

Paleoceanographic and paleoclimatic interpretations of the Mancos Shale (Upper Cretaceous), Black Mesa Basin, Arizona

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ABSTRACT

The Black Mesa Basin of northeastern Arizona contains the stratigraphic record of the transgression and regression of the Greenhorn Sea during late Cenomanian to late middle Turonian time. The transgressive phase of the cycle is much thinner than the regressive phase. Foraminiferal data suggest that peak transgression of the Greenhorn Sea occurred during mid-early Turonian to earliest middle Turonian time (*Mammites nodosoides* to perhaps basal *Collignoniceras woollgari* Biozone) in this area of the interior seaway.

The Cenomanian/Turonian boundary interval is marked by dynamic changes in the population structure of planktonic foraminifera and in foraminiferal abundance. It is suggested that an oxygen minimum zone (OMZ) within the water column was established in the Black Mesa area during this time, based on the marked increase in relative abundance of *Heterohelix*. The OMZ gradually waned through the time of peak transgression. Clay mineral, sedimentological, and foraminiferal data suggest regional climatic warming and increased weathering accompanying the northward advance of warm, normal marine waters during transgression. Cooling, decreased intensity of chemical weathering (leaching), and a slight decrease in oceanic salinity in the Black Mesa area characterized the subsequent regression. These data are also used to reinterpret Upper Cretaceous depositional history in the Black Mesa Basin.

INTRODUCTION

The Black Mesa Basin is situated on the southern Colorado Plateau, in northeastern Arizona (Fig. 1). During Cenomanian-Turonian time (Late Cretaceous), global sea level rose to the highest levels of the Mesozoic, and as a consequence, vast areas of the continents were flooded by epeiric seas (e.g., Hancock and Kauffman, 1979), such as the Greenhorn Sea of the U.S. Western Interior. At peak transgression of the Greenhorn Sea, the shoreline extended as far west as northwestern Arizona and southwestern Utah, forming the Grand Canyon embayment, some 300 km west of Lohali Point (Molenaar, 1983; Cobban and Hook, 1984). During this time, the Black Mesa area was a broad neritic environment with gentle relief.

The purpose of this chapter is to present foraminiferal and clay mineral data from Cretaceous marine rocks of the Lohali

Point section of Black Mesa, Arizona (Fig. 1) and to present a paleoenvironmental interpretation of the results. The material analyzed in this study comes from a stratigraphic section of Mancos Shale that was measured, described, and collected by James Kirkland. R.M.L. and M.S. visited the section in 1986 with Kirkland. The section is located four miles northwest of Lohali Point (36°11'N, 109°53'W) along the erosional scarp of eastern Black Mesa. Details of the section, as well as an overview of the regional geology, are presented by Eaton and others (1987) and Kirkland (this volume).

The Mancos Shale at Lohali Point is 203.2 m thick. It is underlain disconformably by the upper Cenomanian Dakota Formation and is overlain conformably by the middle Turonian Toreva Formation (Kirkland, this volume). Kirkland recognizes four members (three informally, one formally) within the Mancos Shale at Black Mesa (Fig. 2). At Lohali, the lower shale member

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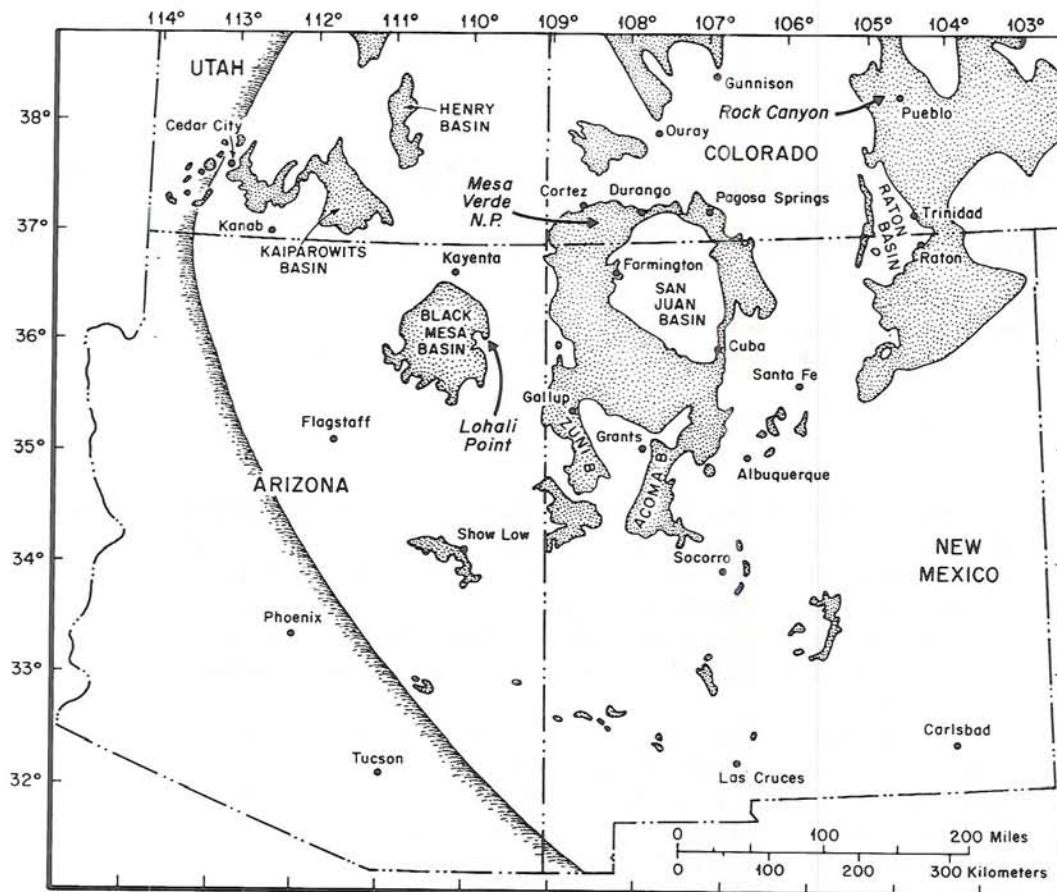


Figure 1. Map showing Black Mesa Basin and the location of the Lohali Point and Rock Canyon sections discussed in the text. Stippled areas depict Cretaceous outcrop of the southern Colorado Plateau and adjacent areas. The line through Arizona and Utah shows the approximate position of the shoreline during peak transgression of the Cenomanian-Turonian Greenhorn Sea (modified after Molenaar, 1983).

is 54.6 m thick and is composed of bioturbated, highly calcareous shales with numerous prominent bentonites, calcisilts, and several concretion horizons. The Cenomanian/Turonian stage boundary occurs within this unit. The middle shale member is 42.4 m thick at Lohali and is dominated by well-laminated, moderately calcareous shales with minor bentonites, calcisilts, and silt or fine sand horizons. The Hopi Sandy Member is 21.1 m thick and is composed of thinly interbedded fine to very fine sandstone, silty shale, and shale with minor septarian concretions and cone-in-cone horizons. The upper shale member of the Mancos is 85.1 m thick at Lohali and is composed of noncalcareous claystones with scattered bentonites. Sand content increases over a 25-m interval near the top of the upper shale member, marking the transition with the overlying Toreva Formation.

One of our objectives in this chapter was to document the benthic and planktonic foraminifera through one of the complete sections of Mancos Shale also being analyzed for marine macrofossils by Kirkland (this volume). The Lohali section represents the most distal of Kirkland's sections and therefore is of great

importance for correlation with the central Western Interior basins. The foraminifera of the most proximal of Kirkland's sections around Black Mesa (Blue Point) are documented by Olesen (1987, this volume). A second objective was to test the environmental interpretations of Hazenbush (1973) and compare our foraminiferal results with those of Olesen (this volume). And lastly, we examined the clay minerals in the section to see how covariations with foraminiferal trends could help constrain the influence of changing depositional conditions on the biota with transgression and regression of the Greenhorn Sea.

PREVIOUS WORK ON BLACK MESA FORAMINIFERA

Hazenbush (1973) was the first to document the microfossils in the Mancos Shale of Black Mesa, including the planktonic and benthic foraminifera, ostracods, and plant "megaspores". He analyzed the foraminifera from five sections around Black Mesa, including Lohali Point. However, his Lohali section is truncated

above the Hopi Sandy Member by a gravity slide and is therefore incomplete. Hazenbush defined three informal assemblage zones in the Mancos Shale of Black Mesa, each composing about one-third of the section. The lowest zone, the *Hedbergella detrioensis* Zone, contains abundant planktonic and benthic foraminifera and was interpreted as a partially restricted embayment, periodically cut off from the open ocean to the east, with maximum water depths of 10 to 20 fathoms (18 to 36 m). The middle zone, the megaspore zone, was described as nearly barren of foraminifera, according to Hazenbush, but containing abundant plant "megaspores," and was interpreted as a marginal marine mudflat under subaerial conditions (i.e., upper part of the intertidal zone). The upper zone, the *Gaudryina bentonensis* Zone, contains an exclusively arenaceous benthic foraminiferal fauna and was interpreted as a partially flooded mud flat (i.e., lower part of the intertidal zone).

METHODS

In the lower 30 m of section, one sample per meter was examined for both foraminifera and clay mineralogy. This interval embraces the Cenomanian-Turonian boundary. In the remainder of the Mancos, from 31 to 201 m, one sample every 5 m of section was examined for foraminifera and one sample every 10 m was examined for clay mineralogy (the clay samples come from the same levels as the foraminiferal samples). Additional samples were examined for clay mineralogy in the middle shale and Hopi Sandy members. Sixty-six samples were examined for foraminifera, and 57 were examined for clay mineralogy. See Kirkland (this volume) for details of the sampling procedure in the field.

The following procedure was used to process the samples for foraminifera. The shales were crushed to marble size and then

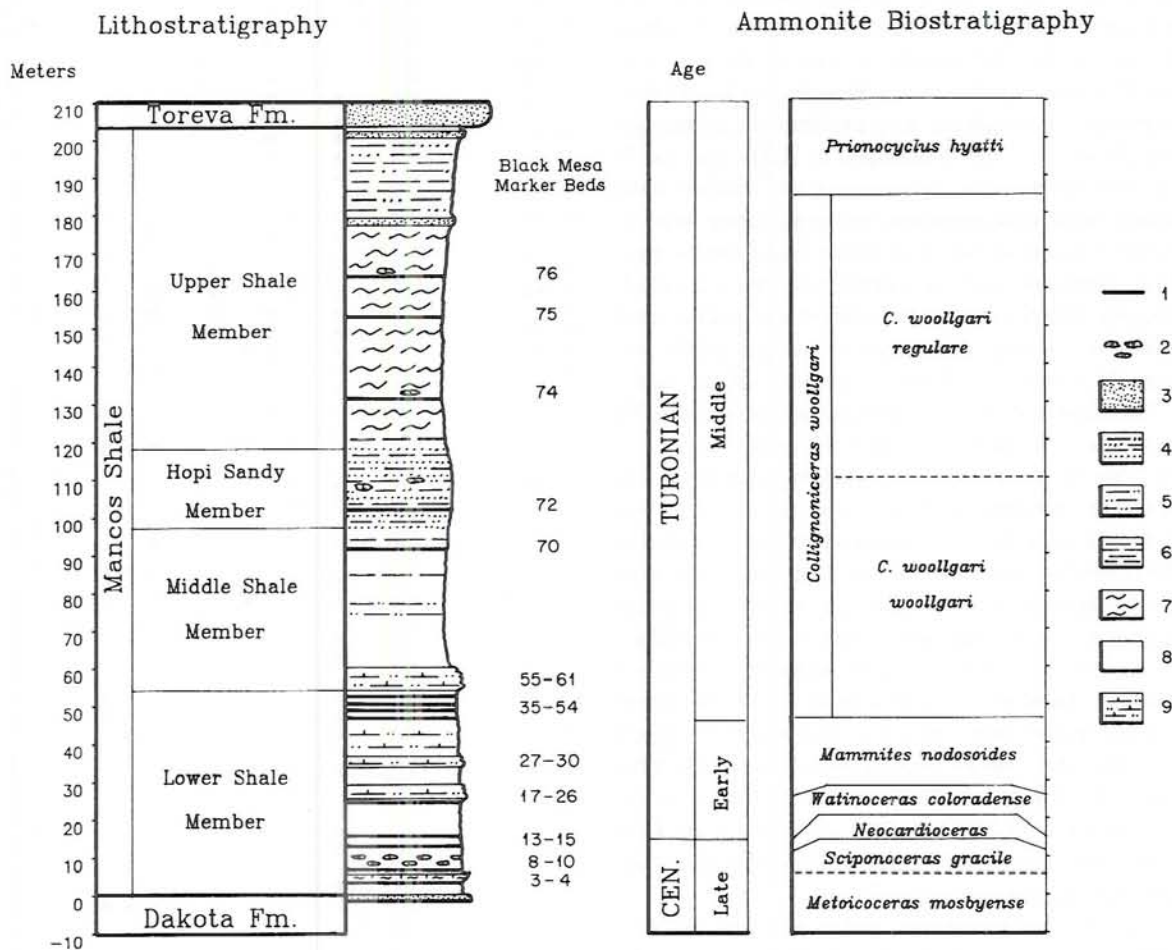


Figure 2. Lithostratigraphy and ammonite biostratigraphy of the Lohali Point section of Black Mesa (data from Kirkland, this volume). Black Mesa marker beds are also from Kirkland (this volume). 1, bentonites; 2, concretions; 3, sandstone; 4, interbedded sandstone, siltstone, and shale; 5, siltstone; 6, shale; 7, claystone; 8, calcareous shale; and 9, calcisilt (winnowed biogenic silt-size laminae and thin beds, primarily foraminiferal tests).

boiled in a weak hydrogen peroxide–Calgon solution for about an hour. The disaggregated sediment was washed over a 63- μm (230 mesh) sieve. The residue was then dried in an oven. The residues were split, using a Soiltest microsplitter, to a volume of sediment small enough to yield a fairly sparse distribution of particles on a picking tray. Foraminifera were picked from random squares around the tray until at least 300 specimens were collected and mounted on a microslide. Some samples contained too few foraminifera to yield 300 specimens. Other biogenic and lithic components were also noted (Fig. 3). This “first pick” provided the planktonic to benthic ratio, expressed as percent planktonics in Figure 5. A “second pick” was made on samples containing too few planktonic or benthic specimens for population analysis. The residues were then examined for rare species in the >250- μm , 150 to 250- μm , and 63 to 150- μm size fractions.

The following procedure was used to process samples for clay mineralogy. Twenty-five to 30 grams of shale were disaggregated in a ball shaker for 10 minutes. The crushed sediment was transferred to a 250-ml plastic bottle containing 200 ml of sodium acetate solution–acetic acid (1 Normal, buffered to pH 5.0) for approximately 24 hours to dissolve the remnants of carbonates and to replace the exchangeable cations of the clay with sodium ions. The sample solution was then shaken for 30 minutes, and dispersal was completed using an ultrasonic disaggregator. The sample solution was centrifuged at 2,000 rpm for 20 minutes, the clear supernatant was decanted, and distilled water added. Shaking, sonic disaggregation, and centrifuging were repeated to remove excess sodium and acetate ions from the sample. Washing continued until the sample solution was cloudy after centrifuging. The cloudy sample solution was not decanted but was shaken and sonified again, then centrifuged at 500 rpm for 9 minutes, 37 seconds, to obtain a suspension of less than 2 μm in size. The suspension was decanted and centrifuged at 1,000 rpm for 9 minutes, 37 seconds, to remove the greater than 1 μm size fraction from the suspensate. The remaining suspension was decanted, and the centrifugate (1- to 2- μm size fraction) was dried at 50°C until paste-like. This size fraction was separated to diminish the overriding abundance of smectite that appeared in preliminary examination of the <2 μm size fraction. From this paste, three oriented smear slides were prepared for x-ray diffraction (XRD) analysis. One slide remained untreated and was put in the desiccation chamber to dry. One drop of ethylene glycol was added to the second slide, and it was then placed in a glycol chamber. The third slide was air dried in the desiccation chamber and then heated for 1 hour at 550°C, cooled, and stored in the desiccation chamber until XRD analysis was carried out. Clay mineral abundances were determined semiquantitatively using peak height measurements (Wilson, 1987).

A Micromeritics sedigraph was used to examine the grain-size distribution of the silt and clay size fractions (less than 63 μm) of 11 shale samples, evenly spaced through the section. Five samples from kaolinite-rich intervals were examined with a scanning electron microscope for authigenic clay minerals.

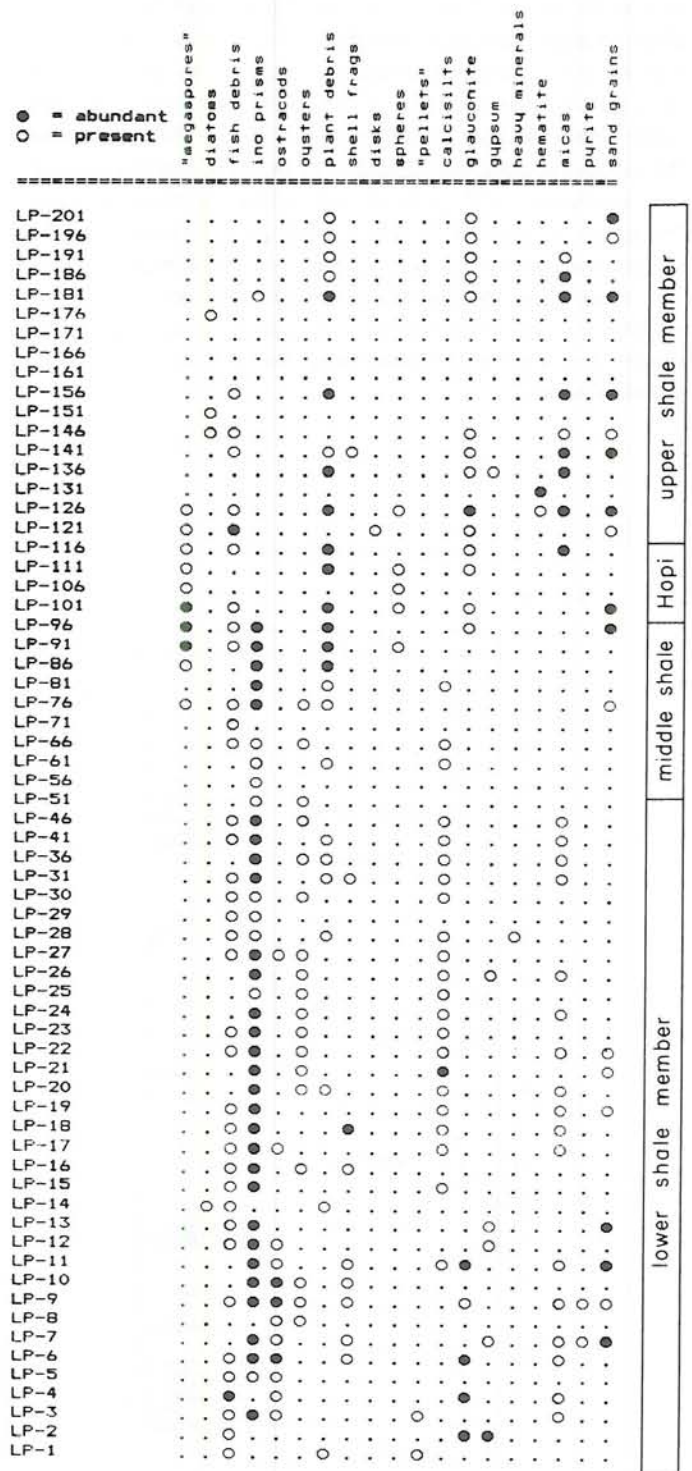


Figure 3. Distribution of biogenic and lithic components observed in the foraminiferal residues.

RESULTS AND ENVIRONMENTAL INTERPRETATION

Lower shale member

The Greenhorn Sea transgressed rapidly across northeastern Arizona during late Cenomanian time (e.g., Elder, 1987; Eaton and others, 1987; Kirkland, this volume). Small specimens of *Hedbergella*, *Heterohelix*, and *Guembelitra* occur in the basal meter of shale overlying the Dakota Sandstone. Planktonic foraminiferal diversity increases rapidly in the lower 5 m of Mancos Shale at Lohali Point, including the first appearance of *Globigerinelloides bentonensis* and species of *Whiteinella*. The proportion of planktonic foraminifera to benthic foraminifera (expressed as percent planktonics) also increases rapidly through this interval, as does the average size of *Hedbergella* and *Heterohelix* and the ratio of calcareous benthic foraminifera to arenaceous benthics (Fig. 5).

Eicher's pioneering work on Cenomanian-Turonian foraminifera of the Western Interior Seaway (e.g., Eicher, 1965, 1966; Eicher and Worstell, 1970; Eicher and Diner, 1985) has clearly established the sequence of planktonic foraminiferal first and last appearances and successive benthic assemblages associated with the transgression and regression of the Greenhorn Sea. The first planktonics to invade the Greenhorn Sea, and the last to leave, are represented by small specimens of *Hedbergella* and *Heterohelix*. Their small size is undoubtedly related to less than optimal environmental conditions for even the hardiest of planktonic foraminifera during the transition from a shallow, hyposaline(?) to a deeper, normal marine seaway. As the abundance of planktonic specimens increases, so does the average size of *Hedbergella* and *Heterohelix* as well as total planktonic foraminiferal diversity, reflecting the establishment of normal marine conditions.

The interval between 5 and 11 m at Lohali corresponds with Eicher and Worstell's (1970) Benthonic Zone and the macrofossil *Sciponoceras gracile* Zone. This interval represents a rapid invasion of warm, well-oxygenated waters deep into the Western Interior Seaway during latest Cenomanian time (e.g., Kauffman, 1977, 1984). *Guembelitra* dominates the relatively shallow, normal marine planktonic assemblages at Lohali, whereas *Hedbergella* dominates the assemblages in the deep, central part of the seaway (Leckie, 1985).

A major shift in the compositional structure of planktonic foraminiferal assemblages coincides with the uppermost Cenomanian *Neocardioceras juddii* Zone. A similar type of compositional shift occurs at the same stratigraphic level in the central part of the seaway (Leckie, 1985). *Heterohelix* replaced *Guembelitra* as the dominant planktonic foraminifer at Lohali. Coincident with the change in planktonic assemblages is a marked decline in the proportion of planktonics to total foraminifera and a decline in the proportion of calcareous benthics to total benthic foraminifera (Fig. 5). In the Black Mesa area, the relatively diverse *Sciponoceras* Zone macrofauna is rapidly depleted and re-

placed by a more generalized *Neocardioceras* Zone macrofauna just prior to the Cenomanian/Turonian stage boundary (Elder, 1987). This also corresponds with the greatest macrofossil turnover rates for the boundary interval (Elder, 1987). At Rock Canyon, in the central part of the seaway (Fig. 1), this interval is characterized by a depauperate epifaunal macrofossil assemblage (Elder and Kirkland, 1985) and a low-diversity benthic foraminiferal fauna (Eicher and Worstell, 1970; Leckie, 1985) indicative of dysaerobic benthic conditions. Oxygen isotope data indicate a significant drop of surface-water salinity coincident with the changes in foraminiferal and molluscan populations immediately preceding the Cenomanian/Turonian boundary (Pratt, 1985).

The increase in *Heterohelix* at both the relatively shallow Lohali section and the much deeper Rock Canyon section indicates a major, nearly synchronous change in the upper water column of the Greenhorn Sea. We propose two hypotheses to account for this widespread change. Perhaps *Heterohelix* was more tolerant of slightly lower salinity conditions than *Guembelitra* (at Lohali) and *Hedbergella* (at Rock Canyon). Or perhaps *Heterohelix* thrived in a niche associated with an oxygen minimum zone (OMZ). We suggest three possible mechanisms that may have been responsible for the development of an OMZ within the upper water column during *Neocardioceras* time: (1) elevated rates of surface-water productivity (stimulated by increased riverine input to the basin or by reorganization of wind-driven circulation), (2) reduced ventilation of the upper water column through enhanced stratification (salinity or thermal), or (3) incursion of an OMZ into the Western Interior Seaway from the south with approach of peak transgression (Frush and Eicher, 1975) associated with the global Oceanic Anoxic Event 2 (Arthur and others, 1987; Schlanger and others, 1987). The oxygen minimum scenario is somewhat analogous with the environmental interpretation for the early Tertiary biserial genus *Chiloguembelina* (Boersma and Premoli Silva, 1987; Boersma and others, 1987). We prefer the oxygen minimum zone hypothesis because *Heterohelix* continues to dominate the planktonic foraminiferal assemblages above the Cenomanian-Turonian boundary at Lohali despite a return to more normal marine oxygen isotope values at the boundary (Pratt, 1985) and a return of healthy, diverse planktonic foraminiferal taxa (see below). We suggest that an oxygen minimum zone persisted in many areas of the Western Interior Seaway through peak transgression of the Greenhorn Sea and was closely linked with the incursion of warm water masses from the south.

Thompson and others (1985) found a well-developed active calcareous macrofauna and heavily bioturbated sediments at oxygen values as low as 0.3 ml/l, within the central California OMZ. They also noted moderately bioturbated sediments at oxygen values as low as 0.1 ml/l. Douglas and Heitman (1979) reported a mixed calcareous and agglutinated benthic foraminiferal fauna (Basin Floor Assemblage) in areas of the California borderland with dissolved oxygen values less than 0.1 ml/l. The development of an OMZ over Lohali Point during the deposition

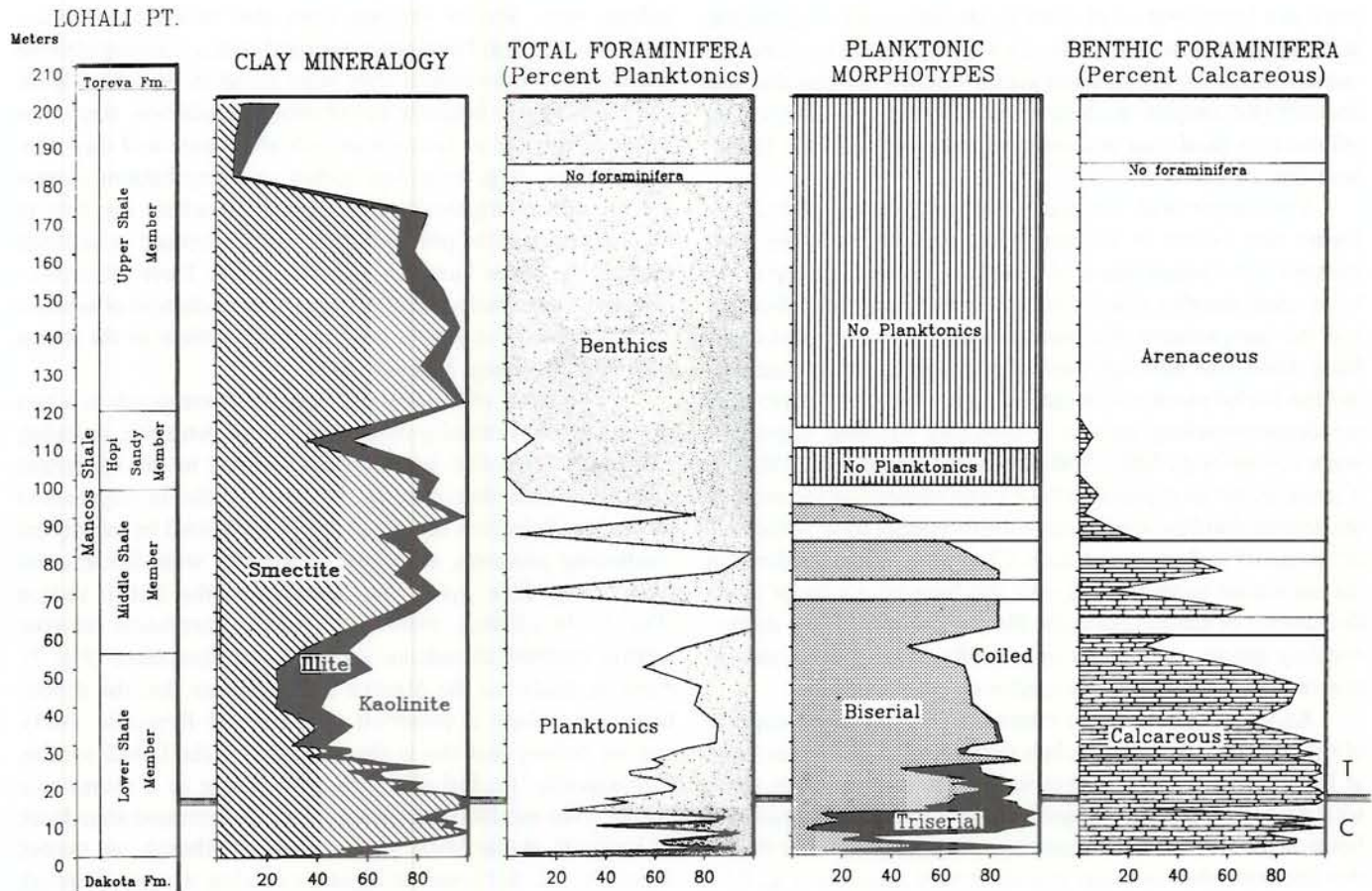


Figure 5. Foraminiferal and clay mineral trends through Lohali section. See text for discussion. Open bars correspond to samples with too few foraminifera (either planktonic or benthic varieties) for population analysis.

of the Turonian lower shale member may imply weakly aerobic to dysaerobic conditions on the sea floor. However, the observed moderately to well-bioturbated calcareous shales and their contained low-diversity calcareous benthic macrofauna and mixed calcareous and agglutinated benthic foraminiferal fauna do not contradict this interpretation.

Peak transgression is estimated on the basis of planktonic foraminiferal diversity trends, assemblage composition, and the relative abundance (concentration) of planktonic foraminiferal tests in the sediments. We interpret that peak transgression occurred during mid early Turonian to earliest middle Turonian time in the Black Mesa area, represented at Lohali by the middle and upper parts of the lower shale member (upper part of *Watinoceras* Zone, *Mammites* Zone, and basal *Collignoniceras* Zone; Kirkland, this volume; Fig. 2). This interval correlates with the middle and upper parts of the Bridge Creek Limestone Member of the Greenhorn Formation along the Colorado Front Range and with the Jetmore and Pfeifer members of the Greenhorn Formation in central Kansas. At Rock Canyon, Elder and Kirkland (1985) cited the maximum influx of subtropical molluscs in the middle Bridge Creek Member as evidence for peak transgression in the central part of the seaway.

Abundance of planktonic foraminifera increases dramatically at about 15 m, in basal Turonian strata (*Watinoceras* Zone). Diversity also increases, primarily as a result of the reappearance of species of *Whiteinella* (Fig. 4). The abrupt increase in foraminiferal abundance is coincident with a return of oxygen isotope values indicative of more normal marine conditions (Pratt, 1985). Species of *Clavihedbergella* appear at about 16 m. *Guembelitra cenomana*, a species found only in very rare to trace abundances in deeper water sections (Leckie, 1984, 1985, 1987), virtually disappears above 24 m; whereas species of the keeled genera *Praeglobotruncana* and *Dicarinella*, taxa diagnostic of relatively deep, open marine conditions (Sliter, 1972; Douglas and Savin, 1978; Hart, 1980; Wonders, 1980; Caron and Homewood, 1983; Leckie, 1987), first appear at about 29 m. This trend indicates a deepening water column or an increasing distance from shore (i.e., continued transgression) through at least earliest *Mammites* time.

The trochospirally coiled planktonic foraminiferal morphotypes, represented by the genera *Hedbergella* and *Whiteinella*, increase at the expense of the biserial morphotype, *Heterohelix*, through the middle and upper parts of the lower shale member. This trend could represent improved open marine conditions

(such as a normalization of salinity), changes in density gradients in the uppermost water column, or a waning of the oxygen minimum zone in the Lohali Point area. Although the situation was undoubtedly complex, we believe that an OMZ was an important influence on planktonic foraminiferal communities of the Greenhorn Sea.

The sample with the greatest abundance and diversity of keeled taxa occurs in the uppermost part of the lower shale member. The concentration of keeled taxa toward the top of the lower shale member (basal *Collignoniceras* Zone) may also support the interpretation of a waning oxygen minimum zone in the Black Mesa area with approach of peak transgression. Late Cretaceous keeled planktonic foraminifera are believed to have been the deepest-dwelling taxa in a thermally stratified uppermost water column (e.g., Hart, 1980; Caron and Homewood, 1983). It is possible that an expanded OMZ could impinge on the niche of the deepest-dwelling species and thereby control their "presence" or "absence" in the water column. Changes in density gradients in the uppermost water column may also have been a factor in the distribution of keeled taxa in the Black Mesa area. These deeper-dwelling species proliferated only briefly prior to the deterioration of warm, normal marine conditions with regression.

Kaolinite and, to a lesser extent, illite increase at the expense of smectite and mixed-layer clays through lower Turonian strata at Lohali, despite the apparent increase in distance from shore with approach of peak transgression, as shown by foraminifera. Some studies of recent sedimentary environments have shown that kaolinite often increases in a shoreward direction (e.g., Edzward and O'Melia, 1975; Gibbs, 1977). Thus the trend in the lower Turonian sequence at Lohali could indicate a regression. Moreover, a noticeable shift in the silt and clay grain-size distribution toward coarser modal classes from the base of the section (uppermost Cenomanian) toward the lower Turonian also seems to support a regression (Fig. 6).

However, the foraminiferal data clearly rule out regression through the lower Turonian, and closer inspection of the mineralogic and sedimentologic data (Figs. 6 and 7) raises further questions. In the uppermost Cenomanian part of the section, there is no change in grain-size distribution despite a pronounced increase in smectite relative to kaolinite and illite. Moreover, the coarser grain size of the Turonian section is maintained throughout, despite fluctuations of the clay mineral abundances (compare Figs. 5 and 6).

The interval of elevated kaolinite corresponds with the occurrence of numerous horizons and thin beds of calcisilt (Fig. 7). The calcisilts consist wholly of biogenic components, primarily foraminiferal tests, and their abundance implies active circulation on the sea floor. Pollastro (1981) has documented the formation of authigenic kaolinite and associated pyrite within foraminiferal tests from the Cretaceous Niobrara Formation. According to his model, an aluminous gel or solution formed from volcanic ash deposited during chalk sedimentation and "sulfate-reducing bacteria created a favorable microenvironment for the simultaneous crystallization of kaolinite and pyrite" within organic-rich foram-

iniferal tests. Several samples from the kaolinite-rich lower Turonian at Lohali Point were examined with a scanning electron microscope. Foraminiferal tests were found to be calcite filled, and no authigenic kaolinite was observed. In addition, there is no apparent correlation between calcisilt abundance and clay mineral changes, suggesting that neither changing bottom current activity nor authigenic kaolinite formation within the tests of foraminifera was the principal cause for the increase in kaolinite through the lower Turonian of Lohali Point. Three other processes must be considered: (1) postdepositional changes of smectite into kaolinite, (2) a greater production of kaolinite in the source area, or (3) a change in source area.

The interval of elevated kaolinite also corresponds to a part of the section containing numerous beds of bentonite, including Kirkland's "bentonite swarm" (this volume) in the uppermost part of the lower shale member. Storr and Hattin (in preparation) show that Cretaceous bentonites can be kaolinized by subsequent weathering processes, especially in sections with disseminated pyrite. Very little pyrite was observed in the Lohali section (Fig. 3). In addition, there is little direct correlation between relative kaolinite abundance and bentonite abundance (Fig. 7). Previous studies of the Mancos Shale indicate that the depositional mineralogy is preserved (Nadeau and Reynolds, 1981), and we believe that this is also the case for the Lohali section. Consequently, we feel that a climatic change or a source-area change is the most likely explanation for the increased abundance of kaolinite in the lower shale member, although we cannot definitely rule out some authigenesis pending a more thorough SEM examination of the rocks.

Kaolinite is produced by the chemical weathering of aluminosilicate minerals under warm, wet climatic conditions. We propose that the expanding Greenhorn Sea may have modified regional climate patterns with the approach of peak transgression during early Turonian time. The spread of warm water masses deep into the central and southern seaway (Kauffman, 1977, 1984) provided a greater source of latent heat and potential for increased rainfall and maritime climates. Recall that the maximum influx of subtropical molluscs occurs in the middle Bridge Creek Member at Rock Canyon (Elder and Kirkland, 1985), the same interval that shows the marked increase in kaolinite at Lohali Point.

Increased storm intensity, or storm-induced geostrophic circulation in the Black Mesa area, may have been responsible for the accumulation of calcisilts below storm wave base (see also Kirkland, this volume). The enhanced circulation vigor in the Black Mesa area may also have been responsible for maintaining the relatively healthy benthic biota through the lower shale member (compare Kirkland's data with biotas of same age from the central, deeper parts of the seaway, e.g., Elder and Kirkland, 1985).

Middle shale member

The abundance of planktonic foraminiferal tests decreases rapidly in the lower 5 m of the middle shale member. All species

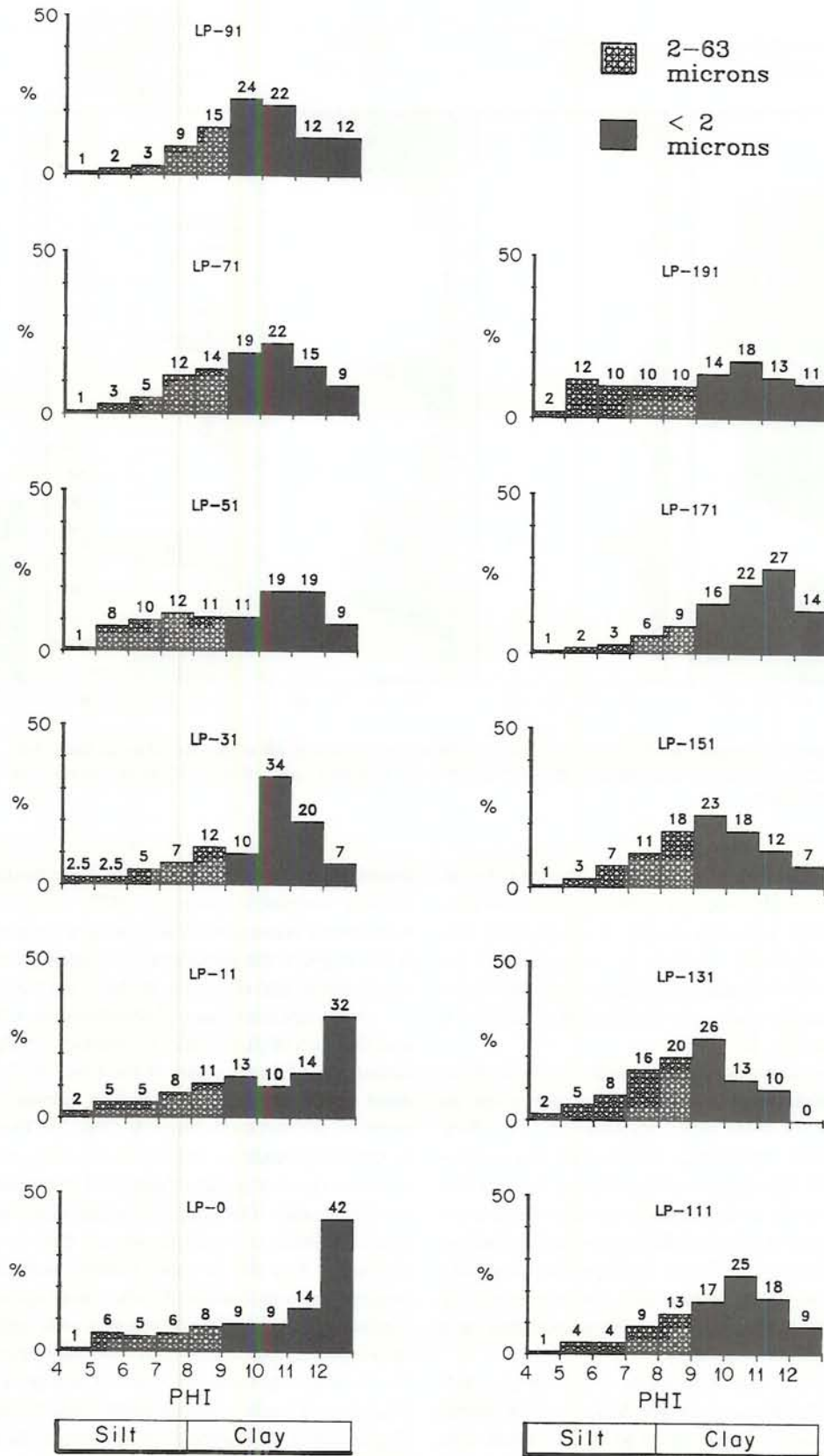


Figure 6. Grain-size distributions in the silt and clay size fractions. LP numbers represent meters up from base of Mancos Shale section. Note how samples LP-0 and LP-11 (uppermost Cenomanian) differ from the remainder of the section (Turonian).

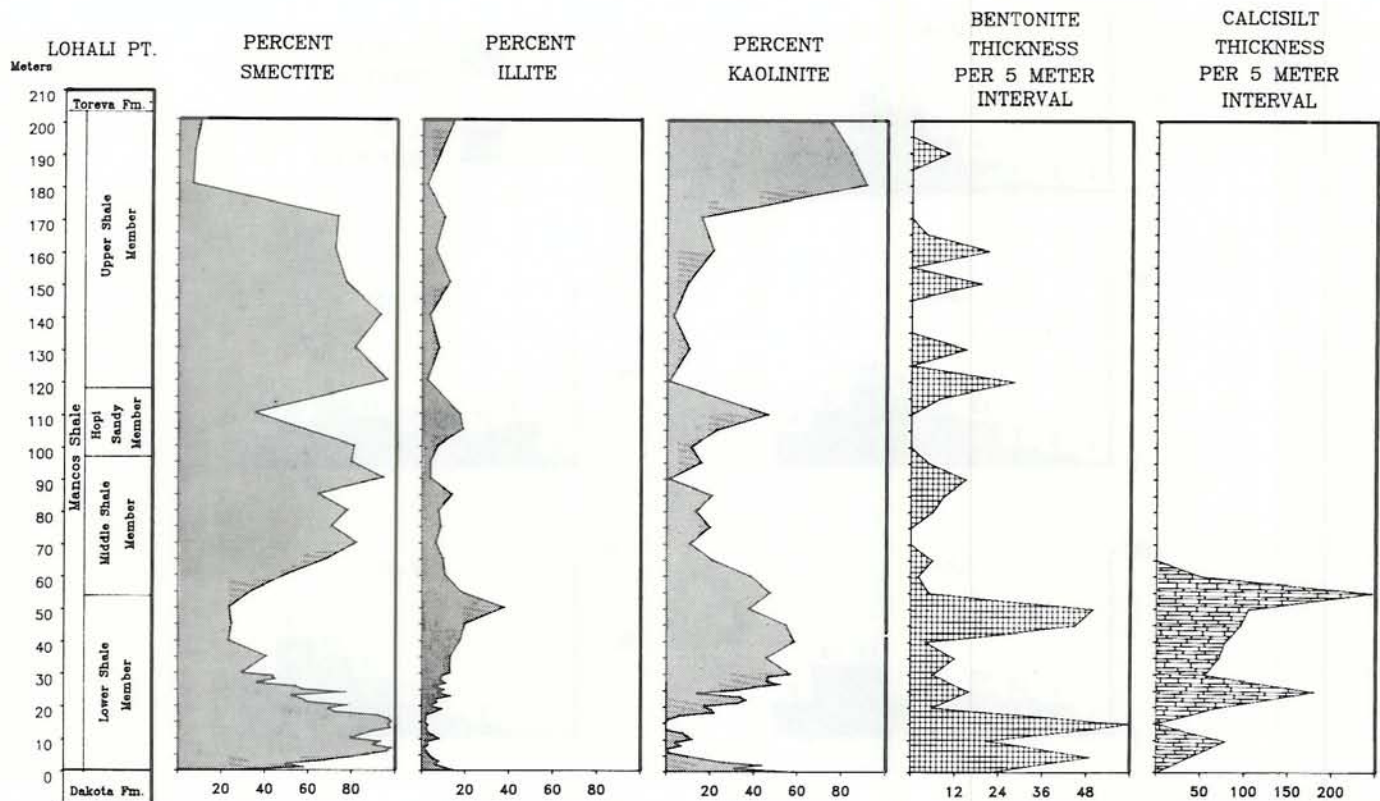


Figure 7. Comparison of clay mineral species with bentonite and calcisilt occurrence through the Lohali section (bentonite and calcisilt data computed from Kirkland, this volume). Units of thickness in centimeters.

of *Clavibergella* and all keeled planktonics disappear by 56 m, the basal strata of the middle shale member. Species of *Whiteinella* disappear by 66 m, and only species of *Hedbergella* and *Heterohelix* persist sporadically through the remainder of the unit. The abrupt reduction of foraminiferal abundance and diversity at the base of the middle shale records the onset of regression in the Black Mesa area (Fig. 4).

The deterioration of environmental conditions through the lower part of the middle shale member is also borne out by changes in the proportions of the major planktonic foraminiferal morphotypes. *Heterohelix*, the biserial morphotype and component of Leckie's (1987) Epicontinental Sea Fauna, increased at the expense of *Hedbergella*, a simple trochospirally coiled morphotype and component of Leckie's (1987) open marine Shallow Water Fauna (e.g., 61 m, 66 m, 76 m). Perhaps this reflects the redevelopment of an oxygen minimum zone, an overall cooling of the surface-water mass as warm waters were displaced, or a slight decrease of surface-water salinity.

Planktonic foraminifera are stenohaline organisms; i.e., they will tolerate only small changes of salinity. Most modern species proliferate in normal marine waters of 33 to 37 ‰; a few taxa may be reproductively viable to 29 ‰ (Be, 1977). A gradual reduction of salinity by only 3 to 5 ‰ with the onset of regression would probably have been catastrophic for the planktonic

foraminifera of the Greenhorn Sea. Most benthic foraminifera are likewise stenohaline (Murray, 1973). Oxygen isotope data from numerous Cenomanian-Turonian sections across the western interior support the hypothesis of changing salinities during the transgression and regression of the Greenhorn Sea (Pratt, 1985).

Although abundance of planktonic foraminiferal tests is high and the ratio of planktonics to benthics (P/B) is relatively stable through the Turonian part of the lower shale member, the sediment assemblages of foraminifera through the middle shale member are markedly unstable (Fig. 5). The major drop in foraminiferal abundance reflects deteriorating environmental conditions for the stenotopic calcareous foraminifera, particularly for the planktonics. The dramatic swings in percent planktonics and percent calcareous benthics suggest that the offshore effects of regression were due to either shifting water mass boundaries or mixing processes associated with current activity on the sea floor. Planktonic foraminifera in samples with high P/B ratios in the upper part of the middle shale member (e.g., 81 m and 91 m) show signs of mechanical abrasion and perhaps current sorting. Therefore, the paleoecologic significance of changing proportions of planktonic foraminiferal morphotypes through this interval is inconclusive.

As regression of the western shoreline began, a gradual decline of salinity, particularly in near-surface waters, began to

affect the calcareous plankton. A decline in carbonate content through the middle shale (Kirkland, this volume) probably records a decline in carbonate productivity by both planktonic foraminifera and calcareous nannoplankton (see Watkins, 1985). Shifting water mass boundaries and/or bottom current activity may have been responsible for the dynamic changes in foraminiferal sediment assemblages as the Black Mesa area became increasingly isolated from normal marine water masses of southern affinities. Planktonic and calcareous benthic foraminifera had nearly disappeared from Black Mesa by the time the Hopi Sandy Member was deposited (see also Hazenbush, 1973; Olesen, this volume).

Kirkland's macrofossil data from Lohali (Kirkland, this volume) show a marked decline in benthic suspension feeders and ammonites above the lower shale member and their continued demise through the middle shale and Hopi Sandy members, but deposit feeders remain virtually unchanged through this interval. These trends may suggest an increase in turbidity and/or an increase of sedimentation rates with the onset of regressive conditions. In addition, the calcareous shales and calcisilts of the lower shale member are gradually replaced upward by decreasing carbonate content and increasing silt and fine sand through the middle shale member, recording the decline in pelagic deposition and increase in clastic deposition as regression began in the Black Mesa area. Plant "megaspores" first appear at 76 m but do not occur abundantly until 91 m (Fig. 3).

The proportion of kaolinite in the clay mineral assemblages gradually decreases upward through the middle shale member, while smectite and mixed-layer clays increase. We suspect that this trend is also climate- or source-related rather than a winnowing effect, because calcisilts and silt or fine sand horizons persist throughout the unit, indicating fairly active bottom currents (see discussion in previous section). With the onset of regression, warm water masses were gradually displaced southward, perhaps by cooler, somewhat hyposaline waters from more northerly sources in the Western Interior Seaway. The retreat of warm waters could have contributed to a reduction of temperatures and rainfall and therefore a reduction of kaolinite production by chemical leaching in the adjacent terrestrial environs.

Hopi Sandy Member

Kirkland (this volume) interprets the Hopi Sandy Member as an offshore sand body and related shelf sands above storm wave-base depth. Kirkland suggests that sea-level stillstand allowed for the repeated winnowing and reworking of sand during storms and seaward transport of sand as turbid sediment plumes. Plant "megaspores" are abundant, and a fairly diverse arenaceous benthic fauna occurs throughout this unit. Very rare planktonic and calcareous benthic foraminifera were recovered from only one sample.

Hazenbush (1973) interpreted the Hopi Sandy interval as a mudflat or salt marsh environment by drawing on an analogy with modern *Dystichlis-Salicornia* mudflats. Sedimentologic fea-

tures, particularly in the Hopi Sandy and upper shale members, raise questions about Hazenbush's environmental interpretations for these units around Black Mesa. For instance, given the small tidal range proposed for much of the Greenhorn Sea (e.g., Ericksen and Slingerland, 1989), a mudflat as extensive as Black Mesa on the margin of the sea would be highly unlikely (Reinson, 1984). Sedimentary structures that would be predicted, such as desiccation cracks, bidirectional current ripples, herringbone cross-stratification, bioturbation and pelletization, and flaser and lenticular bedding (Davis, 1983; Frey and Basan, 1985), are not present. Although plant debris is abundant, especially in the Hopi Sandy Member, there is no evidence of roots in this part of the section, nor is there evidence of tidal channel deposits (Kirkland, this volume). In addition, ammonites are found throughout the Hopi Sandy Member. Structures that are observed in the Hopi Sandy Member, such as hummocky cross-stratification, have been interpreted as sediments reworked by storm-generated surges below fair-weather wave base (Davis, 1983; Walker, 1984; Niederoada and others, 1985). Fair-weather wave base varies but is typically in the depth range of 5 to 15 m (Walker, 1984).

Upper shale member

The basal few meters of the upper shale member contain silty shale, with silt content decreasing upward. The overlying 54 m consist of nearly pure noncalcareous claystone. Clay mineral and sedigraph analyses show this interval to be dominated by smectite and to be rather uniform in grain size and clay mineral composition (Figs. 5 and 6). The fine grain size and lack of structure led Kirkland (this volume) to suggest that the claystones were deposited below storm wave base following an episode of local(?) subsidence. The principal component of the depauperate macrofauna through much of the upper shale member is the inarticulate brachiopod *Lingula*. The microfauna consists entirely of arenaceous foraminifera, which persist throughout the unit.

The upper shale member represents a similar facies and is partially time equivalent to the noncalcareous Blue Hill Shale Member (Carlisle Shale) along the Colorado Front Range. Calcareous foraminifera occur sporadically in the Blue Hill Shale at Rock Canyon (Eicher, 1966). Eicher (1966) attributed the near-absence of planktonic and calcareous benthic foraminifera to decreased salinity and/or increased turbidity with the approach of peak regression. It is quite possible that relatively low oxygen levels and low pH conditions within the sediments, or at the sediment-water interface, may have postdepositionally altered the foraminiferal biocoenoses and sediment assemblages. The paucity of shelly macrofossils in the Blue Hill Shale of central Colorado and Kansas may reflect benthic dissolution (Hattin, 1962; Glenister and Kauffman, 1985).

The paucity of macrofossils through the upper shale member at Lohali and the occurrence of only arenaceous benthic foraminifera probably reflect a combination of influences in the offshore environment as regression proceeded. Reduced salinities,

moderate to high sedimentation rates of mud, increased turbidity and reduced water clarity, and reduced benthic ventilation as progradational shorelines to the north and south hindered circulation all probably had some effect on the marine biota with the approach of peak regression. The presence of *Lingula* in the upper shale member is consistent with our interpretation of reduced salinities (Gall, 1983). Gall (1983) also noted that lingulids can easily adapt to turbid waters or rapid sedimentation.

In addition to the effects of changing environmental conditions on the living animals, perhaps postdepositional changes also modified the original assemblages. The noncalcareous upper shale member contains more crystals of gypsum as veins and fracture fill than do the calcareous lower and middle shale members of the Mancos at Lohali Point (Kirkland, this volume). Kirkland also notes the occurrence of limonite (hydrated ferric oxide) and jarosite (hydrated iron sulfate) in the upper shale member. The occurrence of these three diagenetic mineral phases indicates the oxidation of sulfide (probably pyrite) and dissolution of calcite (e.g., Schnitker and others, 1980). We therefore suspect that dissolution may be partially responsible for the absence of a calcareous fauna in the upper shale member.

An increase in silt and sand content in the transition from the upper Mancos Shale to Toreva Formation has been interpreted as a transition from prodelta to delta-front deposits along a wave-dominated deltaic coastline (Franczyk, 1988). Arenaceous foraminifera occur as high as 196 m in samples examined in this study (the sample at 201 m is barren of foraminifera). Kaolinite again increases in abundance in the transition interval (Fig. 5), consistent with increased proximity to the encroaching shoreline (e.g., Edzwald and O'Melia, 1975; Gibbs, 1977).

CONCLUSIONS

1. We suggest that changes in salinity were the principal controls on the comings and goings of planktonic foraminifera in the Greenhorn Sea. A difference of only 3 to 5 ‰ may have been sufficient to cause either their "presence" or "absence."

2. The planktonic foraminiferal genus *Heterohelix* is believed to be an indicator of oxygen minimum zone conditions in the Cenomanian-Turonian Greenhorn Sea.

3. We suggest that an oxygen minimum zone (OMZ) developed within the water column over the Lohali Point site by *Neocardioceras* time (latest Cenomanian) and was associated with the incursion of warm water masses from the south. The OMZ persisted through the time of peak transgression, although it may have waned by late *Mammites* or earliest *Collignonicerias* time.

4. Peak transgression in the Black Mesa area is interpreted to have occurred during mid-early Turonian to earliest middle Turonian time, perhaps slightly later than in other parts of the seaway. These findings concur with those of Olesen (this volume) based on the foraminifera from the Blue Point (landward) section of Black Mesa.

5. An increase in the ratio of kaolinite to smectite with approach of peak transgression is believed to reflect changing

climatic conditions as latent heat was pumped into the seaway with the northward spread of warm waters. Increased temperatures and rainfall facilitated chemical weathering and the formation of kaolinite in terrestrial environments adjacent to the seaway. Changes in source area may also be partially responsible for the observed changes in clay mineralogy.

6. The middle shale member marks the onset of regression in the Black Mesa area. A dramatic reduction in foraminiferal abundance and in planktonic foraminiferal diversity and a gradual decrease in the kaolinite:smectite ratio reflect a subtle decrease in surface-water salinity and change in climate as warm waters were gradually displaced southward by cooler, slightly hyposaline waters. Dynamic shifts in water mass boundaries during the early phases of retreat may be responsible for the marked changes in foraminiferal assemblages through the middle shale member.

7. Calcareous foraminifera (planktonics and benthics) are virtually absent in the Hopi Sandy and upper shale members, but a fairly diverse arenaceous benthic foraminiferal fauna persists through both units, much like that of the Blue Hill Shale along the Colorado Front Range (Eicher, 1966). Foraminiferal and sedimentologic evidence argues against Hazenbush's (1973) model of intertidal conditions for the upper two-thirds of the Mancos Shale around Black Mesa. We support the depositional models of Kirkland (this volume), who interprets the Hopi Sandy and upper shale members as neritic deposits, first within reach of storm wave base and then below it as a result of renewed subsidence prior to progradation of the shoreline and deposition of the overlying Toreva Formation. The absence of calcareous foraminifera may be partially due to environmental factors: decreased salinity, probably coupled with elevated sedimentation rates and turbidity, reduced water clarity, and perhaps reduced oxygen. However, taphonomic and/or diagenetic processes, particularly dissolution, are also suspected to be partially responsible for the absence of calcareous taxa in the upper shale member.

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