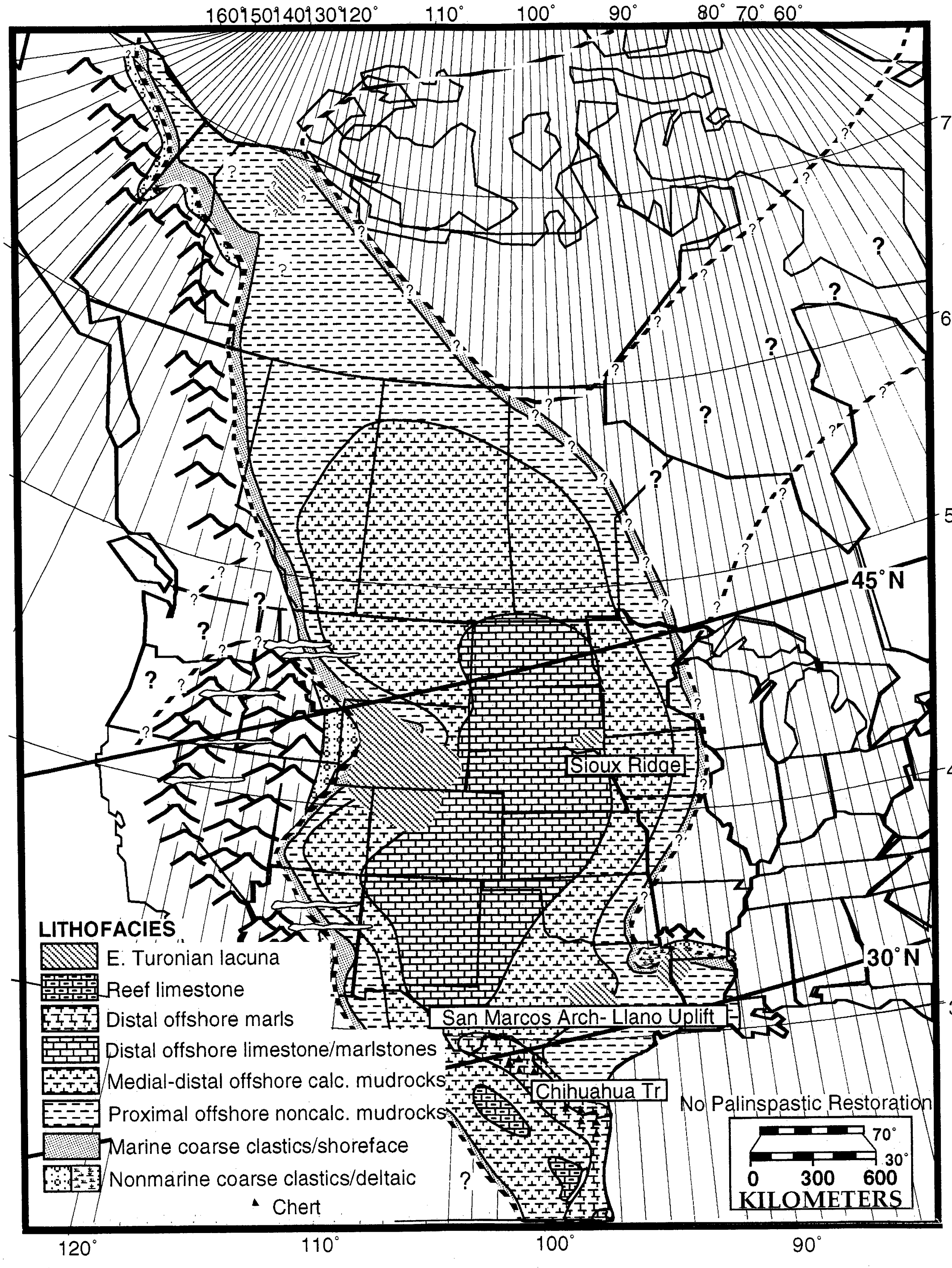


Figure 1. Paleotopographic and lithofacies map of the early Turonian *Watinoceras coloradoense* biozone in the Western Interior basin (from Sageman and Arthur, 1994).

horn cycle (Sageman and Arthur, 1994). Shoreline positions and depth contours were based on the relationships between lithofacies and depths observed in modern marine settings, and were supported by biofacies data from selected sites within the basin.

Of particular importance are assumptions made about sill depths at the northern and southern entrances. Definitive evidence as to the exact width and paleobathymetry of these sills is missing, because of either coeval formation of lacunae or subsequent erosion. Kauffman (1975) favored a 700-km-wide northern entrance to the Western Interior seaway and a 1200-km-wide southern entrance during the latest Cenomanian–earliest

Turonian. Jeletzsky (1970) suggested a width of only 100 km for the northern opening during the Turonian. Kauffman (1984) suggested that the seaway openings were broad and shallow, but allowed for a possible deep-water conduit through the so-called Chihuahua trough at the southern end of the seaway (e.g., Scott, 1977; Kauffman, 1984). Elder and Kirkland (1994) suggested that this trough was filled with sediment by Late Cretaceous time, but also allowed for the possibility that it constituted a deeper-water passage during the late Cenomanian–early Turonian. In discussing the early Turonian transgression, Kauffman (1988, p. 630) continued to favor a southern sill, stating that "warm, Gulf of Mexico watermasses breach the southern sills." Elder and Kirkland (1994; see also Sageman and Arthur, 1994) outlined the following constraints on the geometry and paleobathymetry of the southern entrance to the seaway: (1) the eastern limit is constrained by the Arbuckle and Ouachita Mountains extending into eastern Oklahoma; (2) intermittent progradation of sand into northeast Texas during the Late Cretaceous suggests proximity to shore there; (3) most of the region was characterized by relatively shallow water carbonate deposits developed over the Lower Cretaceous northwest Texas platform, including scattered beach and lagoonal facies associated with Late Cretaceous volcanic cones across Central Texas; (4) the San Marcos arch and Llano uplift (Scott, 1977; Young, 1986) formed highs in the center of the sill. It is clear that water depths over much of the southern sill were not great, perhaps 100 m during the early Turonian sea-level highstand, as shown by Sageman and Arthur (1994) and reproduced in Figure 1.

The mean annual P – E balances, surface temperatures, and wind field (described below) as computed by GENESIS provided the initial and boundary conditions for the ocean model. Although the ocean model accepts seasonal forcings, we used mean annual values to average the seasonal forcing. The initial conditions consisted of the steady-state temperatures, densities, and velocities at each node in the seaway that are in equilibrium with the meridional air temperature gradient as hindcast by GENESIS. The boundary conditions were all temporally invariant. Precipitation or evaporation over the seaway was simulated by adding or subtracting fresh water from the upper layer of the seaway in proportion to the net precipitation indicated by GENESIS. Fresh-water runoff from the adjacent continent entered the model seaway through 18 rivers spaced equally every 450 km along the seaway's east and west shorelines. River discharges into the seaway were set equal to the P – E for each river's drainage basin. Surface shear stresses arising from the mean annual wind field were applied to each wet node. Output of the model consisted of U, V, and W velocities, temperature, salinity, and water surface elevations. Results show that after seven years of spin-up, the system approaches (but has not quite reached) dynamic equilibrium, wherein the mass of water entering the seaway through precipitation, runoff, and counterflow at the entrances is balanced by the mass leaving by evaporation and surface flows to the world ocean.

RESULTS

Climate over Western North America as Predicted by GENESIS

Annual average net precipitation (P – E) over land (Fig. 2) is determined to have been from 0.7 to 3.1 mm/day (from 27 to 113 cm/yr), the wettest areas being on the margin of Tethys. This is consistent with paleobotanical assemblages collected along the seaway that suggest a warm, subhumid, and nonseasonal climate with ≈100 cm/yr of precipitation (May and Traverse, 1971; Wolf and Upchurch, 1987; am Ende, 1991; Ludvigson et al., 1992) and with widespread laterites and bauxites (Barron and Frakes, 1989) and extensive coal deposits (Beeson, 1984). GENESIS also indicates a wetter Turonian world globally, with a global-average precipitation over land of 142 cm/yr, compared to the present-day computed value of 123 cm/yr.

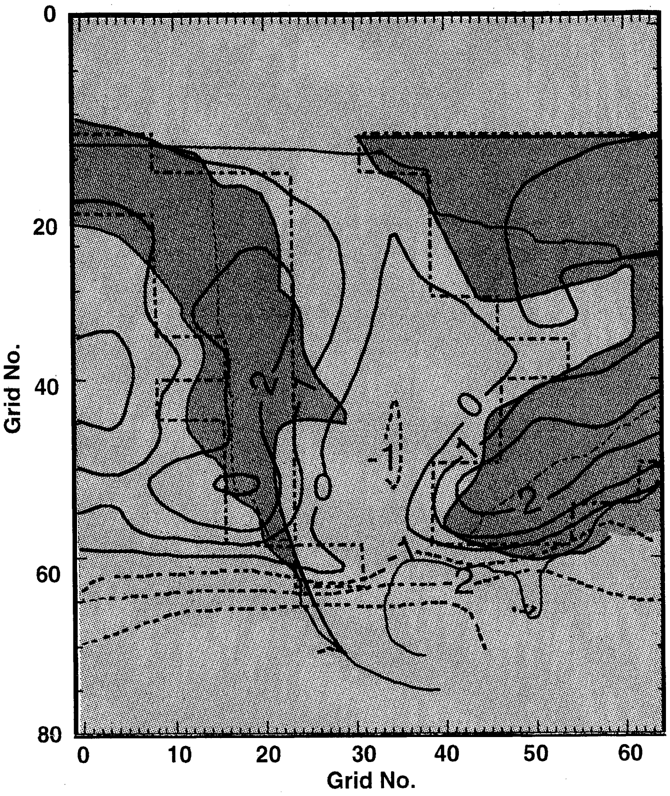


Figure 2. Contours in millimetres per day of precipitation minus evaporation over North America as predicted by GENESIS for the Turonian with four times present-day CO_2. The thick dashed line is outline of GENESIS grid; the thin dashed line denotes drainage divides used in partitioning runoff; the shoreline is from Sageman and Arthur (1994). GENESIS is a climate model developed at the National Center for Atmospheric Research.

Over the Western Interior seaway, up to 1.1 mm/day (41 cm/yr) of net evaporation occurred in the southeast, whereas in the northwest the maximum was 2 mm/day (73 cm/yr) net precipitation. This amounts to a total net evaporation loss over the seaway of 0.24×10^{12} m^3 of water during the year. To calculate fresh-water runoff into the seaway, the P – E over the adjacent continent was summed, assuming drainage divides as shown in Figure 2. Approximately 1.9×10^{12} m^3/yr entered the seaway from the west, and 2.6×10^{12} m^3/yr entered from the east. For comparison, the Mississippi discharge is 0.58×10^{12} m^3/yr. The computed fresh-water input in the Turonian is ≈20 times the evaporation deficit, indicating that the seaway was a net exporter of fresh water (Black Sea–type estuary). This conclusion remains true even if GENESIS overpredicts P – E by 20%, as Pollard and Thompson (1992) have suggested.

Average surface air temperatures, as determined by GENESIS for December, January, and February (Fig. 3), decreased monotonically from 20 °C at the entrance to Tethys to 4 °C in the Boreal ocean. No sea ice is predicted in the seaway, although land temperatures were below 0 °C above 60°N. The oceanic 0 °C isotherm lay entirely within the Boreal Ocean in both seasons. June, July, and August average seaway tempera-

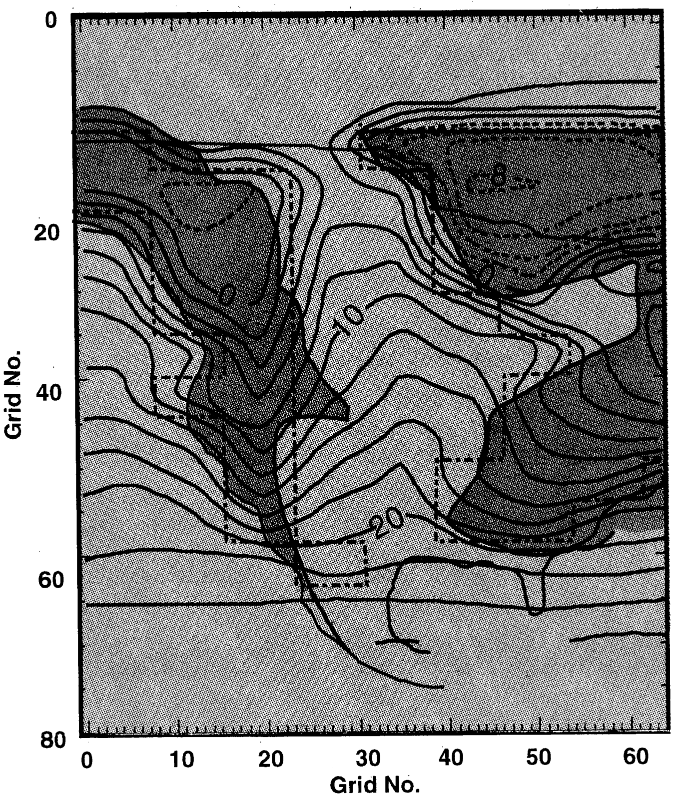


Figure 3. Contours (in °C) of December, January, and February average surface temperature as predicted by GENESIS for the Turonian with four times present-day CO_2. GENESIS is a climate model developed at the National Center for Atmospheric Research.

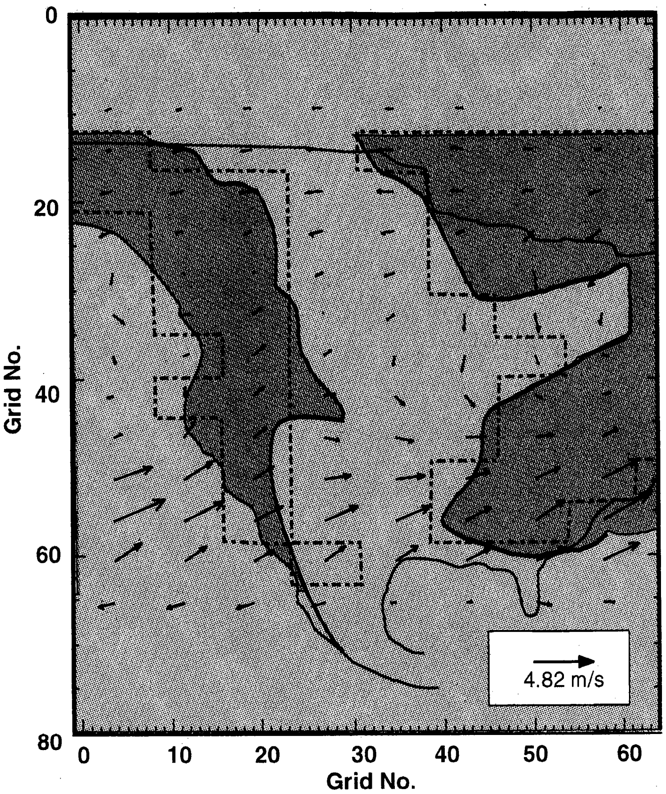


Figure 4. Mean annual wind field over North America as predicted by GENESIS for the Turonian with four times present-day CO_2. GENESIS is a climate model developed at the National Center for Atmospheric Research.

tures ranged between 26 and 8 °C. The mean annual temperatures determined by GENESIS (and used in the CIRC experiment) ranged from 25 to 6 °C, respectively.

These GENESIS results are consistent with observed paleoclimate indicators. Although Frakes and Francis (1988) reported possible ice rafting in Spitsbergen ca. 110 Ma, there is no evidence of ice rafting or continental glaciers by 100 Ma, suggesting no permanent large ice caps at the poles. Fossil floral assemblages on the north slope of Alaska (Spicer and Parrish, 1986) indicate mean annual temperatures of about 10 °C, consistent with these results. This is much warmer than present but does not preclude cold winters and seasonal sea ice.

The mean annual wind field indicated for North America during the Turonian consisted of easterly winds in the north, southwesterly winds along the southern margin, and a zone of convergence over the central seaway (Fig. 4). Estimated velocities were weak, with maximum values in the south being ≈4 m/s. Mid-latitude winter storms tracked far south, crossing over the seaway at ≈35°N. The pattern of Figure 4 is consistent with Elder's (1988) conclusions based on isopachs of ash beds.

Circulation of the Seaway as Predicted by CIRC

The resulting steady-state surface circulation of the seaway consists of a basin-scale counterclockwise gyre (Fig. 5). In the upper 100 m of the water column, currents flow to the north along the outer edge of the eastern shelf and to the south along the outer edge of the western shelf. This pattern also is evident in surface temperatures (Fig. 6). Although roughly matching the north-south meridional gradient in the atmosphere, the isotherms are distorted as waters of the gyre carry heat northward along the eastern shelf and cooler waters penetrate farther south along the western shelf. Below 100 m (Fig. 7), waters collect in the core of the seaway through weak caballing, and flow along its thalweg, exiting to the north and south.

Salinities in the seaway (Fig. 8) principally reflect the riverine discharge and inflows from Tethys and the Boreal ocean, with evaporation in the south-central region playing a lesser role. The seaway was continuously freshened by rivers, yet maintained a salty core. This requires that it continuously import ocean water. Summing inflows and outflows through a cross section along grid row 60 reveals that 28.8×10^{12} m^3/yr of slightly freshened water exited the southern entrance, while 27.1×10^{12} m^3/yr of saltier water entered from Tethys. Along row 19 at the northern entrance, 41.2×10^{12} m^3/yr of seaway water flowed out, while 38.8×10^{12} m^3/yr of Boreal waters flowed in. Considering that the total volume of the seaway was $\approx 1100 \times 10^{12}$ m^3, these fluxes are considerable, yielding a residence time in the basin of only ≈16 yr.

ORIGIN OF THE CIRCULATION

The simple estuarine circulation described here owed its existence to a relatively complex forcing. Sensitivity studies in which the circulation was computed independently for each forcing factor reveal that the temperature-, salt-, and wind-driven patterns were additive, the thermohaline forcing being the strongest. Fresh and therefore buoyant river waters en-

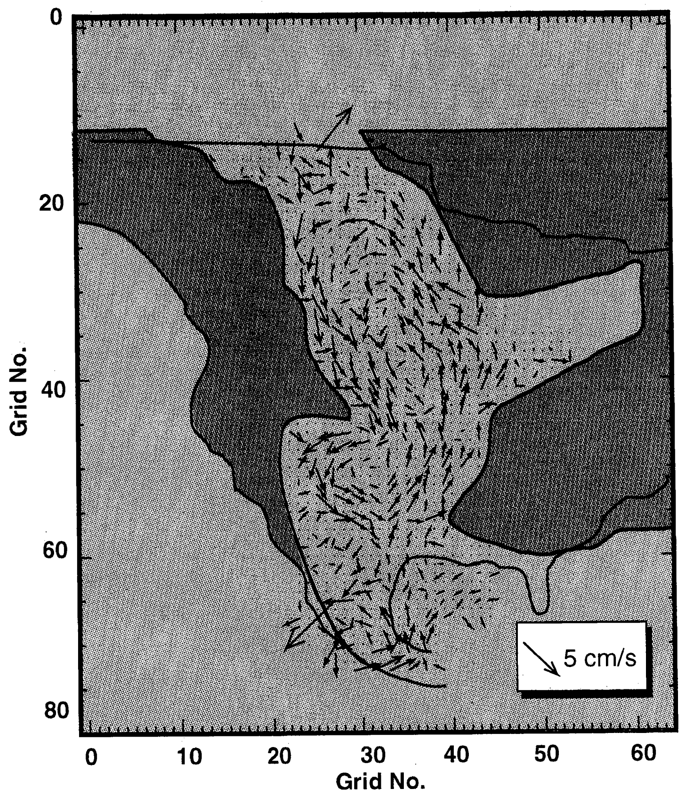


Figure 5. Mean annual steady-state circulation in top 10 m of water column as predicted by CIRC under conditions listed in Table 2. Circulation in the seaway consists of a large cyclonic gyre. CIRC is a three-dimensional formulation of turbulent flows in coastal seas developed by Leendertse and Liu (1977).

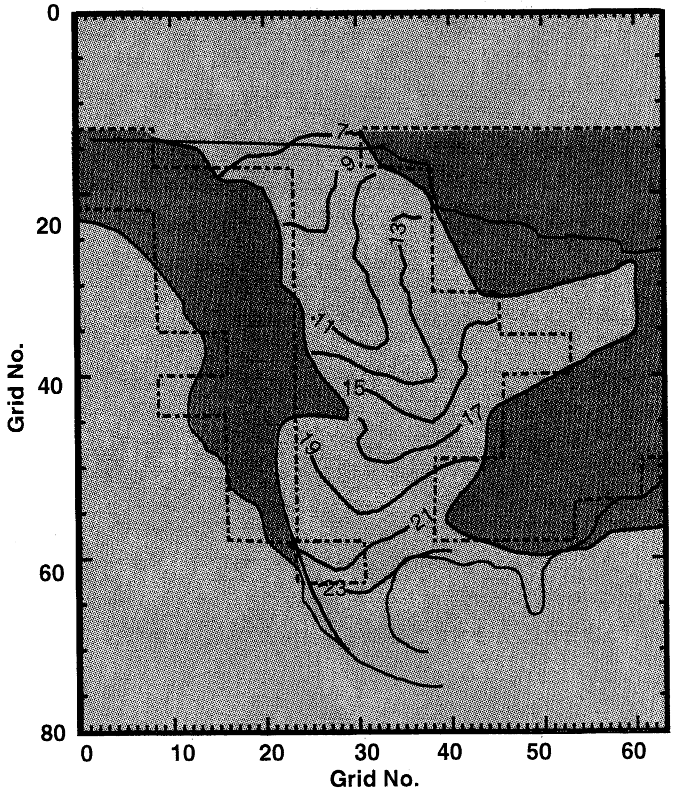


Figure 6. Contours (in °C) of mean annual steady-state temperature field in upper 10 m of water column as predicted by CIRC under conditions listed in Table 2. CIRC is a three-dimensional formulation of turbulent flows in coastal seas developed by Leendertse and Liu (1977).

tered the seaway from its eastern and western margins and created offshore-dipping water-surface slopes, down which these fresh waters subsequently flowed. In the process they were deflected to the right by the Coriolis force and piled up along each coast until the offshore pressure force arising from each surface slope just balanced the Coriolis force. These waters then moved isobathyally alongshore as geostrophically confined jets, avoiding the center of the seaway.

The shear couple arising from the coastal jets, and water surface slopes arising from contraction of the water column as it densified toward the basin center, drew Boreal and Tethyan surface waters into the seaway where they mixed as they sheared past one another. The mixed waters, being denser than either component, downwelled, split into two flows, and returned to the global ocean, with 60% of the flux into the Boreal ocean.

Even the mean annual wind field contributed to the counterclockwise gyre. Inspection of Figure 4 might suggest that Ekman transport would have caused divergence of flow in the center of the seaway and upwelling, but this was not the case. The southwesterlies were strong and sufficiently northward directed to accelerate water toward the seaway's southeastern shore, from which it was deflected northward, thereby contributing to the northward-directed geostrophic flow.

Is there any seaway on Earth today that exhibits similar behavior? If we account for the obvious differences, the answer is Hudson Bay. Hudson Bay is 200 m deep at maximum, has a comparable east-west width, but is only one-quarter the length of the Western Interior seaway. It does not connect two different oceans, but it does receive significant fresh waters from runoff: 10^{11} m^3/yr (Martini, 1986) compared to 10^{12} m^3/yr for the Western Interior seaway. The freshened water (with salinities in the range 27–28 psu [practical salinity units]) moves to the right, counterclockwise, hugging the coast in response to Coriolis, mixing, and warming, similar to predictions of the EST model for the Western Interior seaway. Hudson Bay exports this lighter, warmer surface water and imports normal marine waters, similar to the EST model.

DISCUSSION OF THE EST HYPOTHESIS

The estuarine circulation described above explains many major elements of the stratigraphy and paleontology of the Greenhorn cycle. Foraminiferal and macroinvertebrate faunal type and diversity (Eicher, 1965; McNeil and Caldwell, 1981; Hay et al., 1993), plesiosaurs, turtle, and shark abundances (Nicholls and Russell, 1990), planktonic diversity (Caldwell et al., 1993, p. 501), and distribution of calcareous nannoplankton (Watkins, 1986) can be rationalized by these model results as can oxygen isotopic data, lacuna, sediment type and distribution, and paleocurrent indicators. We expand upon each here.

Faunal Evidence for Water-Mass Properties

The CIRC model for the early Turonian predicts waters of relatively lower salinity on both eastern and western margins of the Western Interior

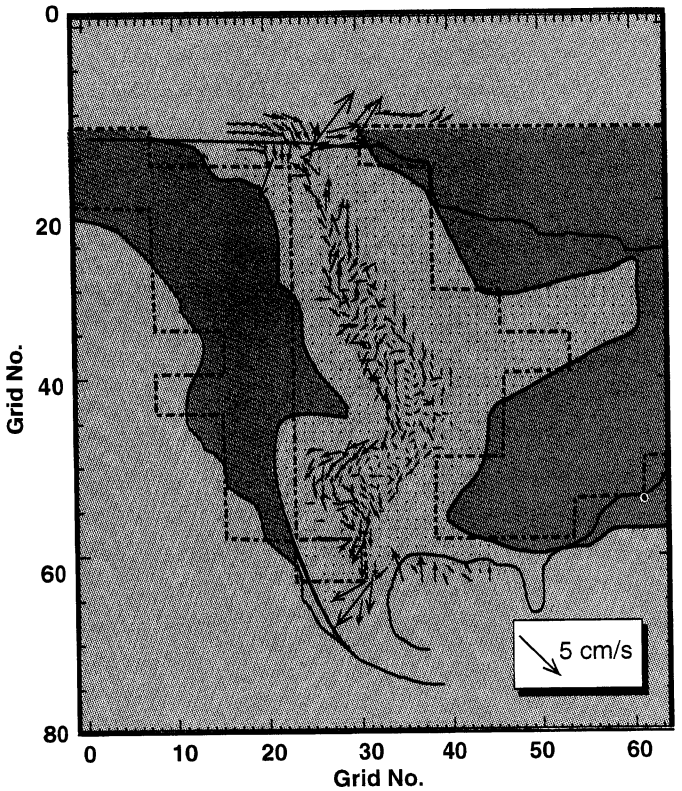


Figure 7. Mean annual steady-state circulation from 100 to 150 m water depth as predicted by CIRC under conditions listed in Table 2. CIRC is a three-dimensional formulation of turbulent flows in coastal seas developed by Leendertse and Liu (1977).

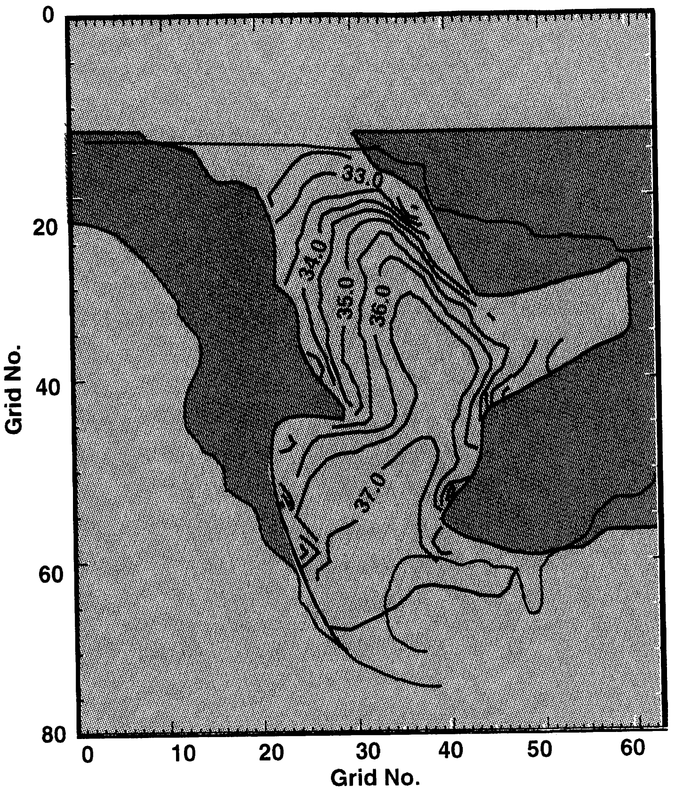


Figure 8. Contours in practical salinity units (psu) of steady-state salinity in the upper 10 m of water column as predicted by CIRC under conditions listed in Table 2. CIRC is a three-dimensional formulation of turbulent flows in coastal seas developed by Leendertse and Liu (1977).

seaway. In large part, this is a function of mixing ambient water masses with inflowing river water along the margins. The CIRC model nowhere produced surface-water (<10 m depth) salinities less than ≈32 psu (Fig. 8), the assumed initial salinity of the boreal water mass. The relatively high (assumed 37 psu) salinity of the Tethyan water mass appears to have dominated the salt balance as the result of the low residence time of water in the basin. Only very near the margins and in the far northern part of the seaway might we expect surface-water salinity to have influenced faunal and floral distributions. Therefore, it is useful to compare known patterns of faunal and floral occurrence to the CIRC predictions. Table 3 summarizes possible constraints on water-mass characteristics based on important extant groups of calcareous plankton and nekton, the ancestors of which were found in the Western Interior seaway strata.

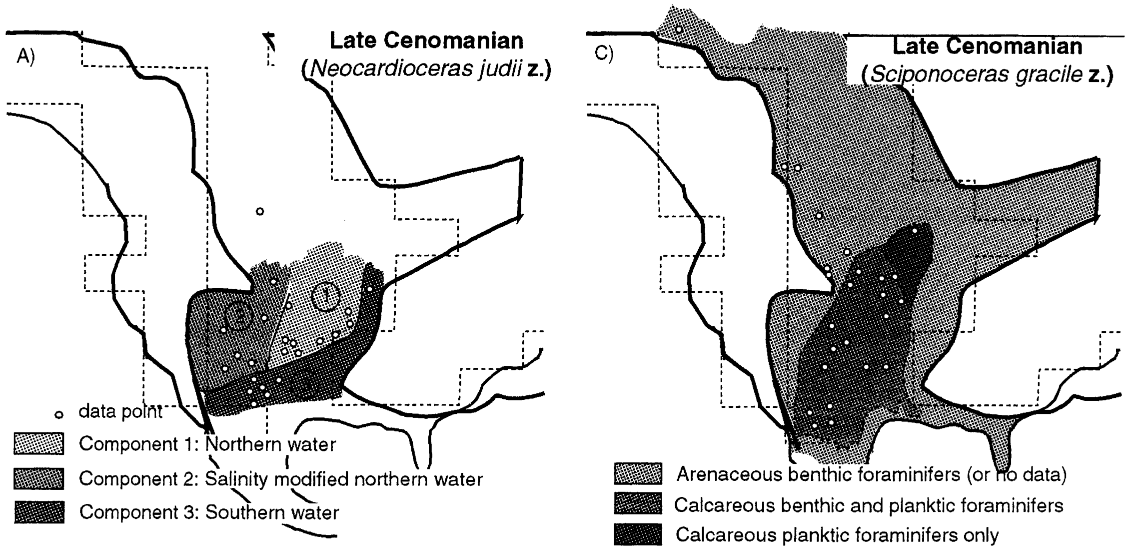
Data on calcareous nannofossil assemblages for the southern half of the seaway led Watkins (1986) to construct a surface water-mass model for the late Cenomanian (time-slice sampled from just above the HL3 bentonite). He identified three major components in the assemblages (Fig. 9A). Component 1, occupying part of the central seaway, was dominated by *W. barnesae* and is thought to represent a northern source water (cool or boreal in nature). Watkins (1986) suggested that his salinity-modified Component 2, dominated by *B. ellipticum*, was a boreal water mass freshened somewhat by river inflow from the western margin. Component 3 is represented by a mixed assemblage and is interpreted to represent a southern water mass, probably warm, dense water derived from the Tethys. Although the characteristics of these components are interpretive and are for the late Cenomanian rather that the early Turonian, one can see that the characteristics inferred by Watkins (1986) and the patterns of distribution are very similar to our predicted circulation for the early Turonian. A southern water mass sweeps northeastward up the eastern margin, while a somewhat "freshened" boreal water slides down the western side of the seaway. Note that in neither case was salinity apparently low enough to exclude fairly diverse nannoplankton assemblages.

Other such detailed faunal and floral distribution data are generally lacking for the early Turonian. For example, Eicher and Diner (1989) produced a locality map for the late Cenomanian showing the distribution of keeled planktonic foraminifers in the Western Interior seaway (Fig. 9B). Keeled planktonic foraminifers appear to have dominated the central region of the seaway, disappearing to the north (Canadian part of the seaway) and toward the western and eastern margins. It would be tempting

TABLE 3. TEMPERATURE AND SALINITY TOLERANCES OF TAXONOMICALLY DIVERSE ASSEMBLAGES OF SOME MODERN CALCAREOUS ORGANISMS

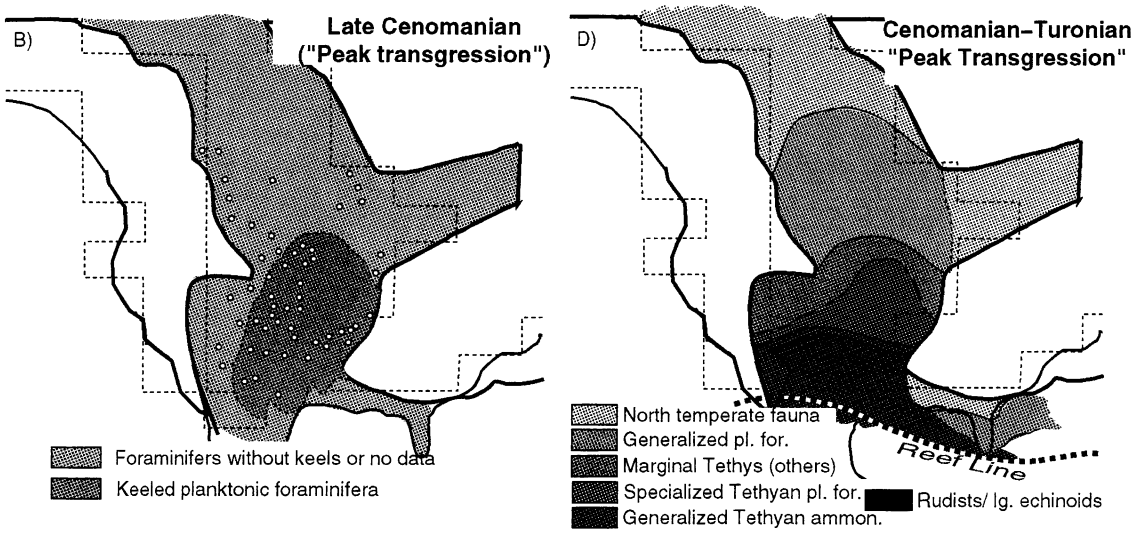
Organisms	Temperature (T °C)		Salinity (psu)	
	Low	High	Low	High
Calcareous nannoplankters	7	28	25(30)	38
Planktonic foraminifers ("dwarf specimens")	0	30	32(30)	40
Cephalopods	?	?	30	?

Note: From Boltovsky and Wright (1976), McIntyre et al. (1970), Tappan (1980), Roth (1989).



Calcareous Nannofossils (after Watkins, 1986)

Foraminifers (after Fisher et al., 1994)



Planktic foraminifers (after Eicher and Diner, 1989)

Groups of Organisms (Kauffman, 1984)

Figure 9. Summary of paleontological data and interpreted water-mass affinities.

to speculate that waters of somewhat lower salinity excluded these foraminifers on both the western and eastern margins. However, it is likely that these keeled planktonic foraminifers inhabited Tethyan water masses and lived at somewhat deeper depths (e.g., Fig. 1) than most planktonic foraminifers. Therefore, their distribution, other than giving an indication of the minimum expanse of Tethyan waters, may only provide an indication of water depths sufficiently deep for their habitat. Elsewhere, the appearance and disappearance of keeled planktonic foraminifers have been used to infer sea-level changes during the Cenomanian (Hart, 1980). Unfortunately, the global late Cenomanian extinction event apparently eliminated keeled planktonic foraminifers, and no such maps are available for the early Turonian.

Diner (1992) has investigated in detail the planktonic foraminiferal faunas of a number of Western Interior seaway Cenomanian-Turonian localities. He pointed to the dominance of *Heterohelix*, a shallow-dwelling planktonic foraminifer, in nearshore regions, particularly on the eastern margin of seaway, and suggested that this foraminifer indicates high fertility and high riverine input, as well as considerable impact of a somewhat lower salinity northern water. In contrast, foraminiferal faunas on the southwest side of the seaway (e.g., Arizona–southeast Utah) are dominated by *Hedbergella*. This suggested to Diner (1992) that salinities were higher and fertility lower than elsewhere in the seaway. This is one area in the CIRC model that is not affected directly by the southward-flowing coastal jet of cooler, somewhat lower salinity water, and instead is characterized by a small clockwise gyre that pulls warm, Tethyan water into the southwestern embayment (Fig. 6).

Fisher et al. (1994) produced a combined map of planktonic and benthonic foraminiferal facies in the Western Interior seaway for late Cenomanian *(Sciponoceras gracile)* time (Fig. 9C). They argued that the distribution of calcareous planktonic and benthic foraminiferal faunas supported the existence of an oceanographic front on the northwest side of the seaway, which they inferred from detailed sampling in Montana and Wyoming. Their interpretation of the extant data was that the front represented a fluctuating boundary between a "northern" and a "southern" water mass. The northern water (Fisher et al., 1994, p. 887) "refers to water that flowed into the seaway from the Arctic but that was modified through precipitation, runoff, and warming as it moved south." The southern water is inferred to have "entered the seaway from the Gulf of Mexico and was modified by evaporation and cooling as it moved north." The region characterized by arenaceous benthic foraminifers without calcareous planktic foraminifers is interpreted as having been occupied by northern waters; exclusion of calcareous elements was due to some combination of lower than normal salinity or temperature (or possibly higher $p\text{CO}_2$). The late Cenomanian foraminiferal biofacies map is similar to the lithofacies map for the early Turonian (Fig. 1, after Sageman and Arthur, 1994), although calcareous facies are distributed farther north in the early Turonian. Calcareous elements are interpreted to have been bathed in southern waters. Fisher et al. (1994) favored environmental exclusion of calcareous plankton, rather than dissolution, as the explanation for the foraminiferal biofacies distribution patterns. Note that there is very little control for the mapped distribution patterns on the eastern and western margins of the seaway, but noncalcareous foraminiferal biofacies were inferred by Fisher et al. (1994) for these regions. Overall, their late Cenomanian foraminiferal biofacies map and inferred controls, as discussed here, would support the circulation model presented here for the early Turonian.

Maps of macrofaunal and microfaunal data for the Western Interior seaway, such as those produced by Kauffman (1984, 1986), are highly generalized and represent mixed assemblages (i.e. benthic, nektonic, and planktonic). Kauffman's map for peak T6 transgression (early Turonian) is reproduced in Figure 9D. The main conclusion that we can draw from this distribution, as shown, is that there were strong faunal gradients from north to south in the seaway, and Tethyan elements dominated the southern half of the seaway by the early Turonian. Although it is likely that this distribution was controlled by temperature gradients, salinity could also have been a factor. If these generalized maps accurately reflect faunal distributions, there would appear to be little effect of lowered salinity along the eastern margin of the Western Interior seaway. Overall, Kauffman and Caldwell (1993, p. 17) favored stratification of "less dense, normal saline to slightly hypersaline, warm surface waters from the proto–Gulf of Mexico, over colder, possibly slightly brackish waters of greater density derived from the northern circumpolar sea ..."

Our interpretation is that the character of faunal assemblages within medial to distal offshore facies of the eastern carbonate shelf does not rule out the possibility of fresh-water influence. For example, the lower Graneros Shale in central Kansas is characterized by a near absence of calcareous beds and ammonites, rarity of planktic foraminifera, abundance of arenaceous foraminifers, and occurrence of *Lingula*, which to Hattin and Cobban (1977) suggested brackish conditions from high river discharge. The overlying strata of the upper Graneros and Greenhorn Formations are characterized by an increase in faunal elements suggesting more normal marine salinity (planktic foraminifera, coccolith-rich fecal pellets), but the macrofossil assemblages of the Lincoln and Hartland Members in Kansas contain the lowest diversity levels of all time-equivalent samples from the Western Interior, and are particularly low in ammonites compared to more normal marine sites to the west and south (Elder, 1991; Sageman, 1991). Every sample that is not barren is dominated by inoceramid and pteriid bivalves, which are in fine-grained Cenomanisn–Turonian facies of the Western Interior. These low-diversity eurytopes may reflect restriction of normal marine faunas by decreased benthic oxygen levels, an interpretation supported by high organic carbon values in the shales. However, their presence does not rule out restriction of normal marine benthos by other environmental causes, such as the effect of lowered salinity surface waters on molluscan planktotrophic larvae.

Oxygen Isotopic Indicators of Water-Mass Origin

Several studies have documented relatively depleted δ^{18}O values for calcareous components of Cenomanian and Turonian strata of the Western Interior seaway (e.g., Pratt, 1985; Arthur et al., 1985; Kyser et al., 1993; Pagani and Arthur, in press). Barring diagenetic overprints (e.g., Pratt et al., 1993), these data appear to suggest the influence of fresh waters on the oxygen isotopic compositions of surface waters. Although a number of workers have taken this to indicate lower than normal surface-water salinities in the seaway, this is not necessarily the case. For example, Eicher and Diner (1989) highlighted the disagreements based on interpretation of faunal and floral data and oxygen isotopes in the same strata.

It is difficult to rationalize the diverse planktonic foraminiferal and calcareous nannofossil biotas with low surface-water salinities interpreted from the oxygen isotopic data. For the middle Cretaceous, one would expect values no more depleted than –4‰ for maximum temperatures of 30 °C and seawater salinities of 34 psu (assuming a δ_w of seawater of –1‰ standard mean ocean water [SMOW] for an ice-free world). The low paleosalinities for Cenomanian–Turonian Western Interior seaway surface waters are inferred from calcite δ^{18}O values of –4‰ to –8‰ relative to the Peedee belemnite standard (PDB). However, the calculation of paleosalinity using a simple mixing equation requires that one know the δ_w of river water and/or precipitation (e.g., see Glancy et al., 1993) as well as that for the initial seawater mass. It can be shown that runoff from the western margin of seaway must have been on the order of –23‰ (SMOW) (Pagani and Arthur, in press) and/or that "northern" water was considerably depleted ($\delta_w = -2.5$‰ [SMOW]) (see Kyser et al., 1993) in order to explain the δ^{18}O values of calcite, assuming that salinities were at the lower limit of "normal" for the faunal and floral components analyzed (see Table 3). There is evidence from fresh-water carbonate cements in Turonian marine strata (Ludvigson et al., 1994) as well as from the oxygen isotopic composition of kaolinitic clays formed in Albian–Cenomanian soils on the eastern margin (Lawrence and Meáux, 1993) that the δ_w of runoff on the eastern margin was about –10‰ (SMOW).

At this time, there are insufficient data to map δ^{18}O of carbonate for a given time slice. However, the lower Turonian appears to be characterized by the most "normal" δ^{18}O values in comparison to stratigraphic intervals above and below. This suggests that more highly saline waters from the south expanded to their greatest extent during maximum transgression, in agreement with faunal and floral distributions summarized below (e.g., Kauffman, 1986). For the early Turonian, these values reach a maximum of –3.0‰ (PDB) for the southwestern margin (Utah: Pagani and Arthur, in press), –3.5‰ (PDB) in the south-central part of the seaway (Colorado and Kansas: Pratt, 1985; Arthur et al., 1987), –2.5‰ (PDB) for the eastern margin (Ludvigson et al., 1994), and –5‰ (PDB) in the north-central seaway (southeast Saskatchewan: Kyser et al., 1993). This distribution of oxygen isotope values supports the circulation predicted by CIRC, within the framework of δ_w of precipitation and runoff discussed above. Other oxygen isotopic data from Texas (Austin Chalk:

Czerniakowsky et al., 1984; marine cements in middle Cretaceous rudist reefs: Woo et al., 1992) suggest that the initial warm, saline Tethyan waters flowing into the basin produced calcite $\delta^{18}O$ values of about –2.5‰ (PDB). Thus waters of most normal salinity were found in the south-central part of the basin and on the southeastern margin, whereas isotopically depleted and somewhat lower salinity "northern" waters occurred in the northern part of the seaway.

Lacuna

An often overlooked observation that may support patterns of circulation derived from the CIRC experiments is the distribution of lacunae (e.g., Merewether and Cobban, 1986; Elder and Kirkland, 1994) in the Western Interior seaway during the earliest Turonian (Fig. 1). A major lacuna appears along the western shoreline (eastern Utah, northwest Colorado, Wyoming) where the strong, southward-flowing coastal jet in our simulations impinged on the sea floor. Elder (1991) suggested that lacunae were formed on "basin highs" and described thin winnowed and condensed strata associated with them. We suggest that the persistence of lacunae in this region is related to erosion, winnowing, and transport of sediment in association with bottom traction currents. Other lacunae are located in the region of the suspected southern sill (Fig. 1: central Texas platform) across which strong surface currents are simulated in the model (Fig. 5). These lacunae represent only indirect evidence in support of the model, because the origins of such hiatuses have not been satisfactorily explained, and unequivocal current paleodirections have not been resolved in these areas.

Sediment Type and Distribution

The distribution of sediment types is generally consistent with the predicted circulation. Shales and marls are observed to rim an interbedded limestone-marl core, thus mirroring the structure of the estuarine gyre. We predict that runoff to the Western Interior seaway was nearly as high on the eastern as it was on the western margin, and therefore one might expect both shores to record large fluvial-deltaic wedges. This was not the case, as can be seen in the lithofacies-paleogeographic maps of Caldwell and Kauffman (1993), Sageman and Arthur (1994), and Elder and Kirkland (1994), who showed silty shales along the eastern margin but no deltas. The reasons for this are twofold: (1) marginal marine, paludal-lagoonal, and fluvial deposits of early Turonian age on the eastern margin of the seaway have been eroded; and (2) in modern rivers, high water discharges are not always accompanied by high sediment discharges, especially when considering streams draining low-relief terrains. Concerning the first point, west of the erosional limit, rocks preserved at sites such as Bunker Hill, Kansas, represent medial to distal offshore environments many kilometres from the paleoshore. Thus, there is simply no preserved record of eastern margin nearshore environments for early Turonian time. However, rocks of Albian–Cenomanian age in Kansas, Iowa, and Minnesota (mainly Dakota Group) include marginal marine to fluvial deposits of the seaway's eastern margin, and provide the best evidence from which to infer conditions for this region during the modeled time interval.

Concerning the second point, although some previous studies suggested arid conditions for the eastern margin of the seaway (e.g., Parrish et al., 1982), abundant evidence exists for a humid subtropical climate with extensive fresh-water runoff and well-developed drainage. For example, Weimer's (1984) mapping of extensive late Albian river drainages in the Dakota Formation suggests a well-developed fluvial meander-belt system prior to the Greenhorn transgression. Similar river valleys, commonly represented by valley-fill sequences up to 16 km wide, have been documented in Cenomanian deposits in Minnesota (Setterholm, 1994) and Iowa (Witzke and Ludvigson, 1994). In many cases clasts reach cobble size, indicating rivers with high competence.

Dyman et al. (1994) described Cenomanian mudstones overlying these fluvial to deltaic valley-fill sequences in Minnesota as "nearshore, brackish." Scott (1977) described macrofaunal assemblages from the upper Albian to lower Cenomanian Dakota Group of Colorado, Kansas, and Oklahoma that are extremely similar to late Cenomanian–early Turonian communities of the western margin (i.e., Utah). Some of these assemblages, which include typical long-ranging brackish-water taxa such as *Brachiodontes* and *Crassostrea*, were interpreted by Scott (1977) to reflect "low salinity bays with marsh shorelines" and "estuarine, tidal marsh, and restricted bay conditions" reflecting significant fresh-water input. Hattin (1967) reported on a number of fresh-water to brackish to "near-normal salinity" assemblages in the Dakota Formation of Kansas, and interpreted the Dakota to represent a complex deltaic coastline.

On the basis of a combination of sedimentologic, petrographic, and geochemical studies in Iowa, South Dakota, and Nebraska, Ludvigson et al. (1994) and Witzke and Ludvigson (1994) concluded that the eastern margin of the seaway during Albian–Turonian time was characterized by a humid subtropical climate with extensive fresh-water runoff. They suggested that discharge from fluvial systems caused brackish surface waters in nearshore regions and quasiestuarine circulation in the adjacent seaway. Huang and Dilcher (1994) presented paleobotanical evidence from the Cheyenne Sandstone of Kansas that confirms the interpretation of a warm temperate to subtropical humid climate with well-developed river systems, swamps, and estuaries. These data support the interpretation of extensive fresh-water input along the eastern margin of the seaway during early Turonian time.

Limited paleocurrent data collected from large-scale trough cross-strata in shelf sediments and inferred from sediment dispersal trains along the western margin (summarized in Ericksen and Slingerland, 1990) indicate transport predominately to the south. This is consistent with the counterclockwise gyre presented here.

Two important puzzles remain unanswered. The geologic evidence of black shale deposition seems to argue convincingly for anoxia during maximum transgression of the early Turonian seaway, yet CIRC did not produce a fresh-water "lid" of low enough density to prevent rapid mixing of the water column. We offer two possible resolutions: (1) stability of the water column was due to a combination of surface freshening and (seasonally modulated) thermal stratification, a combination not yet explored using CIRC; or (2) low oxygen and high nutrient concentrations at the northern boundary and/or southern boundary of the seaway, resulting from a shoaling of the oceanic oxygen-minimum zone to sill depth at sea-level highstand, prevented the oxygenation of the deep basin of the seaway through lateral transport, while providing additional nutrients to stimulate productivity and deep-water oxygen demand. Both conditions are being explored.

We have not examined here how this estuarine circulation responded to changing sea level. In a subsequent paper, we will investigate the idea that when the Tethys sill was shallow, estuarine counterflow was inhibited and the basin was poorly ventilated. It may even have freshened until the density difference across the sill was great enough to cause a catastrophic surge of marine waters into the basin. Events of this sort are well documented from the Baltic Sea and certain fjords today. When the sill was moderately deep, a vigorous estuarine counterflow was well developed, ventilating the seaway bottom waters. At maximum water depths the counterflow still existed, but a rising oxygen-minimum zone may have been tapped to turn bottom waters dysoxic again.

CONCLUSIONS

According to the results of our model simulations, the principal forcing mechanism for circulation—that is, the long-term temporal average flows of the Western Interior seaway at peak Turonian flooding—was fresh-water runoff, and the latitudinal temperature and salinity gradients and mean annual winds played supporting roles. Runoff from eastern drainages exited the seaway as a northern coastal jet; runoff from western drainages exited as a southern coastal jet. Both jets simultaneously drew in Tethyan and Boreal waters, much as laterally inhomogeneous estuaries do today, while exporting bottom waters. The resulting circulation was a strong counterclockwise gyre occupying the entire north-south extent of the seaway. The strength of the gyre and therefore the seaway's salinities and temperatures would have waxed and waned as precipitation minus evaporation or sill depths changed, thereby producing the curious stratal and faunal variations we see today in the Greenhorn deposits.

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