

# *Oligocene-Miocene lacustrine rudite-dominated alluvial-fan delta, southwest Montana, U.S.A.*

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## ABSTRACT

Facies continuum and facies profiles from outcrops and drill cores in the Tertiary Medicine Lodge beds were analyzed in the Medicine Lodge and Horse Prairie basins in Southwest Montana, U.S.A. These beds consist of interbedded conglomerates, sandstones, siltstones, mudstones, limestones, carbonaceous shales, and coals that make up coarsening- and fining-upward megasequences.

The study indicates that the Medicine Lodge beds were deposited in freshwater lake alluvial-fan delta and short-headed stream delta environments. The lake, which probably occurred in an asymmetrical protobasin formed during Laramide deformation and ancestral to the Medicine and Horse Prairie basins, was initially infilled by coal-forming, short-headed stream deltas and littoral lacustrine carbonate platforms along its steeply dipping margin.

This early stage of infilling was characterized by rapid basin subsidence, which was accompanied by lake expansion, and by subdued provenance tectonism developed west-southwest of the protobasin. The late stage of lake infilling continued along the steeply dipping margin of the protobasin where east-northeast flowing alluvial-fan delta complex formed an aggrading, subaerial alluvial fan and a prograding, subaqueous delta front. The alluvial-fan delta complex was bounded to the south by a lacustrine coastal plain that was drained by coal-forming, short-headed streams deltas and to the immediate north by lacustrine littoral carbonate platforms that supported stromatolite

bioherms. This stage of lake-basin infilling was marked by intense provenance uplifts and was accompanied by moderate basin subsidence and local lake expansion with marked lake-level fluctuations. Climate did not significantly influence fluctuations of the lake level since the lake remained freshwater and open throughout infilling. However, microclimate (e.g., rain shadows) may have controlled coal distribution in the Medicine Lodge basin part of the protobasin. Humid-temperate climate is indicated by common presence of debris flows on the alluvial fan, which were triggered by intense rainfall.

Thus, the lake protobasin is a microcosm of clastic, carbonate and organic environments, hydrodynamics, provenance tectonism, climate, and basin subsidence that greatly influenced facies variations.

**Key words:** Rudite alluvial-fan delta, lacustrine alluvial-fan delta, Oligocene-Miocene rudites, rudites, coal-bearing alluvial-fan delta, short-headed fluvial-deltaic systems, lacustrine, stromatolites, microclimate, provenance tectonism, basin subsidence, debris flows, facies continuum.

## RESUMEN

Se analizan los perfiles y los paneles continuos de facies obtenidos a partir de afloramientos y testigos de sondeos de las capas Terciarias de Medicine Lodge en las cuencas de Medicine Lodge y Horse Prairie del suroeste de Montana (USA). Estas capas consisten en alternancias de conglomerados, areniscas, limolitas, lutitas, arcillas carbonosas y carbones, dispuestas en megasecuencias granocrecientes y granodecrescientes.

El estudio indica que las capas de Medicine Lodge se depositaron en ambientes de lagos de agua dulce, delta de abanico aluvial y deltas de ríos de cabecera corta. El lago, que probablemente se situaba en una protocuenca asimétrica generada durante la deformación Larámide y ancestral de las cuencas de Medicine Lodge y Horse Prairie, se rellenó por deltas de ríos de cabecera corta donde se formaba carbón y en plataformas carbonatadas lacustres litorales en las márgenes empinadas del lago.

Este estadio temprano de relleno se caracterizaba por una rápida subsidencia de la cuenca, acompañada de expansión del lago y de tectónica reducida de las áreas fuente al oeste-suroeste de la cuenca. El relleno continuó, en un estadio posterior, en los márgenes abruptos de la protocuenca, donde un complejo de fan delta aluvial que fluía hacia el este-noreste formó un abanico aluvial subaéreo agradacional y un frente deltaico subacuático progradante. El complejo de fan delta aluvial estaba limitado al sur por una llanura costera lacustre drenada por deltas de ríos de cabecera corta e, inmediatamente hacia el norte, por plataformas carbonatadas litorales lacustres con biohermos estromatolíticos. Este estadio del relleno lacustre estuvo marcado por intensos

levantamientos del área fuente acompañados de una subsidencia moderada de la cuenca y de expansión local del lago, con marcadas fluctuaciones del nivel del agua. El clima no influyó apreciablemente las fluctuaciones del nivel, puesto que el lago permaneció con agua dulce y abierto durante todo el relleno. Sin embargo, los microclimas (por ejemplo, sombras de lluvia) pudieron controlar la distribución de carbón en la parte de la protocuenca correspondiente a la cuenca de Medicine Lodge. El clima era templado-húmedo pues en los abanicos aluviales se encuentran, con cierta frecuencia, debris flows disparados por las intensas lluvias.

Así pues, la protocuenca lacustre es un microcosmos de ambientes clásticos, carbonatados y orgánicos, hidrodinámica, tectónica en el área fuente, clima y subsidencia de la cuenca que influyeron mucho sobre las variaciones de facies.

**Palabras clave:** Fan delta aluvial de ruditas, fan delta aluvial lacustre, ruditas Oligoceno-Mioceno, ruditas, fan delta aluvial con carbón, sistemas deltaicos de cabecera corta, lacustre, estromatolitos, microclima, tectónica en el área fuente, subsidencia de la cuenca, debris flow, paneles de facies.

## INTRODUCTION

Siliciclastic sediments deposited at lake and sea margins are transported by rivers either as bedload, suspended load or combination of both. Bedload-prone rivers of alluvial fans (stream- and debris-flow types) that prograde into a lake or sea level, form alluvial-fan deltas dominated by rudite and/or arenite lithofacies (Nemec & Steel, 1988). Rudite-dominated alluvial-fan deltas that formed in marginal marine environments of compressional tectonic basins have been described by Killick (1988) and Marzo & Anadón (1988). The subaerial part of these alluvial-fan deltas consists mainly of framework-supported conglomerates and subordinate matrix-supported conglomerates deposited by stream- and debris-flows, respectively. The subaqueous part of these alluvial-fan deltas comprises mainly sandstones deposited by delta-front distributary channels and mouth bars, and beach-shorefaces.

Despite high sediment discharge on alluvial-fan deltas, it is not unusual to find carbonate lithofacies associated with coarse clastic lithofacies. Dabrio & Polo (1988) reported lithofacies associations of alluvial-fan delta siliciclastics with shallow marine patch- and fringing-reef carbonates. Where alluvial-fan deltas prograded into offshore marine environments, rudite and arenite lithofacies intertongued with and were overlain by lagoonal and shallow-marine shelf micritic and bioclastic limestones (Flint & Turner, 1988; Wescott, 1988). The carbonate lithofacies either resulted from chemical precipitation during widespread marine transgression over alluvial-fan delta

deposits or developed on flanks of alluvial-fan deltas on the side updrift from longshore currents and point sources (i.e., Yallahs fan delta; Wescott & Ethridge, 1980).

Lakes are also settings in which siliciclastic lithofacies of alluvial-fan deltas are associated with carbonate lithofacies. However, carbonate precipitation develops in lakes only where sedimentation is not overwhelmed by detrital influx. Thus, carbonate buildup occurs in lake shoreline, mudflat, nearshore, littoral, and offshore environments removed from detrital point sources, such as from alluvial-fan deltas (Surdam & Wolfbauer, 1975; Link & Osborne, 1978).

This study investigates a different facet of carbonate buildup juxtaposed to a rudite-dominated alluvial-fan delta in a Tertiary freshwater lake in the Medicine Lodge and Horse Prairie basins, southwest Montana (Fig. 1). In addition, peats that were to become coals are juxtaposed to deposits of the alluvial-fan delta, where peat accumulation, like carbonate, was also controlled

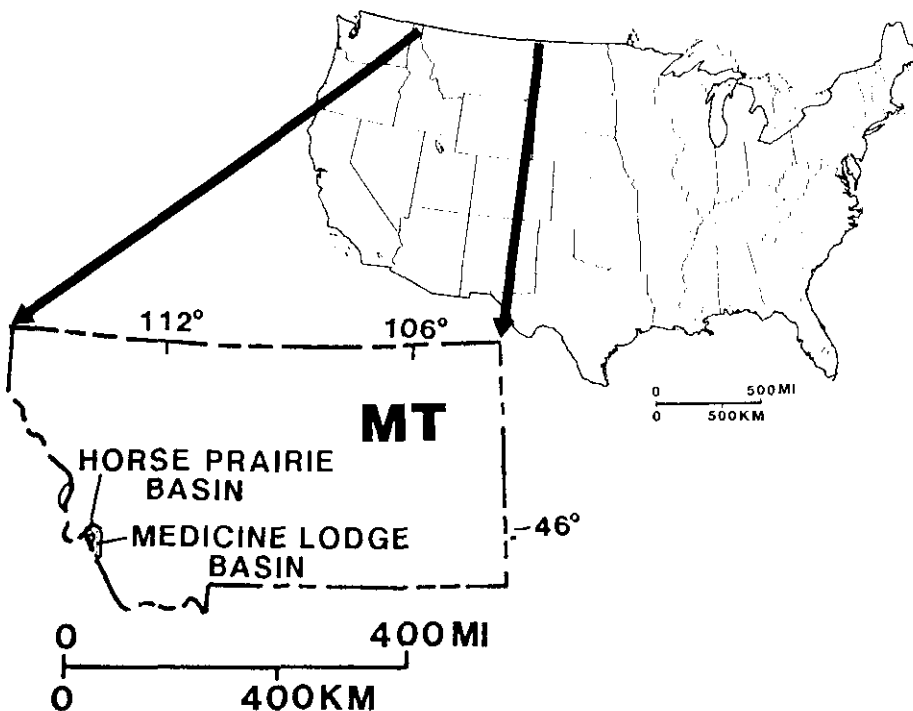


Fig. 1.—Map of the study area showing the Medicine Lodge and Horse Prairie basins in southwest Montana, U.S.A.

Fig. 1.—Mapa del área de estudio con las cuencas Medicine Lodge y Horse Prairie en el suroeste de Montana (U.S.A.).

by detrital-free conditions. The study describes the facies relationships and depositional processes of the coarse siliciclastic, carbonate, and organic deposits, whose modes of origin are in contrast to each other. The effects of provenance tectonism, basin subsidence, and lake fluctuations and expansions in relation to alluvial-fan delta sedimentation are also examined.

Methods of study included generalized lithofacies descriptions from measured sections that were used for a stratigraphic-framework cross section. In addition, detailed lithofacies descriptions from measured sections and drill cores were used to depict facies continuum (lateral facies associations) and facies profiles (vertical facies associations). Petrography of the limestones was analyzed for their mineral composition and diagenesis.  $\delta^{13}\text{C}$  isotope was analyzed to determine the origin (freshwater vs. saline water) of the limestones.

## GEOLOGIC AND TECTONIC SETTINGS

The basement, volcanic, and sedimentary rocks as well as the structural geology of the Medicine Lodge and Horse Prairie basins and surrounding uplifts have been mapped and described by M'Gonigle (1965, in press) (Fig. 2). The basement rocks consist of Archean granite gneiss and Proterozoic sandstones. These basement rocks are overlain by Paleozoic (Ordovician to Permian) and Mesozoic (Triassic and Cretaceous) sedimentary rocks mainly deposited in marine environments. These pre-Cenozoic rocks are unconformably overlain by Eocene volcanic rocks (tuffs, tuffaceous breccias, rhyolites, andesites, and basalts) that were deposited on an erosional surface cut across a terrane previously deformed by Sevier and Laramide uplifts and thrust faults (Fig. 2). During the late Laramide, which was characterized by compressional tectonism, the volcanic rocks were also locally uplifted and eroded. Probably at the same time, an asymmetrical protobasin was created ancestral to the Medicine Lodge and Horse Prairie structural basins. The asymmetry of the protobasin, steeply dipping along the west-southwest margin and gently dipping along the east-northeast margin, may have been caused by basement uplifts, which in turn, controlled facies distribution.

The protobasin served as a depocenter for siliciclastic (as much as 720 to 900 m thick) and/or carbonate (as much as 610 m thick) facies during the Eocene to Oligocene. These sedimentary facies are overlain by Oligocene to Miocene fine-grained siliciclastic facies (as thick as 2,300 m) comprising fish scale- and vertebrae-bearing tuffaceous mudstones, limestones, mudstones, and siltstones interbedded with rudite and arenite siliciclastic rocks and coals. The rudites are as much as 840 m thick and are accumulated on the steeply dipping margin of the asymmetrical protobasin (see Fig. 2). The finer-grained siliciclastics and carbonates were deposited toward the more gently dipping margin of the protobasin. The coals are subbituminous A to high-volatile B

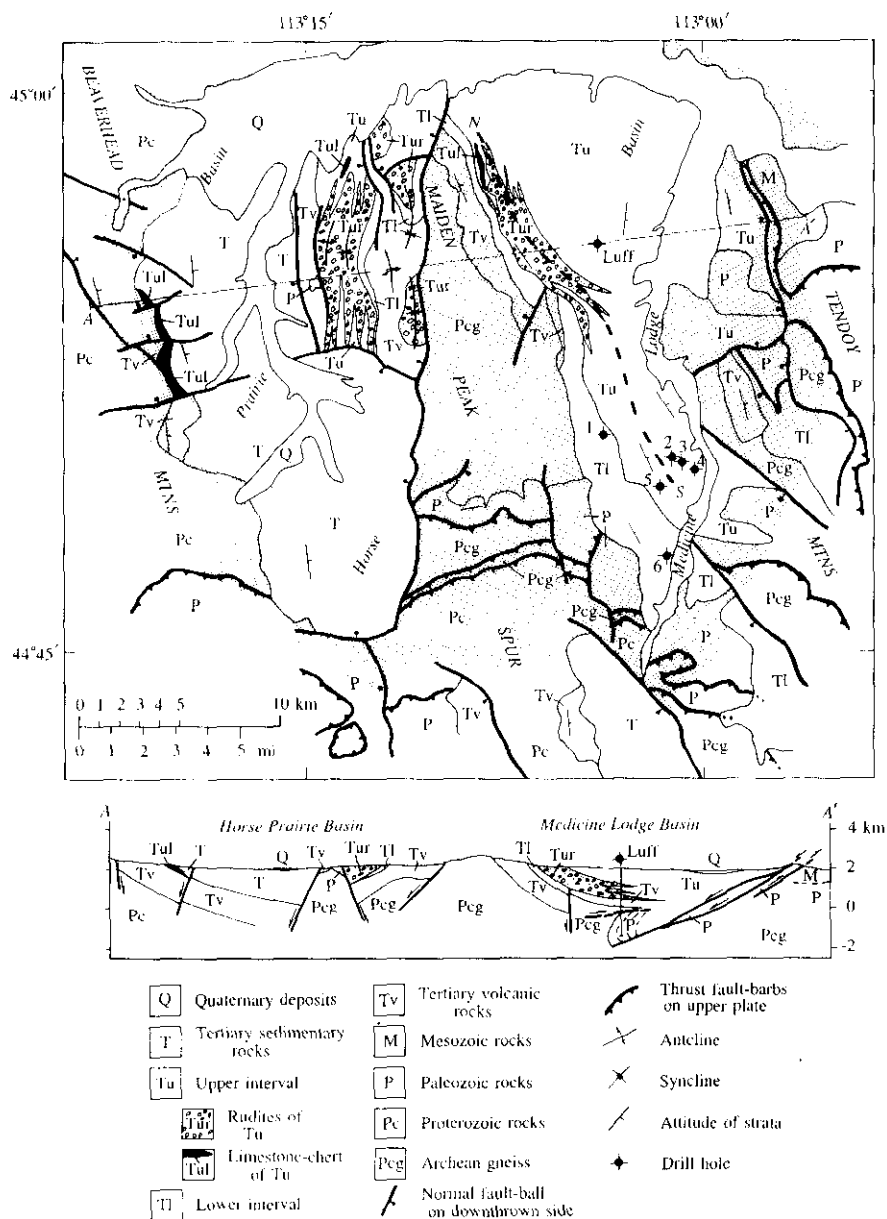


Fig. 2.—Geologic map of the Medicine Lodge and Horse Prairie basins and surrounding areas along with structural cross section (A-A'). Stratigraphic cross section N-S in Figure 3 is on right half of figure.

Fig. 2.—Mapa geológico las cuencas Medicine Lodge y Horse Prairie y áreas colindantes y corte estructural (A-A'). El corte estratigráfico de la figura 3 está en la mitad derecha de la figura.

bituminous, as much as 3 m thick, and generally have high ash (>15%) and high sulfur (>3%) contents (Dyini & Schell, 1982). The coal-bearing rocks, which are mainly in the Medicine Lodge basin, occur in the informally named Medicine Lodge beds (Scholten, Keonmon & Kupsch, 1955; M'Gonigle, Kirschbaum & Weaver, 1986).

The tectonic history of the Medicine Lodge and Horse Prairie basins and adjacent uplifts includes two episodes of deformation (Hait & M'Gonigle, 1988; M'Gonigle, Hait & Perry, 1990). The first episode of deformation was a compressional tectonism comprising eastward-directed, basement-involved thrust sheets of pre-Cenozoic rocks during the Sevier and early Laramide orogenies. The second episode of deformation included widespread late Early Miocene post-Laramide uplift and erosion that affected the pre-Eocene terrane and culminated the Tertiary depositional protobasin. The Tertiary sedimentary and volcanic rocks were tilted eastward and apparently translated several kilometers westward together with slices of the underlying pre-Cenozoic basement and sedimentary rocks (see Fig. 2). The Medicine Lodge and Horse Prairie structural basins were largely differentiated from the protobasin at this time. Subsequent high-angle normal «block» faulting, which continues in the region to the present, has completed the creation of the modern topographic basins and ranges in the area.

## STRATIGRAPHIC SETTING

The stratigraphic framework of the Eocene to Miocene Medicine Lodge beds at the western margin of the Medicine Lodge basin is shown in Figure 3. The stratigraphic study interval may be arbitrarily divided into lower and upper intervals based on dominant lithologies. These intervals are characterized by coarsening-upward megasequences (CUMS) and fining-upward megasequences (FUMS). CUMS are very thick (100-900 m) intervals consisting of fine-grained sediments in the lower part and coarse-grained sediments in the upper part. FUMS are very thick (100-150 m) intervals consisting of coarse-grained sediments in the lower part and fine-grained sediments in the upper part.

### Lower Interval

The lower interval (110 to 900 m thick) is dominated by fine-grained siliciclastics consisting of mudstones, siltstones, and silty sandstones. These siliciclastic rocks are interbedded with subordinate ostracode—and gastropod-bearing limestones, fish scale—and fish vertebrae-bearing tuffaceous mudstones, sandstones, carbonaceous shales, and coals.

Vertical variations within the lower interval may be characterized by three

coarsening-upward megasequences (CUMS1, CUMS2, CUMS3; see Fig. 3). At the southern part of the cross section, the 900-m-thick CUMS1 contains carbonates, tuffaceous mudstones, siltstones, and silty sandstones in the lower part and sandstones, siltstones, mudstones, carbonaceous shales, and coals in the upper part. Seven kilometers to the north, the 100-m-thick CUMS2 consists of mudstones, siltstones, silty sandstones in the lower part and sandstones, siltstones, mudstones, carbonaceous shales, and coals in the upper part. At the northern part of the cross section, the 150-m-thick CUMS3 includes tuffaceous mudstones, mudstones, siltstones, and silty sandstones in the lower part and sandstones, siltstones, mudstones, carbonaceous shales, and coals in the upper part.

Lateral variations within the lower interval show that the carbonates and fine-grained siliciclastics below the fish scale-bearing tuffaceous mudstones in the lower part of CUMS1 interfinger with the coal-bearing CUMS2 7 km to the north. This coal-bearing megasequence is overlain by the fish scale-bearing tuffaceous mudstones, which occur discontinuously at the same stratigraphic level farther north (Fig. 3). Here, the fish scale-bearing tuffaceous mudstones are overlain by a coal-bearing megasequence (CUMS3). This megasequence, in turn, is overlain by fish scale-bearing tuffaceous mudstones that are at the same stratigraphic level as the coal-bearing unit of CUMS1.

### **Upper Interval**

The lower 500 m of the upper interval is the focus of this study. This part of the upper interval is dominated by rudites and coarse-grained siliciclastics. The rudites and siliciclastics are interbedded with subordinate algal-, gastropod- and ostracode-bearing limestones, fish scale-bearing tuffaceous mudstones, mudstones, siltstones, silty sandstones, cherts, carbonaceous shales, and coals.

Vertical variations of the upper interval may be characterized by three coarsening-upward megasequences (CUMS4, CUMS5, CUMS6; see Fig. 3) and four fining-upward megasequences (FUMS1, FUMS2, FUMS3, FUMS4; see Fig. 3). At the southern part of the cross section (Fig. 3), a 320-m thick CUMS4 comprises fish scale-bearing tuffaceous mudstones, mudstones, siltstones, silty sandstones in the lower part and conglomerates, sandstones, siltstones, mudstones, carbonaceous shales, and coals in the upper part. Twelve kilometers to the north, FUMS1, FUMS2, FUMS3, and FUMS4, averaging 125-m thick, consist of conglomerates and sandstones in the lower part and silty sandstones, siltstones, mudstones, carbonaceous shales, and coals in the upper part. The northern part of the cross section (Fig. 3) contains CUMS5 and CUMS6, 200 m and 150 m thick, respectively. CUMS5 comprises algal-, ostracode-, and gastropod-bearing limestones, cherts, mudstones, siltstones, and silty sandstones in the lower part and conglomeratic



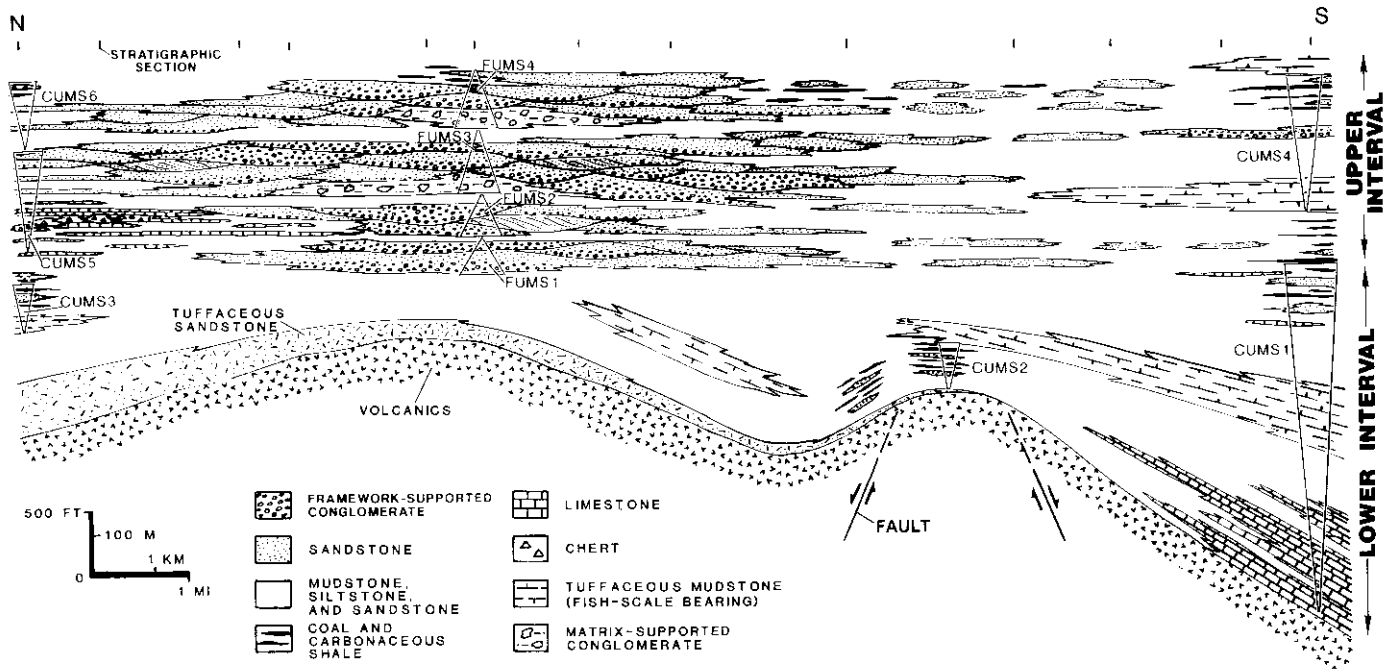


Fig. 3.—A cross section showing stratigraphic framework and facies continuum of the lower and upper intervals of the Medicine Lodge beds along the western margin of the Medicine Lodge basin. Interpolation between stratigraphic sections was by photogeology, photomosaic, and walking out the outcrops. Datum is the base of the lowermost FUMS and equivalent rocks. CUMS is a coarsening-upward megasequence. FUMS is a fining-upward megasequence.

Fig. 3.— Corte estratigráfico mostrando el amazon estratigráfico y el panel continuo de facies de los intervalos inferior y superior de las capas de Medicine Lodge en el margen oeste de la cuenca de Medicine Lodge. La interpolación entre las secciones estratigráficas se hizo mediante fotogeología, fotomosaico y recorriendo los afloramientos. El nivel de referencia (datum) es la base de la megasecuencia granodreciente (FUMS) más baja y las rocas equivalentes. CUMS: megasecuencia granocreciente.

sandstones, sandstones, and siltstones in the upper part. CUMS6 consists of mudstones, siltstones, and silty sandstones in the lower part and conglomerates, sandstones, siltstones, mudstones, carbonaceous shales, and coals in the upper part.

Lateral variations of the upper interval show that the fish scale-bearing tuffaceous mudstones in the lower part of CUMS4 interfingers to the north with FUMS3. The coal-bearing part of CUMS4 passes laterally northward into the FUMS4. The CUMS4 is overlain by fish scale-bearing tuffaceous mudstones, which in turn, are underlain by coal-bearing units (they are vertical continuum of CUMS1), which grade laterally to the north into the FUMS1 and FUMS2. At the northern part of the cross section (Fig. 3), the limestones and cherts of CUMS5 interfinger southward into the FUMS1 and FUMS2. Overlying CUMS5 is CUMS6, from which coal- and conglomerate-bearing units merge southward with the FUMS4.

### Interpretation

Based on the dominant lithologies of the lower and upper intervals and associated CUMS and FUMS, two major successions of protobasin infillings developed. The lower interval, dominated by fine-grained siliciclastics, freshwater ostracode- and gastropod-bearing limestones, and fish scale-bearing tuffaceous mudstones, makes up the initial protobasin lake infill. Infilling is characterized by quiet-water precipitation of chemical sediments and pelagic settling of fine-grained siliciclastics. Quiet-water infilling was accompanied by minor prograding systems as evidenced by deposition of the coal-bearing CUMS deposits. The thick basin fill (CUMS1) in the southern part of the basin may indicate relatively rapid subsidence in contrast to other parts of the basin margin.

The second succession of protobasin lake infill was an upward-shoaling event marked by FUMS deposits of the upper interval. Accumulation of the FUMS deposits indicates a localized aggrading system. That the rudites of this system grade distally into finer-grained, coarsening-upward siliciclastics suggests unconfined progradation of the aggrading system. Nonprogradational or abandonment areas served as platforms for freshwater carbonate precipitation (algal-, ostracode-, and gastropod-bearing limestones).

Fluctuation of base or lake level, which was probably in response to basin subsidence, is indicated by episodic occurrence of the fish scale-bearing tuffaceous mudstones. Widespread precipitation of freshwater limestones in both lower and upper intervals suggest that climate probably was not a significant factor in lake fluctuations since freshwater condition was maintained throughout the lake history and may have been an open body of water. These conclusions are supported by common occurrence of freshwater gastropods and ostracodes in the limestones. In addition,  $\delta^{13}\text{C}$  values PDB of the

limestones (14 samples from the lower and upper intervals), which range from -4.783 to 0.404, averaged -2.703 that falls within the average freshwater limestones observed by Hudson (1977) and Anderson & Arthur (1983). Basin subsidence may have favored repeated retrogradation. Stacked rudite-dominated aggradational sequences were probably controlled by episodic tectonic uplifts of the source terrane. Provenance uplifts may have influenced microclimates (e.g., rain shadows) favoring coal accumulation in wet, humid areas localized in the Medicine Lodge basin part of the protobasin.

## SEDIMENTOLOGIC FACIES ASSOCIATIONS

In order to determine the styles of sedimentation and ultimately the depositional processes, facies associations of various coarsening-upward and fining-upward megasequences of the lower and upper intervals were examined. In addition, carbonate facies associations of the upper interval was also analyzed. The facies associations are depicted in a detailed facies continuum (two-dimensional framework) and facies profiles (unidimensional framework).

### Lower Interval Facies Association

Facies continuum of the lower interval coarsening-upward megasequences is shown in Figures 4 and 5 (the coal-bearing units of CUMS1 and CUMS2, respectively). Comparison of the facies continuum indicates differences in the thickness, continuity, and arrangement of coal beds; thickness, lateral extent, nature of erosional contact, and geometry of sandstone bodies; and occurrence of carbonates and fish scale-bearing tuffaceous mudstones.

The coal beds of CUMS1 (Fig. 4) are as thick as 4.5 m (with numerous carbonaceous shale partings), as much as 0.55 km in lateral extent, and are arranged at random with beds juxtaposed to the sandstone bodies. The coal beds of CUMS2 are as thick as 1.5 m, as much as 0.25 km in lateral extent, and are arranged in zones separated by sandstone bodies. The sandstone bodies of CUMS1 are as thick as 10 m, as much as 0.45 km in lateral extent, have deep erosional bases, and are lenticular. The sandstone bodies of CUMS2 are as thick as 3 m, as much as 0.15 km in lateral extent, have shallow erosional bases, and are elongate. The coal-bearing units of the CUMS1 contain ostracode-bearing bioclastic and micritic limestones. The coal-bearing units of CUMS2 interfinger with and are overlain by fish scale-bearing tuffaceous mudstones.

Facies profiles that show detailed sedimentologic facies sequences in the coarsening-upward megasequences of the lower interval are shown in Figures 6A, 6B, and 6C. Figures 6A and 6B display facies profiles of the coal-bearing units of CUMS1. The facies profiles show interbedded sandstones, siltstones,

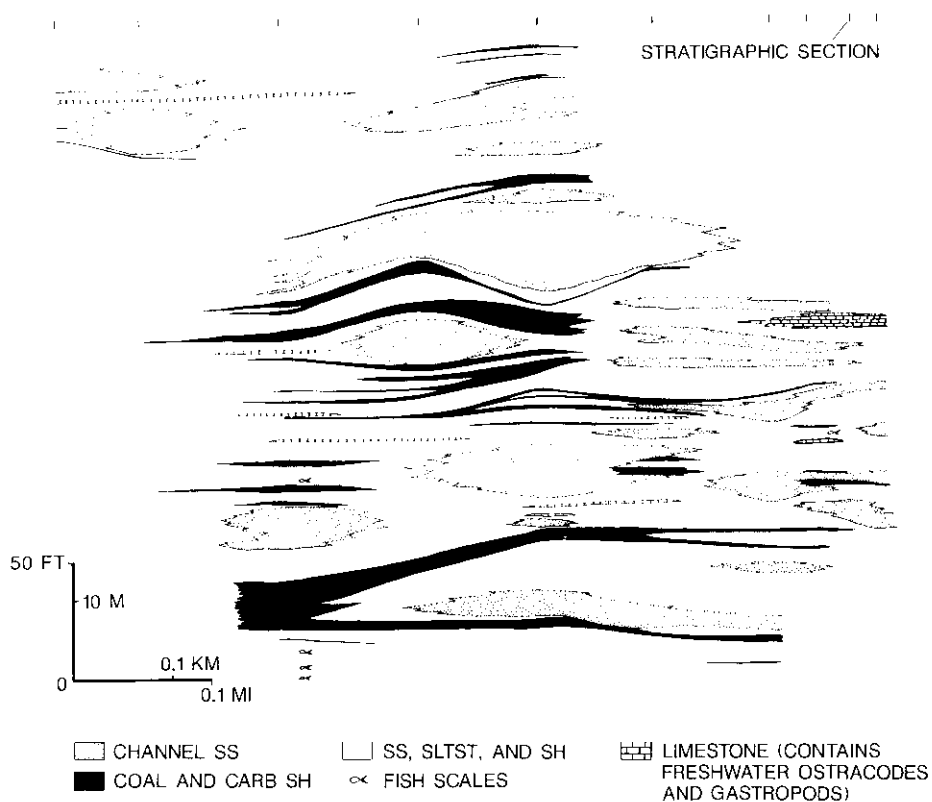


Fig. 4.—Facies continuum constructed from measured sections in the uppermost part of the coal-bearing units of CUMS1 (see Fig. 3). SS = sandstone, SLTST = siltstone, SH = shale, and CARB = carbonaceous.

Fig. 4.— Panel continuo de facies construido a partir de secciones medidas en la parte mas alta de las unidades con carbón de la megasecuencia granocreciente 1 (CUMS 1, ver figura 3). SS: arenisca; SLTST: limolitas; SH: arcillas; CARB: carbonoso.

mudstones, tuffaceous mudstones, limestones, carbonaceous shales, and coals. The facies profiles vary in the nature of the sandstone and coal lithotypes, and in sedimentary structures of the sandstone type.

The facies profiles (Figs. 6A and 6B) in the lower part of the coal-bearing units of CUMS1 are sandstone dominated. One type of sandstone is characterized mainly by bodies with deep erosional bases and some with multierosional bases, fining-upward grain size, and trough-crossbedded to convoluted lower and rippled upper parts (Fig. 7). Grain size ranges from medium to fine with some lag deposits of chert, shale, mudstone, and coal fragments. Another sandstone type (Fig. 8) is fine grained, has a sharp to gradational base and is capped by a unit with a shallow erosional base, and

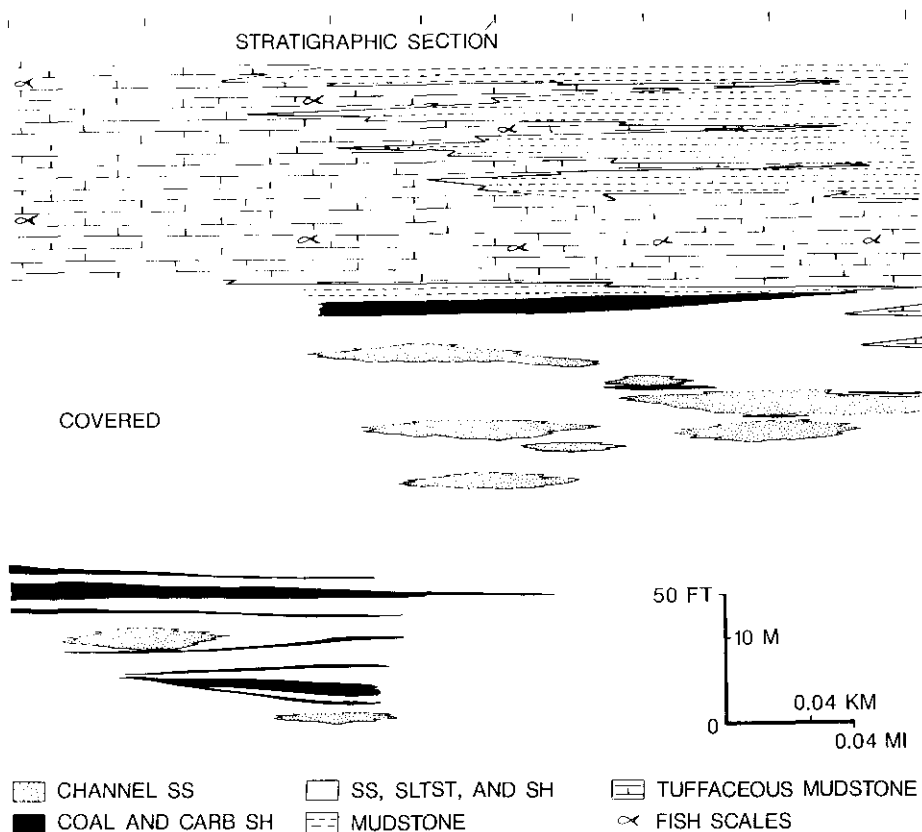


Fig. 5.—Facies continuum constructed from measured sections in the uppermost part of the coal-bearing units of CUMS2 (see Fig. 3). SS = sandstone, SLTST = siltstone, SH = shale, and CARB = carbonaceous.

Fig. 5.—Panel continuo de facies construido a partir de secciones medidas en la parte mas alta de las unidades con carbón de la megasecuencia granocreciente 2 (CUMS 2, ver figura 3). SS: arenisca; SLTST: limolitas; SH: arcillas; CARB: carbonoso.

coarsens upward. The vertical sequence of sedimentary structures of this sandstone type varies from dominantly rippled bodies or bodies with a rippled to burrowed lower part and with a trough-crossbedded and rooted upper part; the crossbedded unit often is underlain by an erosional surface. The coals in the lower part of the coal-bearing units of CUMS1 consist of dominantly woody (blocky, abundant woody structured fragments or more bright than dull bands) and subordinate fine laminated (more dull than bright bands) lithotypes. Bioclastic (ostra-code-bearing) and micritic limestones are commonly interbedded with the coal beds.

The facies profile (Fig. 6C) in the upper part of the coal-bearing units of

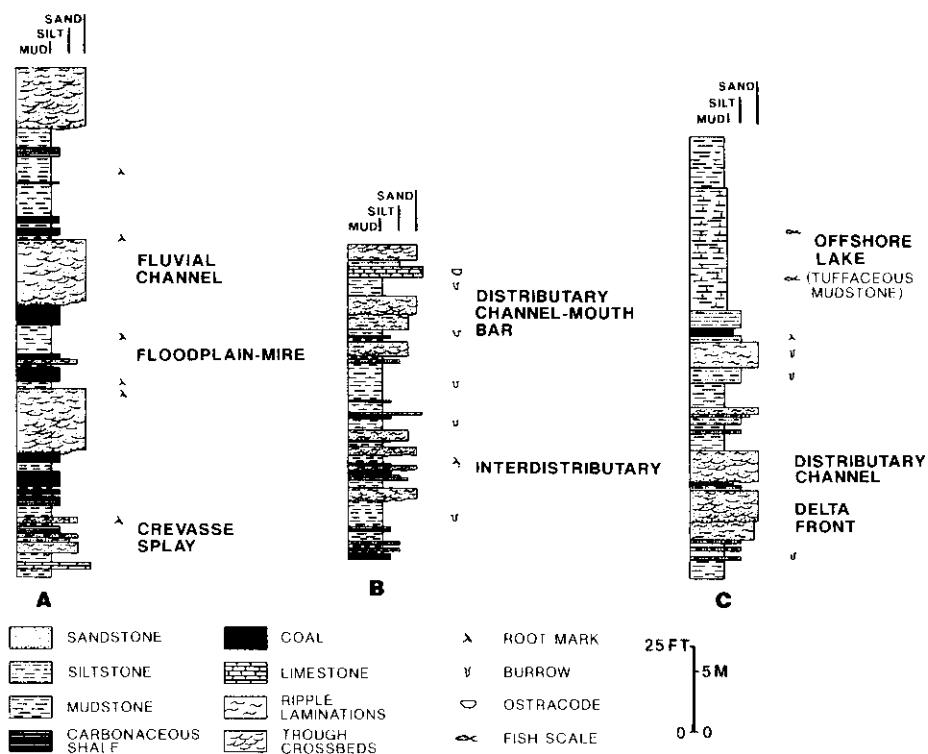


Fig. 6.—Facies profiles of the coal-bearing units of CUMS1 (A and B) and CUMS2 (C). Profile A exhibits fluvial deposits and profiles B and C illustrate deltaic and lake deposits.

Fig. 6.—Perfiles de facies de las unidades con carbón de las megasecuencias granocrecientes CUMS 1 (A y B) y CUMS 2 (C). El perfil muestra depósitos fluviales y los perfiles B y C ilustran los depósitos deltaicos y lacustres.

CUMS1 consist of mainly a coarsening-upward sandstone type. This sandstone is fine to very fine grained, has a sharp to gradational base and is sometimes capped by a unit with an erosional-base. The vertical sequence of sedimentary structures consists of dominantly ripple laminations and burrows, and includes a subordinate ripple-laminated and burrowed lower part and a trough-crossbedded upper part. The coals in the upper part of CUMS1 commonly contain a finely laminated lithotype interbedded with carbonaceous shale. The upper coal-bearing unit is overlain by fish scale-bearing tuffaceous mudstone (Fig 9).

Facies profiles of the coal-bearing units of CUMS1 are in contrast to those of the coal-bearing units of CUMS2. The CUMS2 coal-bearing units are characterized by abundant fine- to medium-grained, fining-upward sandstones with shallow erosional bases. The vertical sequence of sedimentary structures consists of a trough crossbedded lower part and a ripple-laminated upper part.



Fig. 7.—Multistacked, multierosional-based (dashed line), fining-upward sandstones (S1 and S2). Sandstones are trough crossbedded (T) in the lower part and rippled (R) in the upper part. Hammer for scale is 0.3 m long.

Fig. 7.—Apilamiento vertical de areniscas granodecrecientes (S1 y S2) con bases erosivas (líneas discontinuas). Las areniscas muestran estratificación cruzada en surco (T) en la parte inferior y laminación cruzada (R) en la superior. El martillo de escala mide 30 cm.

This sandstone type is commonly underlain by a fine-grained, coarsening-upward, ripple-laminated to trough-crossbedded sandstone. The coals are commonly composed of a woody lithotype with carbonaceous shale partings. The coal-bearing units of CUMS2 are overlain by and interfinger with the fish scale-bearing tuffaceous mudstones.

### Interpretation

The facies continuum and profiles of the coarsening-upward megasequences of the lower interval indicate prograding systems that were aggraded by fluvial and distributary channels (Elliott, 1986). Fluvial channel deposits are deep erosional-based, multierosional, lenticular, trough crossbedded to convoluted-rippled, fine to medium-grained, fining-upward sandstones with lag deposits. The distributary channel deposits are shallow erosional-based, elongate, trough crossbedded to rippled, fine-grained, fining-upward sandstones. Coarsening-upward, rippled to trough crossbedded



Fig. 8.—Coarsening-upward sequence of mudstone, siltstone, and sandstone (S1) capped by an erosional-based (dashed line) sandstone (S2) and underlain by a coal (C). S1 is ripple laminated and S2 is trough crossbedded.

Fig. 8.— Secuencia granocreciente de arcilla, limolita y arenisca (S1) con un nivel de arenisca (S2) de base erosiva (línea discontinua) a techo y carbón (C) a muro. S1 presenta laminación cruzada y S2, estratificación cruzada en surco.

sandstones underlying the distributary channel sandstones represent distributary mouth bar deposits. The thin package of distributary mouth bar and channel sandstones, and the channel depth/width ratio of 1:4-5 suggest drainages of small delta complexes probably fed by short-headed streams. The difference in relief of the erosional bases of the fluvial and distributary channels may be in response to their proximity to base level (lake level).

The common occurrence of thick woody coals in association with the fluvial channel sandstones suggests that mires in the fluvial setting were more favourable for organic accumulation from tree vegetation than were mires in the deltaic system. In addition, proximity of the deltaic mires to lake level that repeatedly fluctuated may have contributed to muddy characteristics (carbonaceous shale partings) of the deltaic coals. The random occurrence of coals juxtaposed to fluvial channel sandstones suggests coeval existence of mires and sediment-laden rivers. This is in contrast to the deltaic setting where coals occur as zones separated by distributary channel deposits indicating development of mires on abandoned deltaic complexes. The interfingering



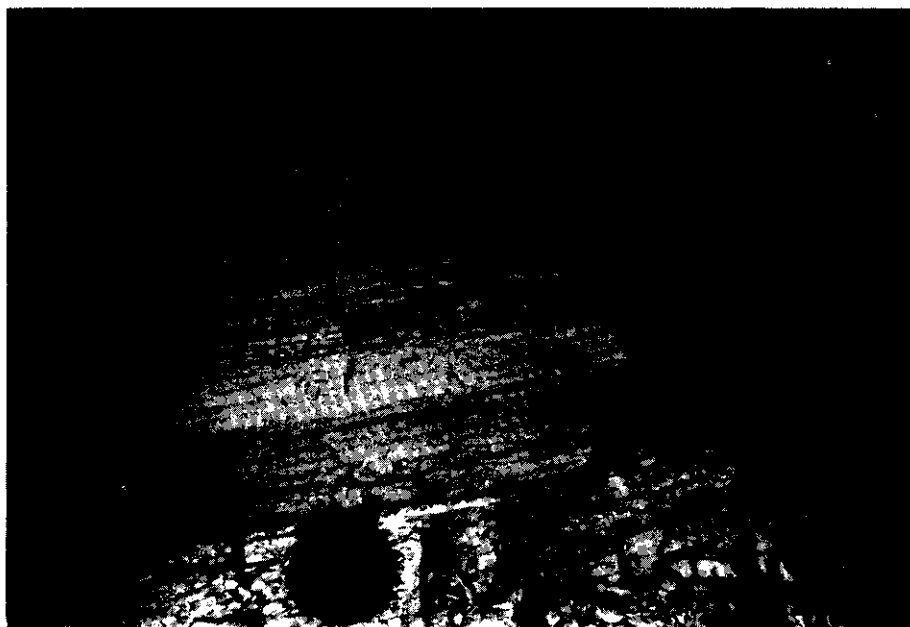


Fig. 9.—Laminated tuffaceous mudstone containing fish scales and fish vertebrae. Mudstone locally contains lenses of rippled (R) siltstone. Lens cap for scale is 5.6 cm in diameter.

Fig. 9.—Lutita tobácea laminada con escamas y vértebras de peces. Localmente, la lutita contiene laminación lenticular (R) de limolitas. El cubre objetivos mide 5.6 cm de diámetro.

with and capping by coal-forming deltaic complexes suggest widespread lake expansion and associated fluctuations of lake levels.

### Upper Interval Facies Associations

#### *Coal-Bearing Facies Association*

Facies continuum and profiles of the coal-bearing units of CUMS4 in the upper interval are shown in Figures 10 and 11. Figure 10, which shows the facies continuum of CUMS4, has characteristics similar to those of the lower-interval CUMS coal-bearing units. The coals are as thick as 3.5 m, are as much as 1.7 km in lateral extent, and are arranged in zones separated by thin sandstone bodies (as thick as 3.5 m and as much as 0.22 km in lateral extent) that have shallow erosional bases and that are lens shaped. However, sandstone bodies immediately above the upper coal zone (see Fig. 10) and below the lower coal zone exhibit elongate shapes (as thick as 6 m and as much as 0.8 km in lateral extent). In addition, the coal-bearing units of CUMS4 interfinger with and are overlain by fish scale-bearing tuffaceous mudstones.

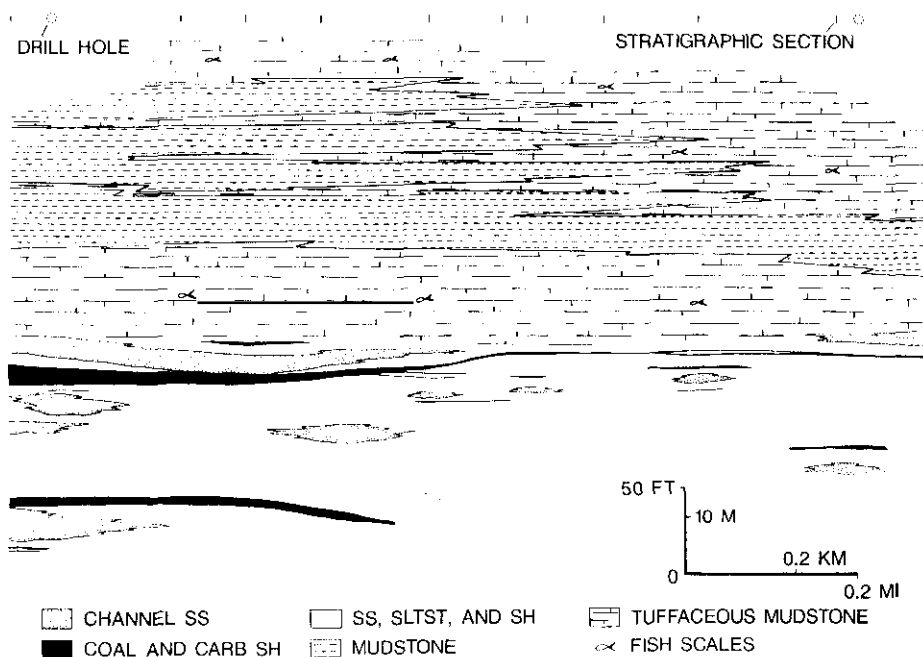


Fig. 10.—Facies continuum constructed from measured sections and drill holes 3 and 4 (see Fig. 2) in the coal-bearing units of CUMS 4 (see Fig. 3). SS = sandstone, SLTST = siltstone, SH = shale, and CARB = carbonaceous.

Fig. 10.—Panel continuo de facies construido a partir de levantamientos de series y de los sondeos 3 y 4 (véase su situación en la figura 2) en las unidades con carbón de la megasecuencia granocreciente CUMS 4 (ver figura 3). SS: arenisca; SLTST: limolitas; SH: arcillas; CARB: carbonoso.

The facies profiles associated with the coal-bearing units of the CUMS4, described from drill cores, are shown in Figures 11A and 11B. Figure 11A exhibits detailed facies sequences that include the upper coal zone. The coal zone is overlain by coarsening-upward, fine- to coarse-grained sandstones that are ripple to subparallel laminated, with a burrowed lower part and a massive to trough crossbedded upper part. These sandstones are underlain by interbedded burrowed and ripple-laminated sandstones and siltstones, which in turn, overlie burrowed mudstones. The lower part of the facies profile (Fig. 11A) consists of fining-upward, fine- to coarse-grained, erosional-based sandstone bodies. These stacked sandstone bodies are underlain by interbedded silty sandstones, siltstones, and mudstones that are burrowed and rippled to subparallel laminated.

Figure 11B displays a facies sequence that includes both the lower and upper coal zones of CUMS4. The upper coal zone, in contrast to the previous facies profile (see Fig. 11A), is directly overlain by heavily bioturbated silty sandstones, which in turn, pass upward into a stack of thin to thick, fining

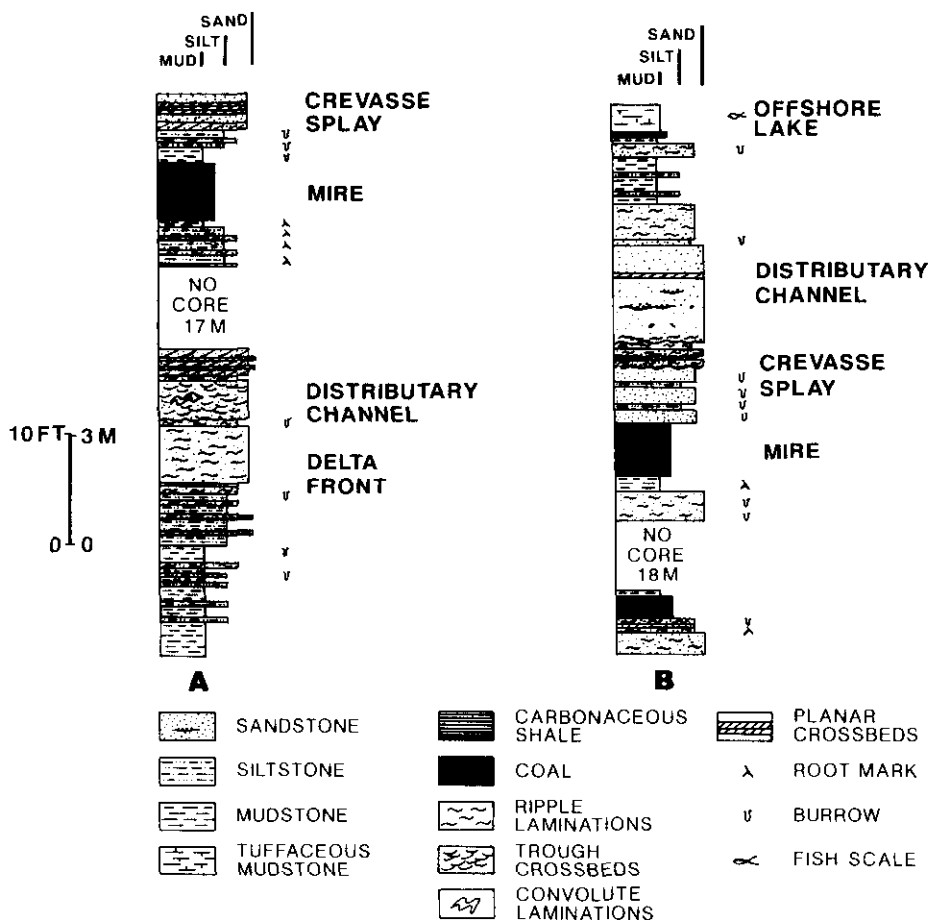


Fig. 11.—Facies profiles of coal-bearing units of CUMS 4 from cores of drill holes 2 (A) and 4 (B) (see Fig. 2 for location). Both facies profiles represent deltaic and lake deposits.

Fig. 11.—Perfiles de facies de las unidades con carbón de la megasecuencia granocreciente CUMS 4 establecido a partir de los testigos de los sondeos 2 (A) y 4 (B) (véase la situación en la figura 2). Ambos perfiles de facies representan depósitos deltaicos y lacustres.

upward, fine- to coarse-grained, erosional-based sandstone bodies separated by burrowed and rippled muddy siltstones. The lower sandstone bodies are composed of two thin, coarse-grained, rippled units interbedded with rippled and burrowed silty sandstones. The upper sandstone body is coarse grained with granule and coal spar lenses and is massive to sparsely trough crossbedded. This sandstone body grades upward into rippled and burrowed, fine-grained sandstones, which in turn, are overlain by interbedded rippled and burrowed silty sandstones, and fish scale-bearing tuffaceous mudstones.

### *Interpretation*

The facies continuum and profiles of the coal-bearing units of CUMS4 reflect characteristics of a deltaic complex similar to those in the lower interval (Elliott, 1986). The facies continuum indicates aggradation primarily by distributary channels as evidenced by the fining-upward, shallow erosional-based, and lens-elongate shaped sandstones. Most of these distributary channel deposits are single cut-and-fill events of waning flows (trough crossbedded to ripple laminated). However, some of these channel sandstones as shown in the facies profile (Fig. 11B) show multi-event cuts and fills. The facies sequence immediately above the upper coal zone indicates a succession of stacked, fining upward, erosional-based sandstones. The lower succession of this sequence exhibits alternation of small channels that may be attributed to amalgamation of crevasse-splay channel fills. The upper succession probably represents reoccupation of the crevasse system by a distributary channel.

The facies profile above the upper coal zone in a nearby corehole (Fig. 11A) shows a coarsening-upward sequence of burrowed mudstones and silty sandstones in the lower part and subparallel to trough crossbedded upper part, which represent crevasse-splay deposits. Some of the crevasse-splay deposits take the form of coarsening-upward delta-front deposits as depicted in the lower part of the profile. The delta-front deposits, consisting of burrowed, rippled silty sandstones and granule lenses in the lower part, reflect subaqueous infilling by traction currents, which occasionally were interrupted by density currents. The upper part of the delta-front deposits comprise multistorey distributary channel sandstones. The rapid textural (fine to granule sizes) and sedimentary structure (trough-planar crossbedded to rippled) variations of these channel sandstones may be explained by the alternation of high and low discharges (Smith, 1974).

The facies association of the coals and deltaic deposits suggests their accumulation in interdistributary settings. This is indicated by the vertical juxtaposition of crevasse-splay and channel facies with the coals. The interdistributary mires were probably low lying to have permitted overtopping by crevasse-splay sediments. However, prior to drowning by crevasse sediments, the peats, which occur in zones separated by channel-interchannel deposits, may have been accumulated in mires formed in detrital-free environments, perhaps on abandoned deltaic complexes.

### *Rudite and Arenite Facies Associations*

The facies continuum of FUMS 1-4 in the upper interval is shown in Figure 3. Detailed analysis of the facies continuum of FUMS3 show deep erosional-based, fining upward, pebble to boulder conglomerates and coarse-grained sandstones (Fig. 12). Although conglomerate bodies range from 1 to

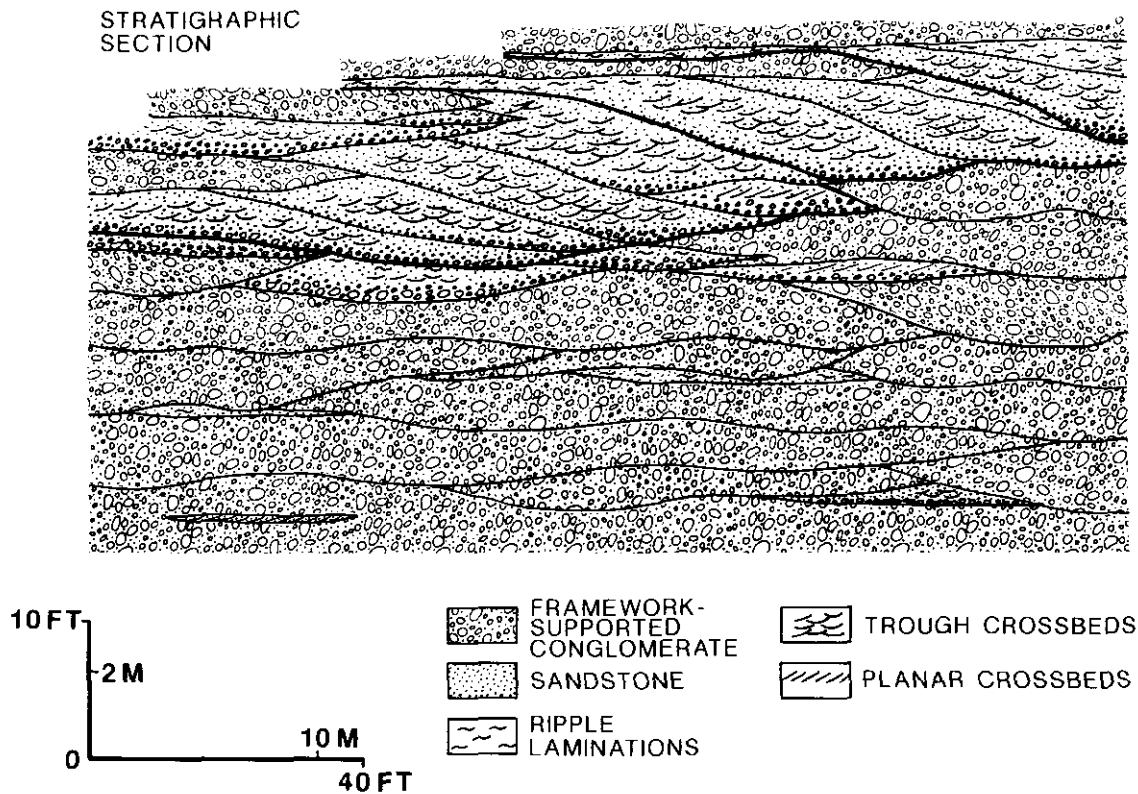


Fig. 12.—Facies continuum constructed from measured sections in FUMS3 (see Fig. 3) showing facies sequences and associations, and geometries of framework-supported conglomerates and conglomeratic sandstones.

Fig. 12.—Panel continuo de facies construido a partir de las series levantadas en la megasecuencia granodreciente FUMS 3 (véase la figura 3) mostrando las secuencias y asociaciones de facies y la geometría de los conglomerados clasto-soportados y las areniscas conglomeráticas.

10 m thick, a rudite zone may consist of multierosional conglomerate bodies as thick as 30 m. The multierosional conglomerate bodies have lenticular (as thick as 10 m and as much as 20 m in lateral extent) and elongate (as thick as 5 m and as much as 50 m in lateral extent) shapes that are randomly arranged. However, it is not uncommon to find lenticular bodies in the lower part and concentrated elongate bodies in the upper part of a rudite zone. The rudite zones are dominated by framework-clast-supported, tightly packed conglomerates (Fig. 13). The rudite zones commonly contain matrix-supported conglomerates, which mainly occur in the lower part of the FUMS and are juxtaposed to framework-supported conglomerates and conglomeratic sandstones (see Fig. 3). Figure 14 shows the disorganized subrounded clasts in a muddy sand matrix that lacks internal stratification found in the matrix-supported conglomerates. The conglomeratic sandstones, which contain basal lag deposits, consist of fining-upward, coarse- to medium-grained, trough-crossbedded to ripple-laminated units. Some of these sandstones show multierosional bases, range from 1 to 4 m thick, and exhibit mainly a lenticular shape (as thick as 3 m and as much as 30 m in lateral extent).

The facies continuum of laterally juxtaposed conglomerates and conglomeratic sandstones is shown in Figure 12. The lenticular to elongate-shaped conglomerates enclose a zone of conglomeratic sandstones. The sandstones, which interfinger with framework-supported conglomerates, display a lenticular shape consisting of three smaller en echelon bodies that are compartmentalized by sharp, inclined surfaces marked by silty sandstones generally extending from the upper to the lower parts of each body. Each sandstone compartment, in turn, is fining upward, is trough crossbedded to ripple laminated, and contains lag deposits. These compartmentalized sandstone bodies are multilateral and do not occur as commonly as sandstone bodies with multierosional bases.

The facies profile of the FUMS is typified in Figure 15. The conglomerates consist of a single body (as thick as 1 m) or multistorey bodies (as thick as 4.5 m) that fine upward, have shallow to deep erosional bases, and are framework clast supported. The clasts are composed mainly of Eocene volcanic (rhyolite, tuff, andesite, and basalt) and Proterozoic sandstone fragments with rare Paleozoic limestone, chert, dolomite, and sandstone fragments and Tertiary siltstone and shale fragments. The clasts are imbricated (strongly west-southwest dip), crudely normally graded (rarely reverse graded), and faintly crossbedded. Individual conglomerate beds show a bimodal to polymodal texture with a generally well-sorted framework of boulders and cobbles, and a matrix of pebbles. Some conglomerate bodies, however, show an unsorted framework of boulders and small pebbles and a sandy matrix. Clast shape in the conglomerate beds varies greatly with common spherical to rod-shaped clasts and rare disc-shaped clasts.

In addition, the facies profile (Fig. 15A) shows that the single to multistorey conglomerate bodies are interbedded with sandstones, siltstones, and

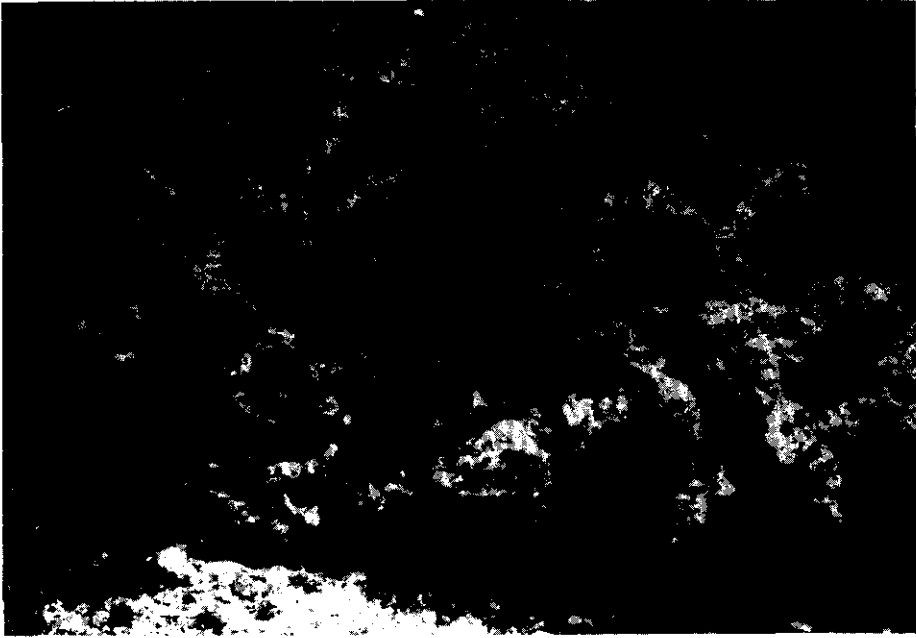


Fig. 13.—Framework clast-supported conglomerate showing crude imbrication (arrows show orientation) and a normally graded bed. Hammer for scale is 0.3 m long.

Fig. 13.—Conglomerado clasto-soportado con imbricación grosera (las flechas indican la orientación) y un estrato con granoclasificación normal. El martillo de escala mide 30 cm.

mudstones. Medium-grained, rippled sandstones commonly drape the conglomerates. Coarse- to medium-grained, fining-upward, erosional-based, trough-crossbedded to rippled sandstones occur as a single body scoured into rippled sandstones and mudstones. The mudstones, which are minor in amount, are silty and are capped either by conglomerates or sandstones.

Lateral facies equivalents of the FUMS are typified by a coarsening-upward facies profile shown in Figure 15B. This facies profile consists of graded, coarse-grained, trough-crossbedded and rippled sandstones interbedded with rippled siltstones and burrowed mudstones in the lower part. The upper part of the facies profile includes disorganized conglomerates, and both fining- and coarsening-upward sandstones interbedded with silty sandstones and carbonaceous shales. The disorganized conglomerates are poorly sorted and consist of subrounded boulders to pebbles floating in a muddy sand matrix that exhibits some convolutions but generally lacks internal structures. The coarsening-upward sandstone is coarse to medium grained, and is subparallel, tabular crossbedded in the lower part and trough crossbedded to rippled in the upper part. The fining-upward sandstone is coarse to medium grained and generally is trough crossbedded in the lower



Fig. 14.—Matrix-supported conglomerate showing outsize boulders «floating» in sandy mudstone. Hammer for scale is 0.3 m long.

Fig. 14.—Conglomerado soportado por la matriz con clastos de tamaño excesivamente grandes «flotando» en la lutita arenosa. El martillo de escala mide 30 cm.

part and rippled to rooted in the upper part, and is overlain by carbonaceous shale.

### *Interpretation*

The rudite-arenite facies associations reflect a dichotomy of aggrading and prograding systems. The rudite-dominated facies, consisting mainly of stacked, fining-upward conglomerates, represents alluvial-fan (subaerial part of the alluvial-fan delta) deposits. The succession of rudite-dominated megasequences (FUMS) suggests vertical accretion in a confined alluvial-fan system. That these rudite-dominated facies were deposited in stream and debris flows are indicated by the rock fabric. Conglomerates deposited by a stream flow are characterized by framework-supported clasts whereas conglomerates deposited by a debris flow are characterized by matrix-supported clasts.

The clast imbrication and grading suggest tractional currents in a channelized flow as evidenced by the erosional bases of the conglomerates. The west-southwest dipping clasts of the imbricate structure indicate transport to the



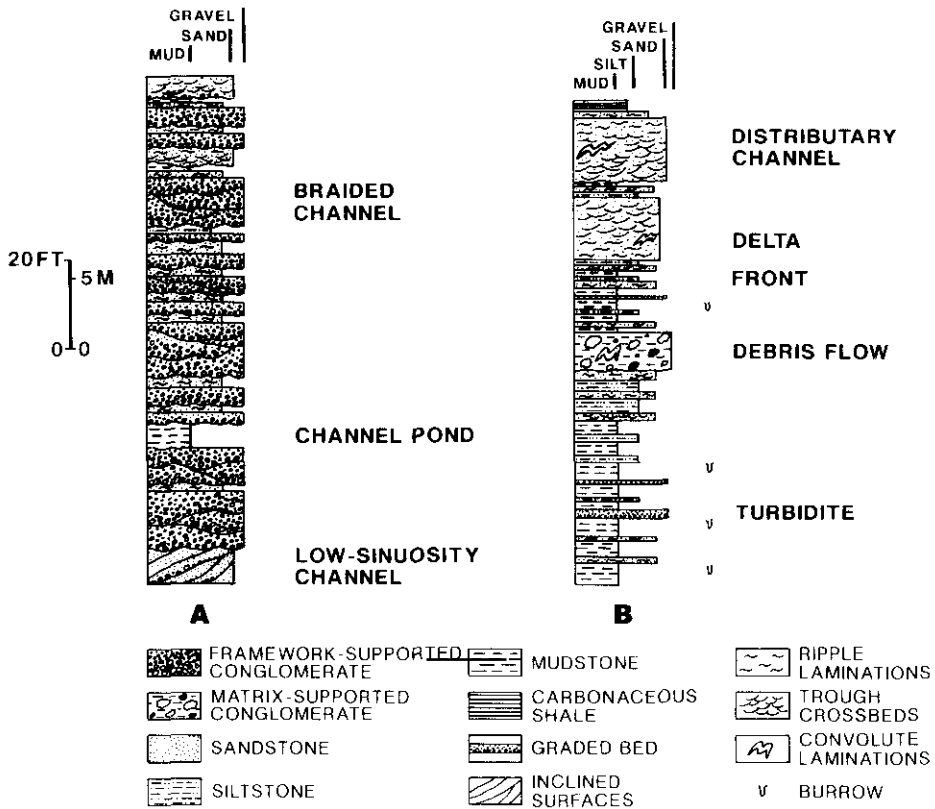


Fig. 15.—Facies profiles of the proximal (A) and distal (B) FUMS, which reflect deposits of aggrading braided stream and delta front complexes, respectively.

Fig. 15.—Perfiles de facies de las megasecuencias granodecrecientes proximales (A) y distales (B) que reflejan (respectivamente) depósitos de complejos de corrientes trenzadas agradantes y de frente deltaico.

east and northeast. The flashy, highly variable discharge of the channels is reflected by the rippled sandstone caps of the conglomerates and the extremely low discharge or ponding in the channels is represented by the mudstone caps. The fining-upward characteristic of the conglomerates may reflect gradual infilling of active channels by migrating gravel bars during floods. The multistorey conglomerates represent deposits of laterally shifting, diverging, and converging channels such as in a broad-belt braided stream.

The matrix-supported conglomerates are debris or mass flow deposits (Bull, 1977; Heward, 1978). Their general lack of internal structures suggests deposition by cohesionless, viscous mass movement. The fluidized matrix and dispersive pressure from the interaction of the clasts are important mechanisms in debris flows (Pierson, 1981; Lowe, 1982). Debris flows

probably originated from deceleration of heavy sediment-laden stream floods as they spread on the alluvial fan surface from proximal feeder channels or canyons (Lawson, 1982; Nemeč & Steel, 1984). The presence of outsize boulders in the matrix-supported conglomerates may indicate short distance of transport from proximal fan areas or canyons. That is, subrounded nature of these boulders probably reflects excavation and incorporation of previously deposited stream gravels in the load of the debris flows. Common occurrence of debris flows in the lower part of the FUMS may suggest development of the alluvial fan in a humid-temperate climate in which they were triggered by intense rainfall (Pierson, 1980; Kochel & Johnson, 1984). This climatic factor may have been enhanced by episodic tectonic uplifts as indicated by the two debris-flow deposits.

The sandstones interbedded with the conglomerates of the rudite-dominated facies occur as either a single body or as compound bodies. The single sandstone body with an erosional base, trough crossbeds, ripple laminations, and which fines upward, is attributed to stream-bed accretion above or marginal to gravel bars during waning flow stages. The compound sandstone bodies, which contain compartmentalized units separated by inclined surfaces, may be explained by lateral shifting of sandy braided channels during low-flow stages. Thus, these braided channels suggest development in a broad, low-sinuosity channel complex with migrating sand bars.

The rudite facies association is particularly indicative of provenance uplifts probably found west and southwest of the protobasin. The rudites contain clasts of Proterozoic sandstones that are present to the south and west of the Maiden Peak Spur, but generally lack clasts of the Archean gneiss common to the spur and the Tendoy Mountains (see Fig. 2). Additional evidence is provided by imbricate structures with west to southwest-dipping clasts that indicate point sources from these directions and transport to the east and northeast directions.

The rudite-dominated facies lose their «monofacies» characteristics, laterally passing into mixed conglomerates, sandstones, siltstones, mudstones, and carbonaceous shales as shown in Figure 15B. These coarsening-upward downfan deposits, which display a lower part of interbedded granule to fine grained, rippled, and graded sandstones, siltstones, and burrowed mudstones indicate subaqueous deposition in a prodelta of the alluvial-fan delta. Intercalation of granule, graded, and rippled sandstones in the lower part of these deposits suggests transportation by density currents alternating with bottom traction currents. The burrowed mudstones indicate pelagic settling of fine sediments that were reworked by bottom-dwelling organisms. The matrix-supported conglomerates immediately above the fine-grained sediments reflect a subaqueous debris-flow deposit (turbidite) similar to submarine fans (Normark, 1978; Stow, 1981). These chaotic turbidites were dispersed by turbidity currents on the delta-front slope. The succeeding deposits overlying the turbidite are coarsening-upward and fining-upward

sandstones capped by a carbonaceous shale. The coarsening-upward, sharp-based, ripple-laminated to trough-crossbedded sandstone represents a delta-front facies of the subaqueous alluvial-fan delta. The fining-upward, erosional-based, trough-crossbedded to ripple-laminated sandstone is a distributary-channel facies of the subaqueous alluvial-fan delta. Upward shoaling of the alluvial-fan delta is indicated by the coarsening-upward sequence capped by carbonaceous shale.

#### *Carbonate-Chert Facies Association*

The facies continuum and profile of the carbonate-chert facies and associated detrital facies are shown in Figures 16 and 17. The facies continuum (Fig. 16) consists of interbedded limestones, cherts, mudstones, siltstones, and sandstones. The limestones, which are commonly micritic (microcrystalline calcite) and biomicritic (containing greater than 10% bioclasts of freshwater gastropods and ostracodes; Figs. 18A and 18B), are thin to thick bedded (a few cm to 0.3 m). Subordinate amounts of the limestones are pelmicrite and oomicrite with oncoids (Figs. 18C, 19, and 20). The limestones also are either partly or wholly replaced by chert and chalcedony as shown in thin sections (Figs. 18A to 18D). The bedded limestones contain chert and chalcedony nodules and lentils parallel to bedding. The chertified, bedded limestones interfinger with partly or wholly chertified limestones that are mound shaped (as thick as 17 m and as much as 175 m in lateral extent; Fig. 21). The mound-shaped, chertified limestones contain undulating algal laminae (stromatolites; Figs. 18D and 22) and oncoids, and are arranged as an echelon bodies occurring at three tiers. The lower tier of mound-shaped bodies interfingers with erosional-based, trough-crossbedded sandstones and are underlain by interbedded burrowed siltstones and mudstones. The middle tier of mound-shaped bodies is enclosed and interfingered with bedded micrite and biomicrite limestones, and burrowed to rippled siltstones and mudstones. These bodies are underlain by erosional-based, trough-crossbedded sandstones, and burrowed to rippled siltstones and mudstones. The upper tier of mound-shaped bodies is mainly enclosed by and interfingered with micrite and biomicrite limestones. This complex of mound-shaped limestone-chert bodies, micrite and biomicrite limestones, mudstones, siltstones, and sandstones merges southward into the FUMS1 and FUMS2 (see Fig. 3). Similar mound-shaped, partly chertified limestone bodies are observed to interfinger with rudite-dominated facies along the eastern margin of the Horse Prairie basin. They also occur as an isolated 3-km-long complex along the western margin of the Horse Prairie basin (see Fig. 2).

The facies profile of the mound-shaped chertified limestones, micrite and biomicrite limestones, and associated terrigenous sediments is shown in Figure 17. The lower part of the facies profile is a terrigenous-dominated facies consisting mainly of interbedded burrowed mudstones and rippled to

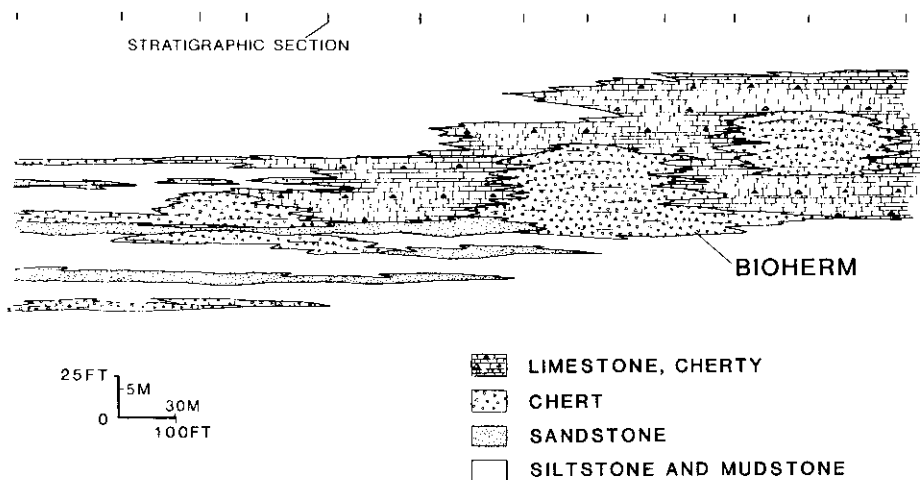


Fig. 16.—Facies continuum constructed from measured sections in the lower part of CUMS5 (see Fig. 3). It consists of limestone, chert, mudstone, siltstone, and sandstone, and shows the offset arrangement of the chertified stromatolite bioherms.

Fig. 16.—Panel continuo de facies construido a partir de secciones medidas en la parte inferior de la megasecuencia granocreciente CUMS 5 (ver figura 3). Se compone de caliza, sílex (chert), arcilla, limolita y arenisca y muestra la disposición en offset de los biohermos estromatolíticos silicificados.

burrowed siltstones, and coarsening-upward mudstones, siltstones, and trough-crossbedded to rippled sandstones. The coarsening-upward deposits are either overlain by basally-erosional, trough-crossbedded to rippled, medium- to coarse-grained sandstones or sharp-based, rippled, fine- to medium-grained sandstones. The lowermost coarsening-upward deposits of the facies profile are overlain by thin mound-shaped, chertified limestone bodies. The lower part of the terrigenous-dominated facies contains thin- to thick-bedded chertified micrite and biomicrite limestones. The upper part of the facies profile is a carbonate-dominated facies, which consists of thick, mound-shaped chertified limestone bodies enclosed by micritic and biomicritic limestones. The micritic and biomicritic limestones contain chert and chalcedony nodules.

### *Interpretation*

The facies association of the carbonate-chert facies and associated subordinate terrigenous facies represents precipitation of chemical sediments on a freshwater lake margin. Carbonate buildup, which was initially in a littoral environment, was intermittently encroached by a delta front-distributary channel complex as indicated by thin packages of coarsening-upward deposits

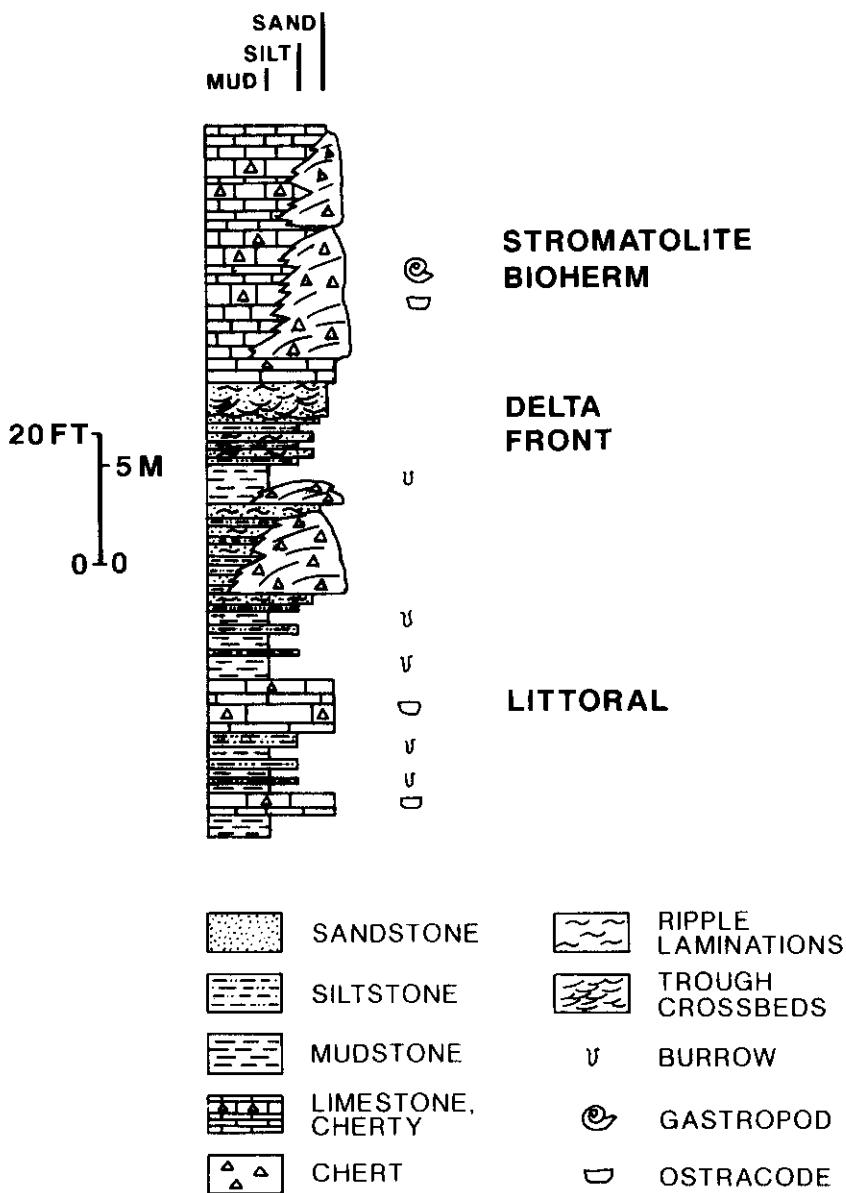
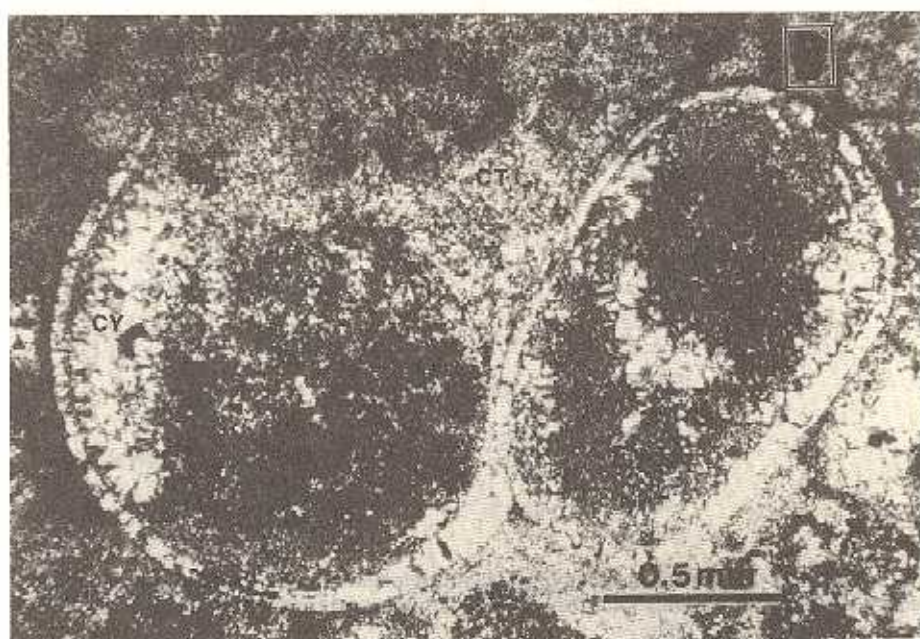
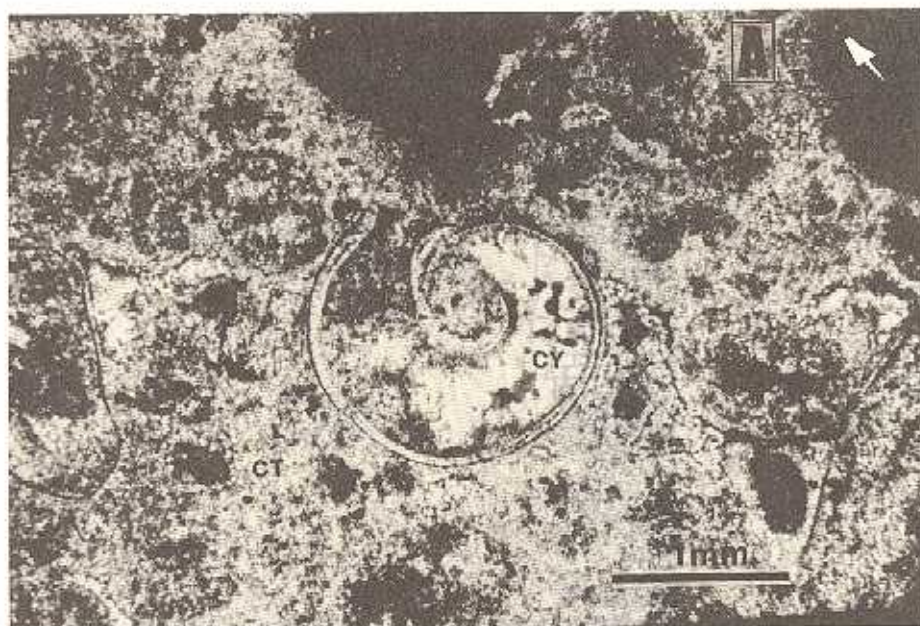


Fig. 17.—Facies profile of the stromatolite bioherm-dominated limestone, chert, and terrigenous sequence that reflects mainly lacustrine littoral carbonate precipitation in an abandoned delta front of the alluvial fan delta.

Fig. 17.—Perfil de facies de la secuencia de calizas dominadas por los biohermos estromatolíticos, sílex (chert) y terrígenos que refleja sobre todo la precipitación carbonatada lacustre litoral en un frente deltaico abandonado del fan delta aluvial.



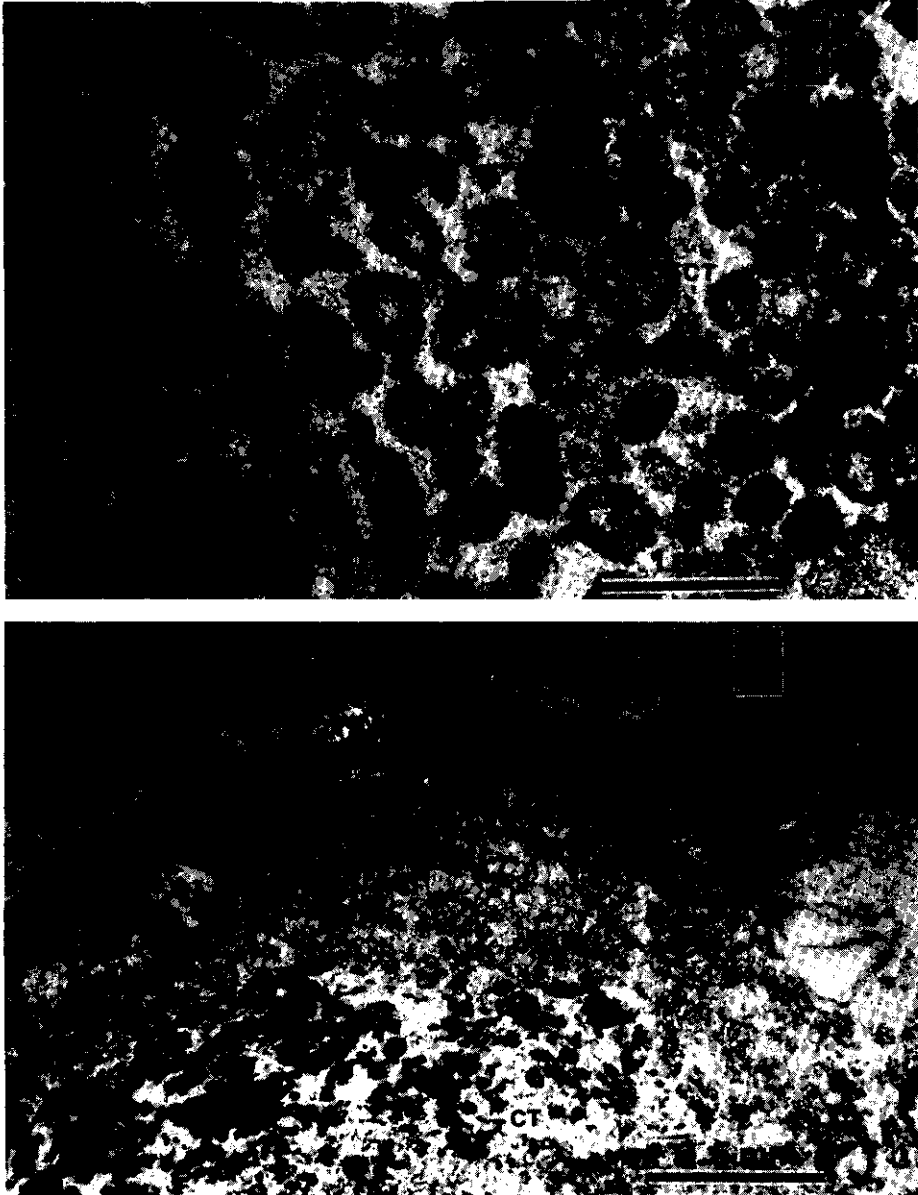


Fig. 18.—Photomicrographs showing gastropods (A), ostracodes (B), pelletoids (C), and algal laminae (D) in the cherty limestones and stromatolite bioherms. CY is chalcedony and CT is chert.

Fig. 18.— Microfotografías de gasterópodos (A), ostrácodos (B), peletoides (C) y laminaciones algales (D) en las calizas silíceas y en los biohermos estromatolíticos. CY es calcedonia y CT es chert

overlain by erosional-based, trough-crossbedded to rippled sandstones. These coarsening-upward deposits served as abandoned platforms for buildups of mound-shaped, stromatolite bioherms and micritic and biomicritic limestones in a littoral setting. That the littoral environment was subjected to some winnowing is indicated by the pelmicrite and oolitic-oncolitic limestones. Stromatolitic limestones and bioherms have been described from lake margins by Surdam and Wolfbauer (1975) and Riding (1979). The upward buildup of carbonates and reciprocal episodic development (three tiers) of stromatolite bioherms indicate local lake transgressions or expansions and fluctuations of lake levels. Expansion of the lake may be related to combined abandonment and local subsidence (due to sediment autocompaction) of the subaqueous alluvial-fan delta sediments outward of FUMS1 and FUMS2 alluvial-fan complex. This local lake expansion was short term since the carbonate buildup was terminated by sediments of the succeeding subaqueous alluvial-fan delta (FUMS3 and FUMS4).

Pervasive chertification of the stromatolite bioherms is due to replacement diagenesis of the carbonates during and/or after deposition. Original porosity must have been good in the bioherm stromatolites and probably developed during decay of the algae leaving spongy, porous structures. The abundance of volcanic rocks in the source terrane suggests that the primary source of authigenic silica was from rhyolites, andesites, basalts, volcanic glass, and tuffs. Silica dissolved from the volcanic rocks was probably transported by rivers and lake currents into littoral carbonate platforms.

## SUMMARY OF DEPOSITIONAL SETTING

The Medicine Lodge beds in the Medicine Lodge and Horse Prairie basins display facies attributes that exemplify a freshwater lake. The lake, probably formed in an asymmetrical protobasin, was infilled by sediments in two stages (Fig. 23): a) early-stage infilling by fine-grained deltas and associated short-headed, consequent streams, and b) late-stage infilling by coarse-grained alluvial-fan deltas and fine-grained short-headed stream deltas.

The early stage of infilling represented by the lower interval of the Medicine Lodge beds included deposition by east-northeast flowing short-headed, bedload and suspended-load fluvial-deltaic systems along the steeply dipping margin of the protobasin. Bedload sediments comprise the framework fluvial and distributary channel sands. Suspended-load sediments make up intraframework overbank-floodplain and interdistributary muds and silts. Coals formed in eutrophic lake-margin mires (interdistributary and abandoned deltaic lobes) and lacustrine coastal-plain mires (interchannel and abandoned channel ridges) of the fluvial system. The lake basin was infilled by nearshore, littoral, and offshore terrigenous sediments and lacustrine carbonates toward the gently dipping margin of the protobasin. The terrigenous sediments were





Fig. 19.—Tightly packed ooid grains locally common in the cherty, micritic limestone. Coin for scale is 2.54 cm in diameter.

Fig. 19.—Granos ooidales con empaquetamiento apretado que localmente, son frecuentes, en las calizas micríticas silicificadas. Diámetro de la moneda: 2.54 cm.

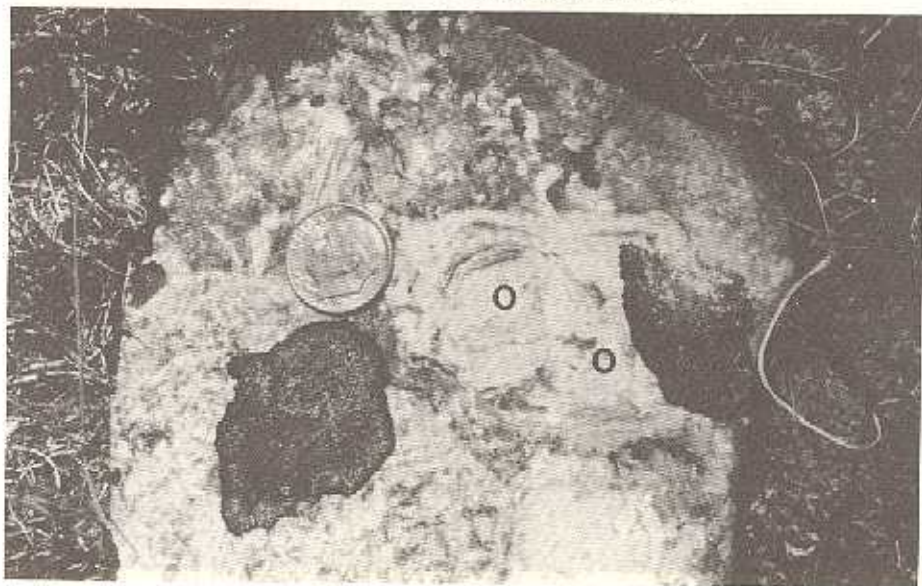


Fig. 20.—Algal-encrusted oncoids (O) found in the chertified stromatolite bioherms. Coin for scale is 2.54 cm in diameter.

Fig. 20.—Oncoides encostrados por algas (O) en los biohermos estromatolíticos chertificados. Diámetro de la moneda: 2.54 cm.



Fig. 21.—A mound-shaped, 8-m thick stromatolite bioherm permineralized by chert and chalcedony.

Fig. 21. Biohermo estromatolítico de 8 metros de espesor y forma de montículo permineralizado por chert y calcedonia.



Fig. 22.—Algal stromatolites (AS), which are a part of laterally-linked spheroids, in the chertified bioherms. The coin is 2.54 cm in diameter.

Fig. 22.—Estromatolitos algales (AS), que forman parte de esferoides relacionados lateralmente, en los biohermos chertificados. Diámetro de la moneda: 2.54 cm.

river borne and suspended-load sediments that bypassed bedload sediments of the fluvial-deltaic channels. Lake nearshore and littoral sands probably were reworked from deltaic sediments, which accompanied lake expansion and fluctuation of lake level. The occurrence of thick carbonates and discontinuous, fish scale-bearing sediments attests to the repeated widespread lake-level fluctuations and expansions as affected by basin subsidence. The freshwater origin of the lake, as evidenced by the presence of gastropods and ostracodes and  $\delta^{13}\text{C}$  values of the limestones throughout the stratigraphic interval, indicates insignificant role of climate to lake fluctuations. Offshore lake sedimentation was mainly from pelagic fallout and subordinately from turbidity or mass flows. The dominance of fine-grained sediments during the early stage of infilling perhaps indicates low-lying, tectonically passive source terrane found west and southwest of the protobasin.

The late stage of infilling represented by the upper interval of the Medicine Lodge beds is marked by east-northeast flowing alluvial-fan deltas and short-headed fluvial-deltaic systems along the steeply dipping margin of the protobasin and offshore lake deposition toward the gently dipping margin. The alluvial-fan delta is divided into subaerial (alluvial-fan) and subaqueous (delta-front) settings. The subaerial alluvial fan is characterized by aggrading gravelly and sandy braided streams. These east-northeast flowing braided streams exhibit flashy, high to low discharges. Occasional sediment-laden, debris flows interrupted normal braided-stream deposition in the proximal part of the alluvial fan. These mass movements may have originated from nearby tributary streams or feeder canyons and triggered by intense rainfall typified in humid-temperate areas. Deposition on the subaqueous delta front, which is comprised of distributary channels and mouth bars, and prodeltas, episodically was interrupted by turbidity currents and mass flows. The source of the alluvial-fan delta system was probably a tectonically active terrane characterized by uplifts west and southwest of the protobasin. Along the same lacustrine coastal plain, short-headed fluvial and deltaic systems drained into the lake. Coal-forming deltaic systems along the lacustrine coastal plain developed south of the alluvial-fan delta system. The source of these fluvio-deltaic systems was presumably a moderately tectonically active terrane. The tectonically uplifted provenance that was the source for the sediments of the alluvial-fan delta and short-headed, fluvio-deltaic systems may have promoted microclimatic rain shadows that enhanced coal development in the Medicine Lodge basin in a generally temperate-humid climate condition.

At the northern flank of the alluvial-fan delta, local buildup of carbonates marked by development of stromatolite bioherms formed in abandoned delta-front deposits of the alluvial-fan delta. Carbonate buildup in these littoral and lake-margin environments was enhanced by lake expansion (local transgression) and fluctuating lake levels. Water-borne, volcanic-derived silica partly or wholly replaced porous stromatolite bioherms probably penecontemporaneous and/or after deposition.

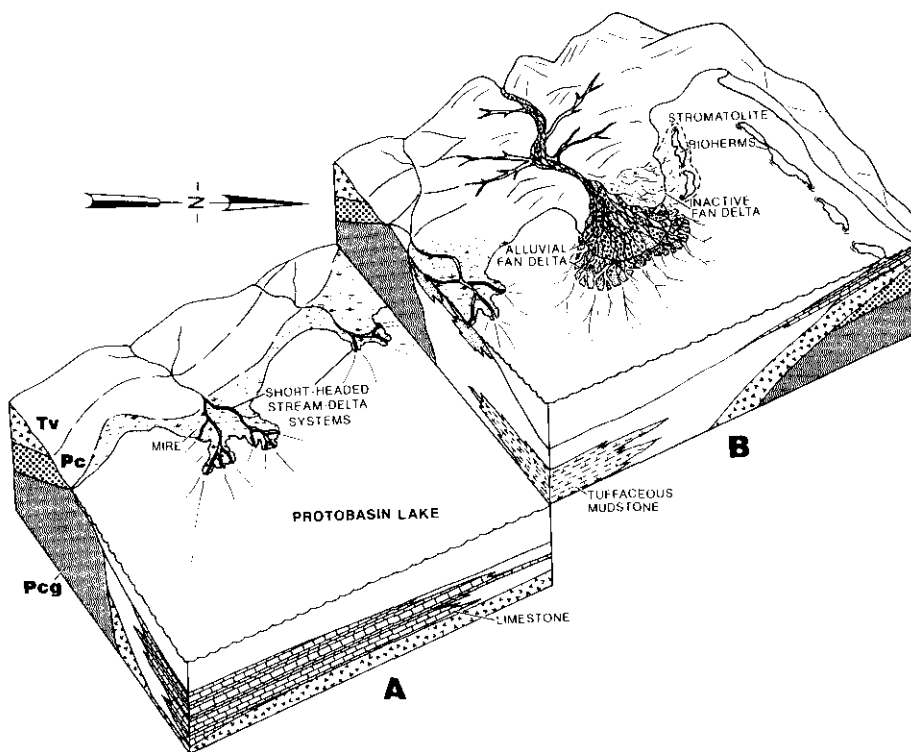


Fig. 23.—Diagrams of models showing short-headed streams and associated deltas and alluvial fan-delta system, which infilled the protobasin lake during Eocene (?) to Miocene time. Carbonates were mainly precipitated in detrital-free lacustrine littoral and bioherm environments. Deposition during the lower interval of the Medicine Lodge beds is represented by model A and during the upper interval by model B. PCG is Archean gneiss, PC is Proterozoic rocks, and TV is Tertiary volcanic rocks.

Fig. 23.—Diagramas de modelos que muestran los sistemas de ríos de cabecera corta y los deltas asociados y de fan delta aluvial que rellenaron el lago protocuenca entre el Eoceno (?) y el Mioceno. Los carbonatos precipitaron sobre todo en ambientes lacustres litorales sin detríticos y en biohermos. El modelo A representa el depósito durante el intervalo inferior de las capas de Medicine Lodge y el modelo B durante el intervalo superior. PCG: gnesis precámbricos; PC: rocas Proterozoicas; TV: rocas volcánicas Terciarias.

In summary, the protobasin of the Medicine Lodge and Horse Prairie basins is a microcosm of terrigenous, carbonate, and organic depositional environments, hydrodynamics, source-area tectonism, climate, and basin subsidence. Interdependence of these factors greatly influenced the lateral and vertical variations of the sedimentary facies. For this reason, detailed study of facies associations (facies continuum and profiles) is necessary to document the full range of sedimentary and tectonic settings.

## ACKNOWLEDGEMENTS

The original paper was reviewed by R. F. Dubiel of the U. S. Geological Survey, Denver, Colorado, and W. A. Wescott of AMOCO, Houston, Texas. I also thank R. Mas and C. J. Dabrio (Universidad Complutense, Madrid) for additional review of the final manuscript.

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*Manuscript received: 4 March 1991*

*Revision accepted: 29 May 1991*