Relationship of Unconformities, Tectonics, and Sea Level Changes in the Cretaceous of the Western Interior, United States[1]

R. J. Weimer
Colorado School of Mines
Golden, Colorado

Intrabasin tectonics and sea level changes influenced patterns of deposition and geographic distribution of major unconformities within the Cretaceous of the Western Interior. Nine major regional to near regional unconformities have been identified. Previous workers have related five of these unconformities to sea level changes and to well known regressive–transgressive cycles. The origin of the other four unconformities may be related either to tectonic movement or sea level changes.

The approximate dates for unconformities are estimated as follows (formations involved are in parentheses): (1) late Neocomian to early Aptian, 112 m.y. (base lower Mannville, Lakota, Lytle); (2) late Aptian–early Albian, ~100 m.y. (upper Mannville, Fall River, Plainview); (3) Albian, ~97 m.y. (Viking, Muddy, Newcastle, or J Sandstone); (4) early Cenomanian, ~95 m.y. (lower Frontier–Peay, and D); (5) Turonian, ~90 m.y. (base upper Frontier or upper Carlile); (6) Coniacian, ~89 m.y. (base Niobrara or equivalents); (7) early Santonian, ~80 m.y. (Eagle, lower Pierre and upper Niobrara); (8) late Campanian, ~73 m.y. (mid-Mesaverde, Ericson, base Teapot); (9) late Maestrichtian, ~66 m.y. (top Lance or equivalents). Variations in the accuracy of the dating are probably within 1 m.y. because of problems in accurately defining the biostratigraphic level of the breaks and in the precision of radiometric dates. The unconformities are grouped into three types: those completely within nonmarine strata such as at the base and top of the Cretaceous, those involving both marine and nonmarine strata, and those within marine strata, as currently mapped.

Three examples are described as typical of the unconformities, all thought to be related primarily to drops in sea level, but with minor influence by tectonic movement. One is the ~97 m.y. unconformity, with which the petroleum-producing J and Muddy Sandstone is related. A second is ~ 90 m.y. unconformity which is recognized by relationships within the shelf, slope, and basin deposits of the Greenhorn, Carlile, and Frontier formations. The third is the ~80 m.y. unconformity within the basin and shoreline regression associated with the upper Niobrara, lower Pierre, Eagle, and Shannon formations.

Several billion barrels of oil were found in sandstones associated with unconformities in the Cretaceous of the Rocky Mountain region. Future stratigraphic trap exploration is guided by a knowledge of tectonic influence on sedimentation during sea level changes and how these factors control distribution of source rock, migration patterns, reservoir rock, and seal.

INTRODUCTION

Depositional systems on the margins of continents, both modern and ancient, have been related to sea level changes. Two simplified diagrams by Vail et al. (1977) illustrate highstand and lowstand conditions and associated unconformities (Figure 1). The highstand diagram represents a depositional system that might be observed in many coastal areas today or at times of highstand in the past. The four main components are the coastal plain, shelf, slope, and rise (or deep water basin). An unconformity related to coastal onlap during the rise of sea level to the highstand condition is shown. With a drop in sea level to the edge of the continental shelf (a lowstand condition), sediment bypasses the shelf and is deposited in deep water. The entire shelf is exposed to subaerial erosion and streams adjusting to the lower base level incise into the older shelf deposits. The depocenter shifts from the deltaic system under the highstand to marine subsea fans of the lowstand. Unconformities are present within the marine strata and

[1]Adapted from R. J. Weimer, 1984, Relation of Unconformities, Tectonics, and Sea Level Changes, Cretaceous of Western Interior, U.S.A., *in* J. S. Schlee, ed., Interregional Unconformities and Hydrocarbon Accumulation: AAPG Memoir 36, p. 7–35.

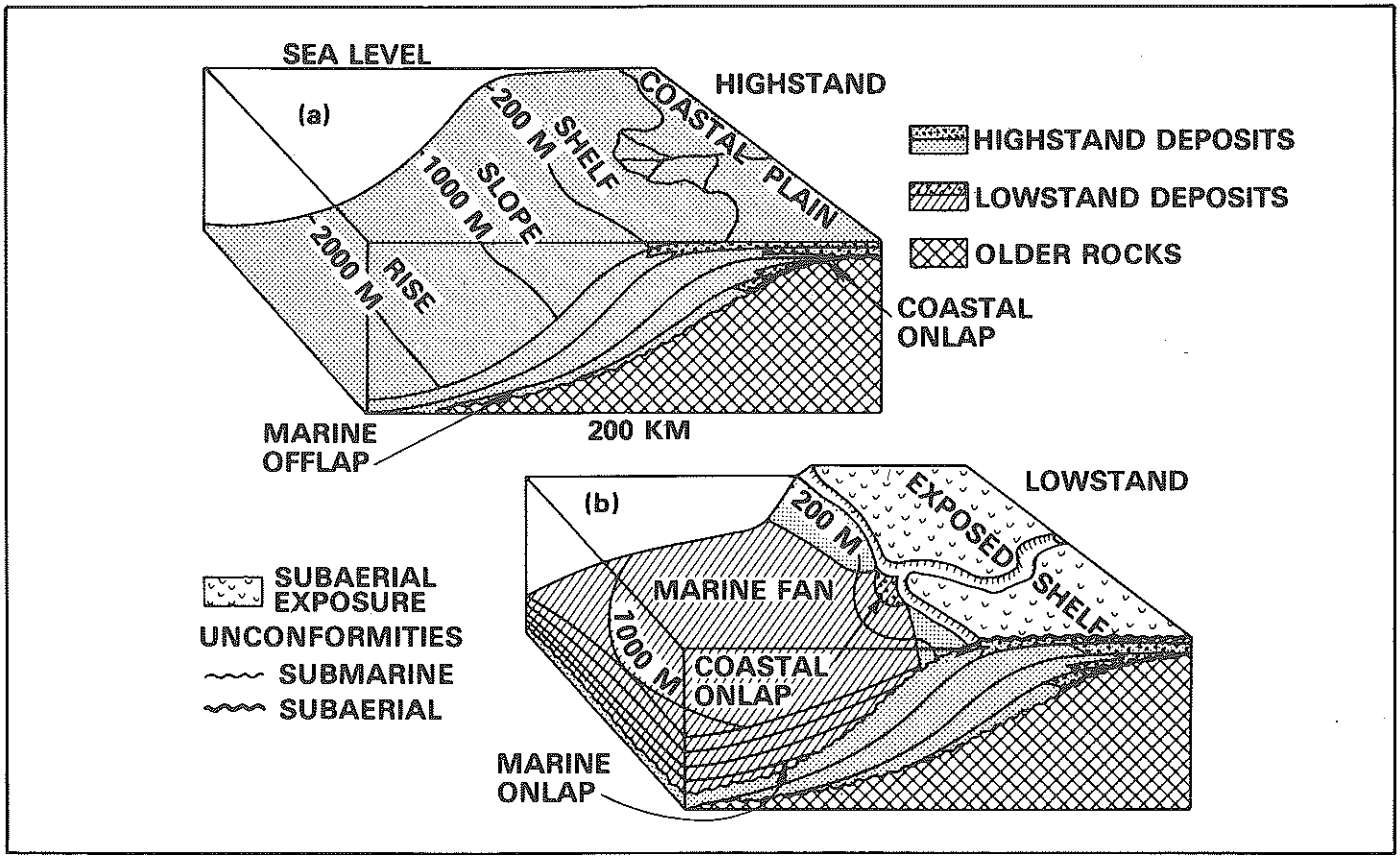


Figure 1—Depositional pattern during highstand (A) and lowstand (B) of sea level. From Vail et al. (1977).

also project into the coastal plain deposits. Several depositional models are possible in ancient strata between these two end members of sea level conditions.

If concepts illustrated by the diagrams from continental margins are applied to ancient interior cratonic basins, then marine and associated deposits represent sea level highstands and unconformities represent erosion during lowstands. Without considering tectonic influence on local depositional basins, a low sea level which exposed much of the shelf on the margin of the continent must have also exposed cratonic regions to subaerial exposure, thus developing interregional unconformities. If a time of significant sea level drop can be identified on a worldwide basis, then a predictive model could be formulated to search for an erosional surface in an ancient interior sequence. Conversely, an incised drainage system with a surface of erosion developed on an ancient marine sequence could be evidence for a significant drop in sea level. The purpose of this paper is to evaluate unconformities observed within the Cretaceous of the Western Interior basin and to determine if the associated surfaces of erosion are related to sea level changes and/or tectonics. Depositional models, previously constructed for the Cretaceous, are expanded to incorporate tectonic influence on sedimentation during sea level changes.

Recognition and Evaluation of Breaks in the Record

Because of the significance of recognizing and evaluating stratigraphic breaks in ancient sequences, how one defines an unconformity is important. I prefer the definition that an unconformity is a sedimentary structure in which two groups of rocks are separated by an erosional surface; the erosion may be by subaerial or submarine processes. Blackwelder (1909) described the factors that must be evaluated to understand the significance of a stratigraphic break. These factors are angular discordance, hiatus (what is missing), nature of the contact (for example, sharp, erosional, or irregular), aerial extent of break, duration of erosion, and cause.

Many types of breaks occur in the stratigraphic record. Unconformity is used for a major break that normally, but not always, can be traced over large areas. This structure records major changes that result from tectonic or sea level variations. A major surface of nondeposition, if recognized within strata, is referred to as a paraconformity. A minor break in the record associated with scour or nondeposition, normally found within a depositional environment, is called a diastem.

The use of unconformities for correlation is widespread. The erosional surface of an unconformity is useful in separating older from younger strata. However, to establish time relations among the strata, independent methods of correlation must be used. Otherwise, one cannot determine an accurate reconstruction of events recorded by the unconformity.

Petroleum Reservoir Rocks and Quaternary Deposits

Reservoir rocks for petroleum in ancient cratonic basins are most commonly associated with highstand conditions.

This concept is illustrated by observing the present high sea level and associated base level for deposition. Sand accumulates in shoreline, deltaic, fluvial (point bar), eolian, or lacustrine settings (Figure 2). During a stillstand or a slow increase in sea level in the Quaternary, the shoreline prograded by lateral accretion (Figure 3) in areas where rates of deposition exceeded rates of subsidence (or submergence). When sea level dropped and base level controlling stream deposition or erosion was lowered, the streams incised into older deposits and an erosional surface formed over large areas. Sand deposits may have developed in the deep water (basin) setting during the lowstand. With a rise in sea level, sediment was deposited in the incised drainage as valley-fill deposits.

Valley-fill deposits are illustrated for the modern Mississippi River valley (Figure 4) by Fisk (1947). The Mississippi and other Holocene fluvial systems have been studied to understand the origin and importance of point-bar sand deposits as a reservoir for petroleum. The lateral changes from point-bar sands to impermeable siltstones and claystones of floodplain or floodbasin deposits have been described as conditions favorable for stratigraphic trapping of petroleum. A more widespread sandstone of a fluvial braided channel complex was identified by Fisk at the base of the valley fill (Figure 4).

The relationship of valley-fill deposits to underlying bed rock and the surface of erosion separating older and younger strata have not been extensively studied in Quaternary deposits. Yet, the recognition of this type of unconformity is important in interpreting ancient strata. It is essential to recognize the difference between the scour surface at the base of a point bar sand within the valley fill (a diastem), and the surface of erosion associated with a sea level drop and drainage incisement (an unconformity) (Figure 4).

Similar problems exist in defining and evaluating breaks in the record of marine sequences in ancient cratonic basins. The most easily recognized breaks commonly occur within shelf sequences. The breaks associated with sedimentation on modern shelves are documented for the Gulf of Mexico. The record of Holocene deposition on the shelf of the northwest Gulf of Mexico is summarized by Curray (1960, 1975). Most of the shelf was subaerially exposed during the Wisconsin glaciation lowstand. With the Holocene rise in sea level, mud, sand, or shell were deposited over shelf areas where a sediment supply was available. Pleistocene sediments are exposed over a large area of the shelf, or are covered by a thin veneer of relict or palimpsest sands, reworked by waves during the transgression. Thus, an erosional surface modified by marine processes occurs at the base of the Holocene.

Incisement of a drainage system into Pleistocene shelf deposits, with a subsequent Holocene valley fill, is well documented by Nelson and Bray (1970). An area of the Texas shelf encompassing 2600 sq km (Figure 5) was studied in detail by using bottom samples, marine sonoprobe profiles, and cores. A paleovalley from 9.6 to 12.8 km wide was mapped for a distance of approximately 80 km (Figure 6). The valley was incised to an unknown depth by the combined flow of the Sabine and Calcasieu rivers (Figure 5) during the Wisconsin lowstand. The stratigraphic relations of three types of fill in the paleovalley are plotted on longitudinal and transverse sections (Figures 6 and 7). The lowest fill, older than 10,200 years, consists of fluvial–deltaic sands of unknown thickness because the base of the valley was not mapped. As the rising sea flooded the valley, estuarine and lagoonal clay and sandy mud were deposited in the valley. These deposits vary in thickness from 6 to 15 m and range in age from 10,200 years to approximately 5200 years. The final fill is composed of marine mud and sandy mud which varies in thickness from a wedge edge to 12 m. During the past 5000 years a marine sand bar complex known as the Sabine and Heald banks has formed approximately 30 km seaward from the present shoreline. The offshore bar is 10 to 13 km wide, 65 km long, and varies in thickness from a wedge edge to 6 m (Figures 6 and 7). The sand bodies may have a transitional base with underlying Holocene marine mud or may rest on an erosional surface on the Pleistocene (Figure 7). Although the sand is dominantly detrital quartz, local concentration of shells make up 100% of the banks. The offshore sand bar has a northwest trend parallel with the present shoreline and a portion of the paleovalley; it overlaps the southern margin of the paleovalley (Figures 6 and 7).

This study by Nelson and Bray (1970) illustrates three types of Holocene sand bodies associated with sea level changes that have potential as petroleum reservoirs. These are the fluvial–deltaic sands of the valley fill; the linear offshore marine bar and associated thin lag deposit; and the thin sands of the shoreline zone. Important stratigraphic breaks are associated with these sand bodies. Similar sand bodies have been recognized in ancient sequences but not always have their origin been related to eustatic changes.

Criteria for recognition of sea level changes in cratonic basins are listed here.

1. Regression of shoreline with incised drainage followed by overlying marine shale.
2. Valley-fill deposits (of incised drainage system) overlying marine shale:
   A. Root zones at or near base of valley-fill sequence.
   B. Paleosoil on scour surface.
3. Unconformities within basin:
   A. Missing faunal zone.
   B. Missing facies in a normal regressive sequence (e.g., shoreface or delta front sandstones).
   C. Paleokarst with regolith or paleosoil.
   D. Concentration of one or more of the following on a scour surface: phosphate nodules, glauconite, recrystallized shell debris to form thin lenticular limestone layers.
4. Thin widespread coal layer overlying marine regressive delta front sandstone deposits indicate rising sea level.
5. Correlation with the record of sea level changes from other continents.

When these criteria are used in conjunction with the factors listed above in evaluating unconformities, breaks which are the result of local tectonic influence can be separated from those caused by sea level changes.

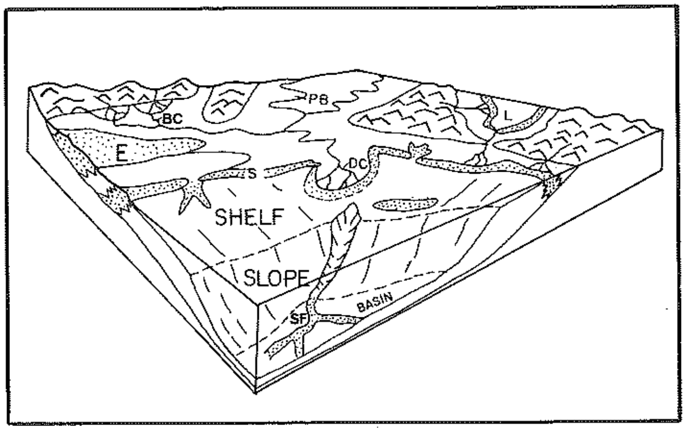


Figure 2—Environments of deposition for sandstone reservoirs under highstand conditions: S, shoreline; SH, shelf; DC, delta distributary channel; PB, fluvial point bar; E, eolian; L, lacustrine. For lowstand conditions: DW, deep water or basin.

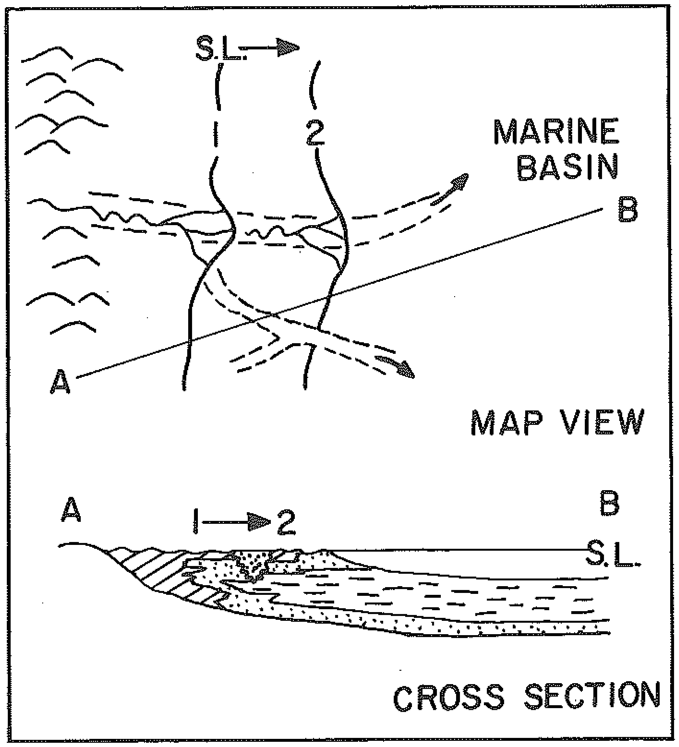


Figure 3—Shoreline regression from position 1 to position 2 during high sea level with high terrigenous influx. Drainage incised during sea level drop (dashed lines) and filled during subsequent sea level rise (section A–B).

REGIONAL SETTING OF CRETACEOUS BASIN

The Western Interior Cretaceous basin of the North American continent is one of the largest cratonic (foreland or back-arc) basins in the world. Because of economic products, mainly petroleum and coal, strata deposited in this basin have been thoroughly studied, both in outcrop and subsurface occurrences. The original basin was 800–1650 km wide and extended from the Arctic to the Gulf of Mexico (Figure 8). The relationship of the basin to other structural elements in the western part of North America is outlined by Dickinson (1976) (Figure 9). The foreland basin formed on a thick continental crust and was bordered on the west by a fold-thrust belt and on the east by the Canadian shield.

During the Early Cretaceous, sediments were derived from both sides of the basin, though the thickest strata are along the western margin. During the Late Cretaceous, the dominant source of sediment was along the western margin and lithofacies were controlled by changes in environments from coastal plain to shoreline to marine shelf and the deeper water of the basin. Intertonguing of nonmarine strata on the west with marine strata in the center of the basin is the dominant pattern of sedimentation (Figure 10). Thickness of the Cretaceous strata varies from 600 to 7000 m. The thinnest sections occur in the geographic center to the eastern margin of the basin because sedimentation rates were slower there. Total organic content is higher in these strata because of the slow sedimentation rates and because of anoxic conditions in deeper water that favored preservation of organic matter.

The Cretaceous basin was deformed during the Laramide orogeny and segmented into the present-day intermontane basins of the Rocky Mountain region. Areas between these basins were uplifted and subsequent erosion has removed Cretaceous strata from the structural high areas. Hence, reconstruction of the entire original depositional basin requires correlation among the intermontane Laramide structural basins. Because of widespread faunas and floras and closely spaced subsurface well control, accurate correlations are possible within much of the stratigraphic

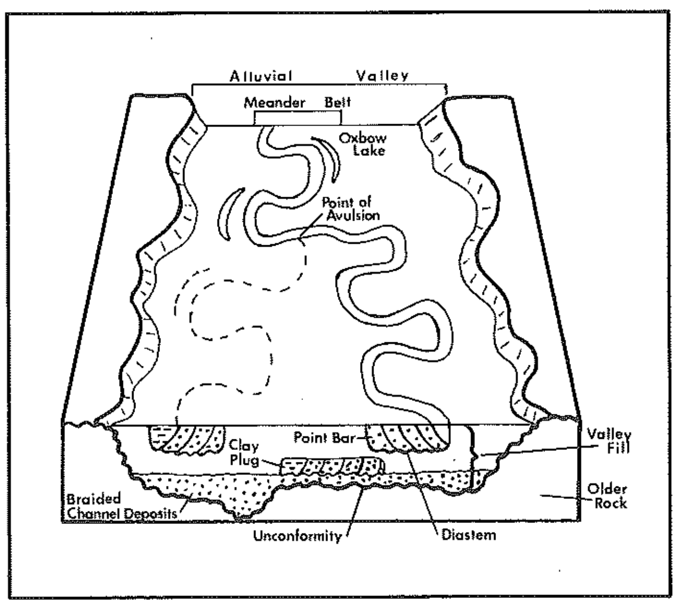


Figure 4—Schematic block diagram of valley-fill deposits of the Mississippi River (modified from Fisk, 1947). Breaks in the sequences are diastems at the base of meander-belt sands and the unconformity at the base of the valley fill. Braided channel deposits are widespread sands at base of valley fill; sand lenses in upper part are point-bar deposits with clay plugs of abandoned channel shown in black.

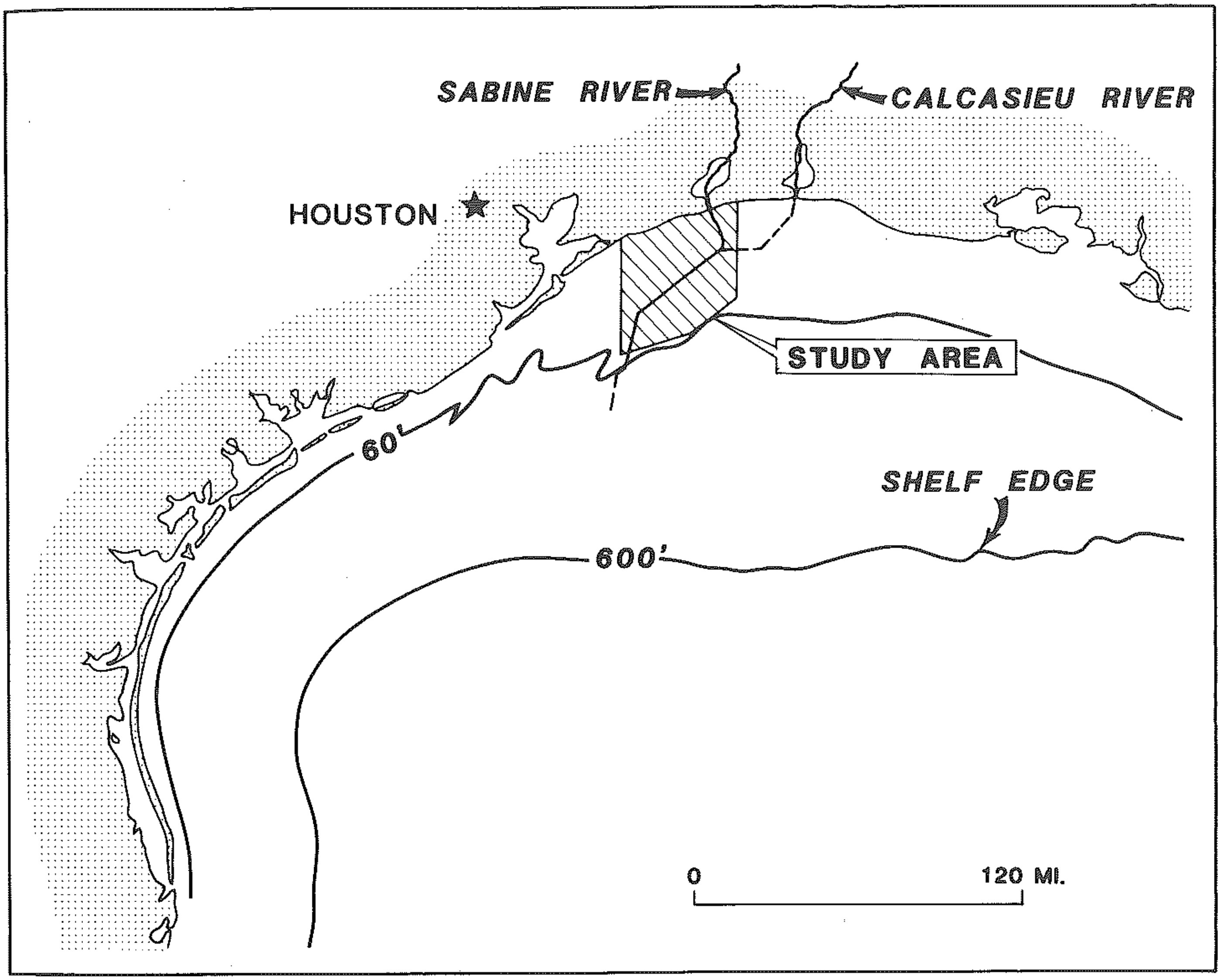


Figure 5—Index map with part of shelf, Gulf of Mexico Holocene sedimentation. Ruled area represents study area of Nelson and Bray (1970).

section. Therefore, time-stratigraphic units can be mapped, breaks accurately evaluated, and facies changes and depositional models reconstructed.

Stratigraphic concepts derived from studies of this Cretaceous depositional basin have widespread application to understanding detrital sequences in all ancient basins which had a structural setting on, or marginal to, cratonic regions of continental plates.

UNCONFORMITIES WITHIN THE CRETACEOUS BASIN

Unconformities within the Cretaceous basin have been recognized by many investigators. The best published synthesis of the Cretaceous system for the Rocky Mountain region in the United States is the Geologic Atlas published by the Rocky Mountain Association of Geologists. The Cretaceous chapter, compiled by McGookey (1972), identifies many unconformities within the system, but only eight or nine within the different structural basins can be placed in a regional framework. A restored section (Figure 10) is plotted from the western margin of the Cretaceous basin (generally western Wyoming and western Montana) to the geographic center of the basin (eastern Colorado, Black Hills area, and eastern Alberta). Strata are dominantly nonmarine in the western portion of the basin and dominantly marine in the geographic center of the basin.

Unconformities are in three positions: those completely within nonmarine strata such as at the base and top of the Cretaceous; those involving both marine and nonmarine strata; and, those totally within the marine strata, as currently mapped. Wavy lines extending completely across the diagram represent times when the entire basin was subjected to subaerial or submarine erosion. In general, the amount of erosion of underlying strata associated with each

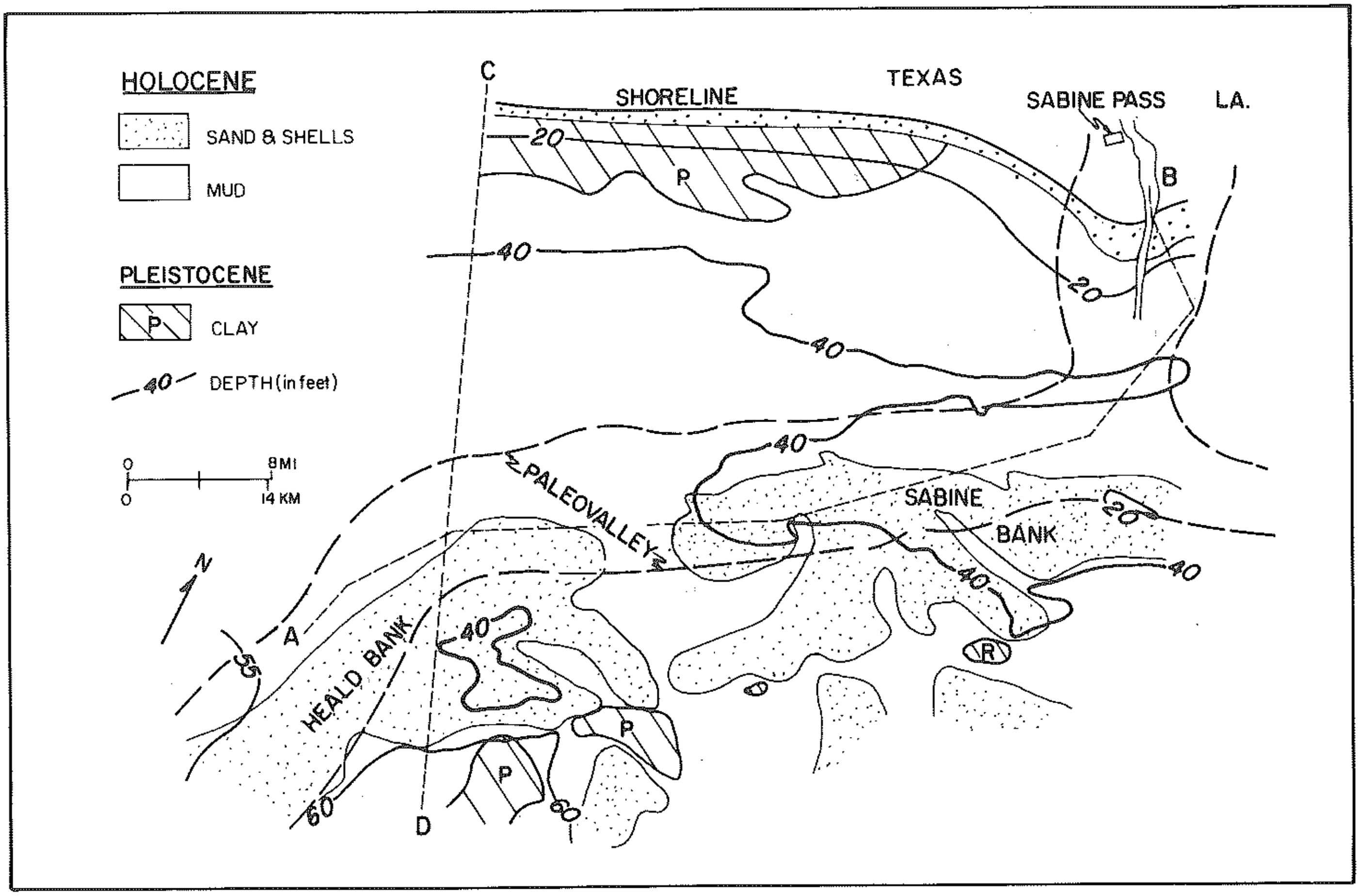


Figure 6—Map of offshore Texas (area shown on Figure 5) with distribution of Holocene and Pleistocene sediments on sea floor. Approximate locations of paleovalleys of Sabine and Calcasieu rivers are shown. After Nelson and Bray (1970).

break is less than one hundred meters. Where regional beveling occurs, the angularity is too small to recognize on a local basis.

On Figure 10 strata are plotted relative to age, and thickness of section is not considered. Uncertainty exists in the dating of many of the unconformities. The time scale and faunal zones of Obradovich and Cobban (1975) and modified by Fouch et al. (1983) were used to date the major unconformities. Their approximate dates (± 1 m.y.), together with associated formations (in parentheses), are estimated as follows: (1) late Neocomian to early Aptian, 112 m.y. (base lower Mannville, Lakota, or Lytle); (2) late Aptian–early Albian, 100 m.y. (upper Mannville, Fall River, Plainview); (3) Albian, 97 m.y. (Viking, Muddy, Newcastle, or J); (4) early Cenomanian, 95 m.y. (lower Frontier–Peay and D); (5) late Turonian, 90 m.y. (base upper Frontier, upper Carlile or Juana Lopez); (6) Coniacian, 89 m.y. (base Niobrara or Fort Hayes); (7) early Santonian, 80 m.y. (Eagle, lower Pierre–upper Niobrara); (8) late Campanian–early Maestrichtian, 73 m.y. (mid-Mesaverde, base Ericson, base Teapot); and (9) late Maestrichtian, 66 m.y. (top Lance or equivalents). The ages of stage boundaries are based on work by Obradovich and Cobban (1975) for the Western Interior Cretaceous, and modified by Lanphere and Jones (1978) and Fouch (1983). The positions of some of the stage boundaries relative to this radiometric time scale are not in agreement with those published by other workers, for example Van Hinte (1976) or Kauffman (1977). These variations in the age of stage boundaries are plotted on Figure 11.

Many of the above unconformities can be related to sea level changes and to well known regressive and transgressive cycles. However, one major problem is determining if some of the breaks are associated with regional or local tectonics instead of sea level changes. The difficulties in relating transgressions and regressions to sea level changes or tectonics in the Canadian portion of the Cretaceous basin were discussed by Jeletzky (1978).

INFLUENCE OF SEA LEVEL CHANGES ON DEPOSITIONAL SYSTEMS

Changes in sea level have a direct influence on base levels of erosion and deposition, which control sedimentation. The influence varies among major environments of deposition but the most noticeable effect is in nonmarine and shallow-marine environments. Overall, drainages adjust to a lower

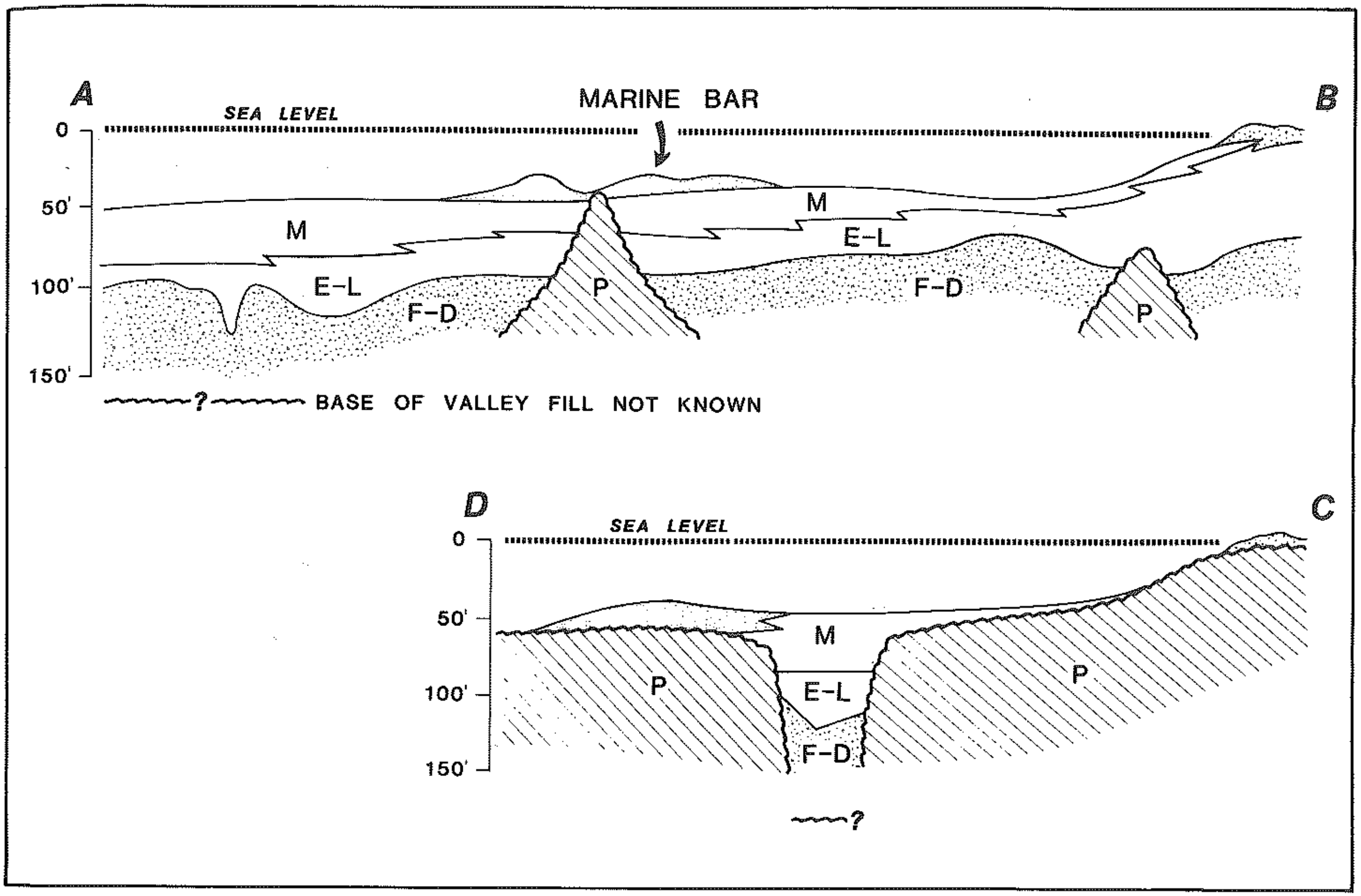


Figure 7—Cross sections A–B within the paleovalley of the Sabine River and C–D across the valley (locations on Figure 6). After Nelson and Bray (1970). M, marine; E-L, estuary-lagoon; F-D, fluvial-deltaic; P, Pleistocene.

base level (lowstand) by incisement (erosion) into underlying strata; when base level rises, streams aggrade and deposition resumes in valleys and marginal areas. Shorelines normally regress during lowstands and transgress during highstands. Depending on the magnitude of change, marine shelf sedimentation may be influenced only slightly, or widespread erosion may occur either in a subaerial or submarine setting. Generally, the deposits that are studied in cratonic basins are associated with highstands, whereas lowstands are represented by breaks that may or may not have been identified, especially in nonmarine strata.

Many of the unconformities in the Cretaceous basin are associated with overall regressive cycles of shoreline movement. The widespread regressive shoreline and shallow marine sandstones may be related to a stillstand or a slow rise or lowering of sea level where a high rate of sediment supply prevails. The Holocene Mississippi River delta complex is an example of a regressive event during a Holocene stillstand, or slightly rising sea level, because of a high sediment input to the basin. The shoreline has prograded seaward approximately 160 km during the last 5000 years. Thus, a shoreline regression in an ancient sequence need not be related to a sea level drop. The best single indicator of an ancient falling sea level is incised drainage with root zones or paleosoils on the surface of erosion at the base of valley-fill deposits, as summarized in the list of criteria previously given. Other criteria that are useful in establishing eustatic changes are also listed.

Sea level curves for the Cretaceous have been published by Hancock (1975), Kauffman (1977), and Hancock and Kauffman (1979). These authors relate major transgressive and regressive cycles for the western United States with those of north Europe and relate these recorded events to sea level changes. Based on criteria discussed in this paper, a modified sea level curve for the Western Interior has been prepared (Figure 11) and compared with Hancock's curve for north Europe. The comparison of events between continents allows for discrimination of those shoreline movements caused by sea level changes. However, when the unconformities are added, a more accurate dating can be determined for the lowstands.

Transgressions in the Cretaceous are represented by widespread marine shale strata between sandstone units of regressive events, some of which are capped by unconformities (Figure 10). From oldest to youngest these shale or chalk formations are as follows: (1) Clearwater of Canada, an event represented by nonmarine strata in the United States (the Lakota or Lytle); (2) Skull Creek; (3)

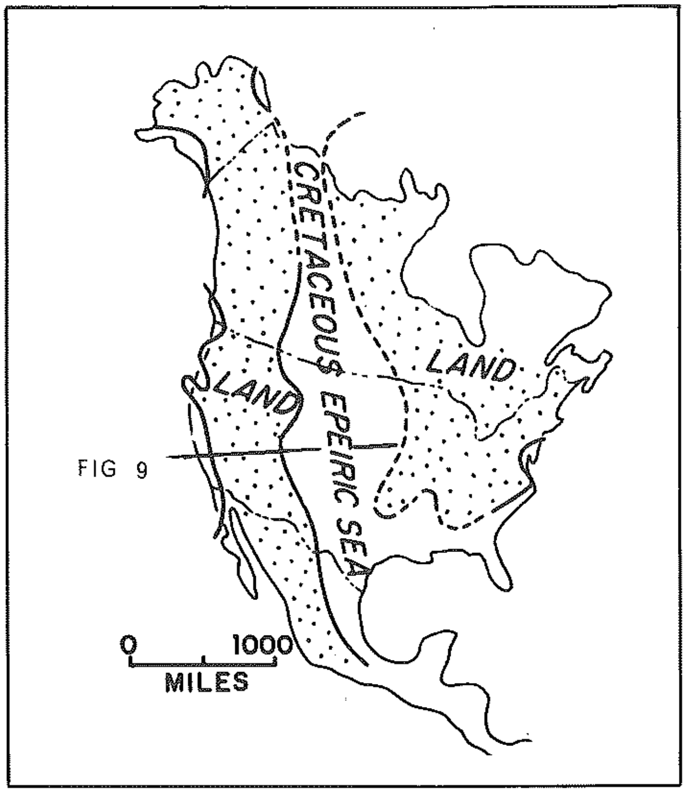


Figure 8—Index map showing geographic distribution of Cretaceous seaway in interior of continent. Location of cross section (Figure 9) with representative tectonic elements is indicated.

Mowry–Huntsman; (4) Greenhorn; (5) upper Carlile; (6) Niobrara; (7) Claggett; and (8) Bearpaw. Because of their wide distribution, these formations have been related to highstand conditions. However, underlying valley-fill deposits, where present, are also related to rising sea level and transgressive events. Because of the unconformities, in many areas regional sedimentation patterns cannot be easily related to symmetric cycles of transgression and regression, although locally this has been done (Kauffman, 1977). Because the breaks are generally on top of the regressive phases, cycles, if present, are asymmetric in favor of the regression event.

TECTONIC INFLUENCE ON SEDIMENTATION

Depositional models proposed for the Cretaceous do not generally consider whether or not syndepositional tectonic movement occurred. Detailed studies in eastern Colorado have clearly established that structural elements had periodic movement on the Cretaceous sea floor (Weimer, 1978), 1980). Major northeast-trending basement fault blocks in the northern Denver basin are mapped as extensions of well-documented Precambrian shear zones observed in Front Range outcrops (Figure 12). Recurrent movement occurred on several of these paleostructures during the Pennsylvanian, Permian, and Cretaceous (Sonnenberg and Weimer, 1981).

The shear zones, Precambrian in age, are "weak rock" and bound rigid fault blocks. At times during the Phanerozoic when the crust was highly stressed, the stress was relieved primarily by movement along these preexisting lines of weakness. Cretaceous strata clearly show that fault movement was sporadic, affecting some layers but not others. The strata which record movement are referred to as "tectonically sensitive intervals." They are the keys to reconstructing the size and distribution of paleotectonic elements. Recurrent movements on the basement fault blocks are normally in the same direction, but important reversals in movement (structural inversions) along faults have been recorded.

Fault block boundaries may be recognized in the sedimentary sequence overlying the basement by direct offset of sedimentary layers, abrupt change in strike and dip related to drape folding, and closely spaced fractures in competent layers. Strata overlying major basement blocks generally have uniform dip over the extent of the block. Different sized blocks are referred to as first, second, or third order features.

One of the most important premises in establishing a tectonic control on sedimentation is that fault block movement controls topography and bathymetry (referred to as structural topography). We can make the following generalities concerning sedimentation. In continental deposits rivers flow on topographic lows, whereas interchannel areas generally occur over higher structural areas. However, because of the leveeing process associated with channels, interchannel deposits may be deposited in areas topographically lower than the channel.

In shoreline deposits with a high sediment influx, deltas develop in structural and topographic low areas and interdeltaic deposits occur over and around the more positive structural blocks. When sediment influx is low the structural and topographic low areas (deltas) may become estuaries. In marine deposits, topographically high blocks may be shoal areas and thus control the distribution of sand bodies or reefs. Moreover, in deeper water deposits, sand turbidites (both calciclastic and siliciclastic) are deposited in bathymetrically low areas, which may coincide with downthrown blocks. In summary, thin successions are associated with paleohighs and thick successions are associated with paleolows, but sand deposits may occur in either setting depending upon the depositional environment.

Depositional topography may have developed within the Cretaceous basin because of thickness variations in units related to rates of sedimentation (Asquith, 1970). Thick and thin sediment accumulations, associated with depositional topography, can be confused with thickness patterns related to tectonics, and a careful analysis of depositional environments, processes, and subtle breaks is needed to determine what controlled thickness variation.

Tectonic movements can influence the accuracy of time correlations. Older units can be elevated to the same or a higher stratigraphic level than younger strata. An example of this relation is demonstrated in the discussion of the J Sandstone.

By applying the above concepts, the cause of an unconformity can be evaluated—tectonic, sea level change,

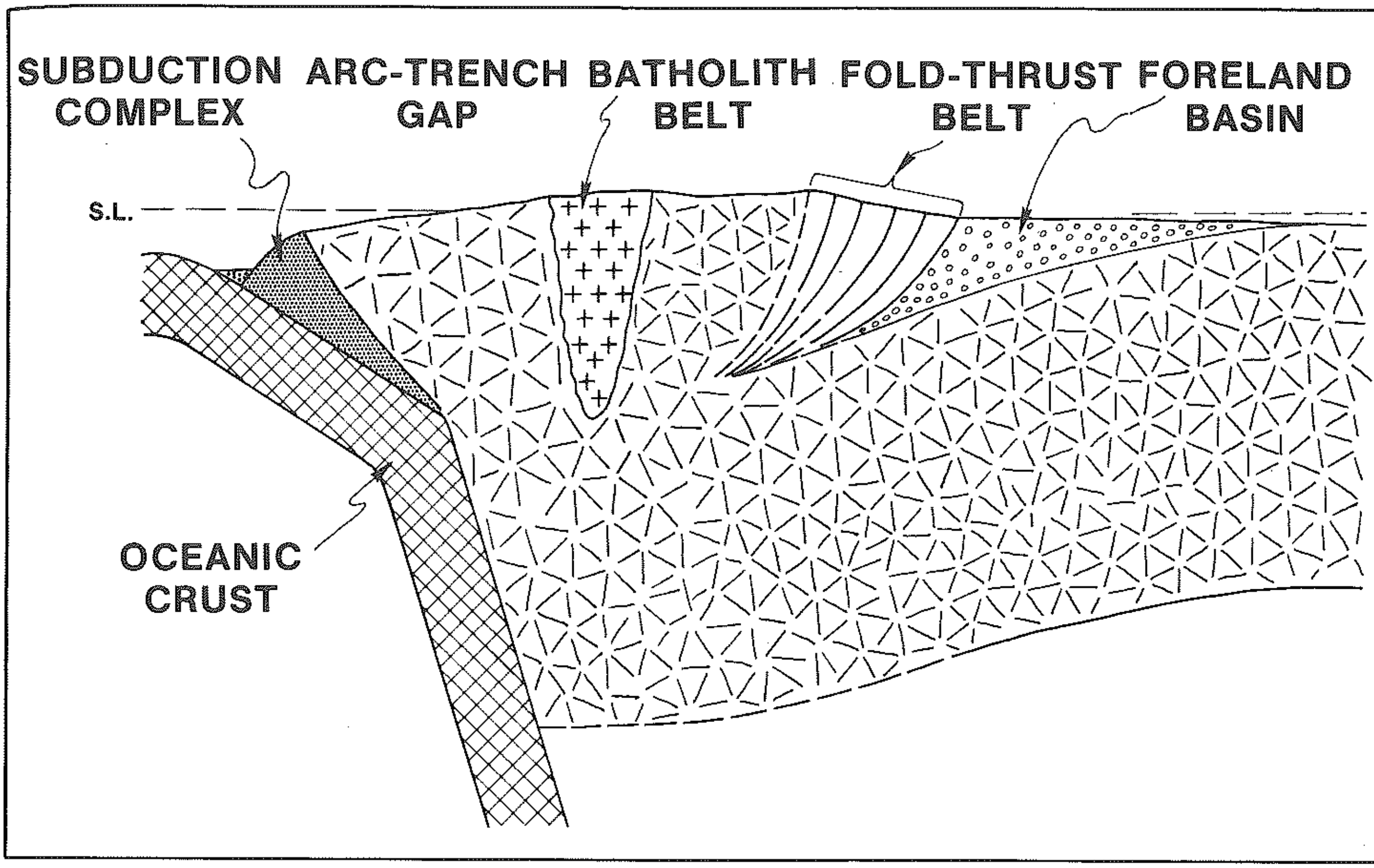


Figure 9—Schematic diagram to illustrate tectonic elements across western United States during the Cretaceous. S.L., sea level. After Dickinson (1976).

or a combination of both. Depositional models constructed for all ancient depositional basins should consider these factors to reconstruct accurately the recorded geologic events.

EXAMPLES OF UNCONFORMITIES ASSOCIATED WITH CRETACEOUS SEA LEVEL CHANGES

Although field, paleontologic, and subsurface data are available to support all of the unconformities in the Cretaceous shown on Figure 10, only three breaks, regarded as typical, are described in the following discussion. The 97 m.y. and 90 m.y. unconformities can be related to events on the continental margins and are, therefore, interregional in nature. The 80 m.y. break is now best defined within the marine basin deposits but probably extends to the margin of the basin and elsewhere on the continent.

BASINWIDE INCISEMENT OF DRAINAGE DURING SEA LEVEL CHANGE (97 M.Y. AGO)

An important transgressive–regressive–transgressive sequence is recorded in the Albian strata of the Western Interior Cretaceous basin. A widespread marine shale, mapped throughout the basin, is known in different areas as the Skull Creek, Kiowa, Thermopolis, and Joli Fou (Canada) shales (Figures 10 and 13). Equivalent strata in western Wyoming in the basin margin area are generally included in the Dakota Group or Bear River Formation. The shale deposits, which accumulated during a highstand of the Albian Sea, are correlated over large areas, either by contained faunas or by stratal continuity. The shales, generally 30 to 60 m thick, represent the first widespread transgression of the Cretaceous sea into the United States portion of the Western Interior basin. Overlying regressive sandstone units named the Muddy, J, or Viking (Canada) sandstones are widespread and productive of petroleum in stratigraphic or structural traps. Generally less than 30 m thick, these sandstones were deposited in a range of environments from freshwater to marine. They are generally regarded as deposits related to a lowering of sea level. The following transgression is recorded by the widespread marine Mowry Formation and other highstand deposits. When the history of these strata is related to radiometric dates from associated bentonite beds, the sequence spans the time interval of approximately 96 to 98 m.y. ago. The major event correlates with the worldwide sea level drop 97 m.y. ago, reported by Vail et al. (1977) and Hancock (1975).

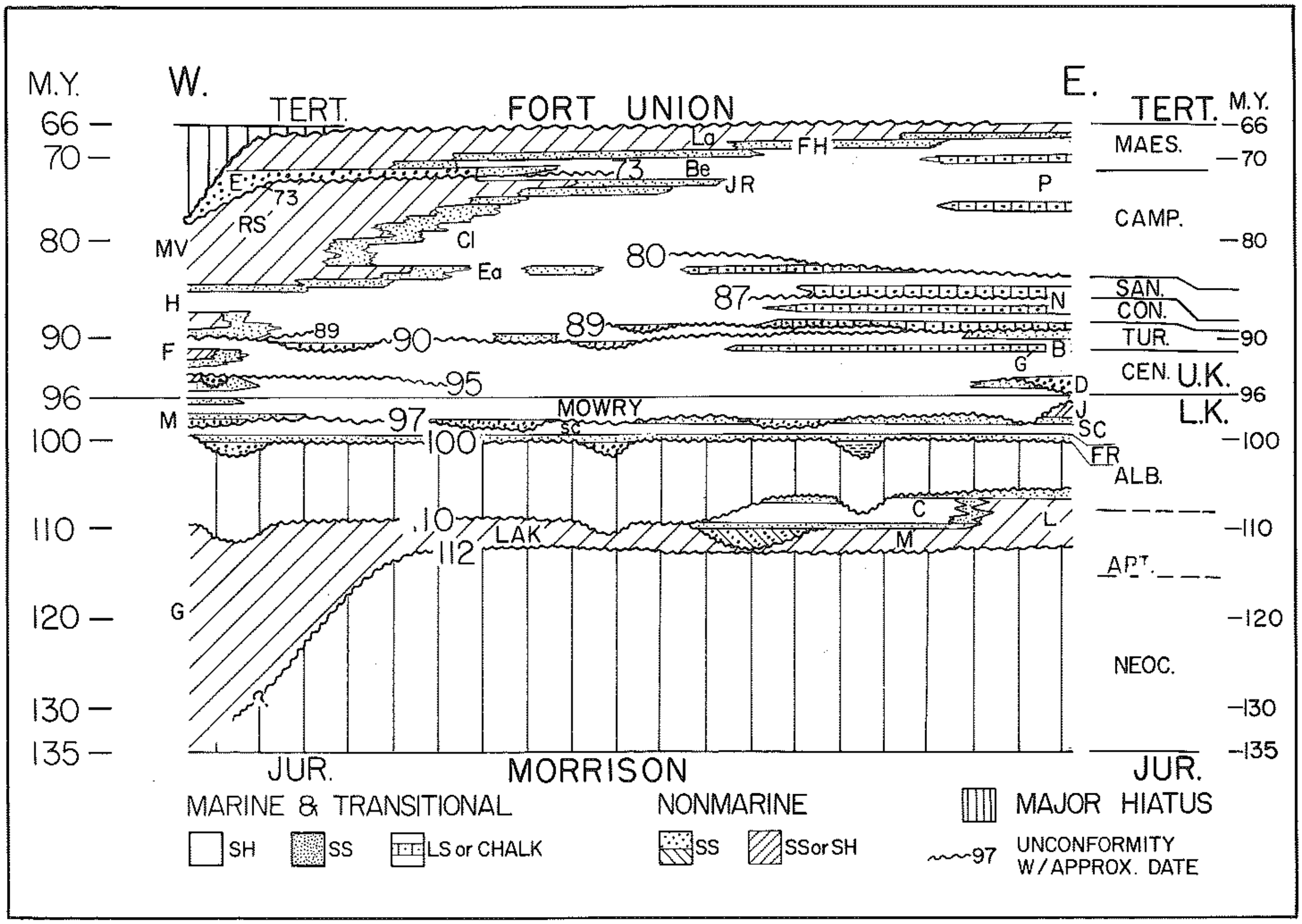


Figure 10—Diagrammatic east–west section across Cretaceous basin showing stratigraphic position and approximate dates of major intrabasin unconformities (modified after McGookey, 1972). Formations or groups to the west are G, Gannett; SC, Skull Creek; M, Mowry; F, Frontier; H, Hilliard; MV, Mesaverde; RS, Rock Springs; E, Ericson; Ea, Eagle; Cl, Claggett; JR, Judith River; Be, Bearpaw; FH, Fox Hills; La, Lance. To the east, formations are L, Lytle; LAK, Lakota; FR, Fall River; SC, Skull Creek; J and D, Sandstones of Denver basin; G, Greenhorn; B, Benton; N, Niobrara; P, Pierre; M and C, McMurray and Clearwater of Canada. The vertical ruled lines represent unconformities where a major hiatus is recognized. When the gap is a million years or less, vertical ruling is omitted.

The events described above are known largely from detailed stratigraphic studies in the Powder River basin, Wyoming, and the Denver basin, Colorado, Wyoming, and Nebraska. Only the Denver basin work is summarized in this paper but literature describing the Powder River basin is extensive (Weimer, 1982).

Denver Basin

Petroleum was discovered in upper sandstones (D and J) of the Dakota Group in the Denver basin in 1923. Since the discovery of the Wattenberg gas field in 1970, more than 1000 wells have been drilled to the J Sandstone in an area covering 600,000 acres across the deeper portion of the Denver basin (Figure 14). Production is about 24 km east of outcrop sections which are described by MacKenzie (1971), Clark (1978), and Suryanto (1979). Details of the Wattenberg field have been published by Matuszczak (1976) and Peterson and Janes (1978). Because of new data from the outcrop and subsurface, a reinterpretation of the depositional model for the J Sandstone is now possible. An important new element is the recognition of the Wattenberg area as a paleostructure that influenced J Sandstone deposition (Weimer, 1980; Weimer and Sonnenberg, 1982).

The J Sandstone (Muddy) is present in outcrop sections from the Wyoming state line to the South Platte River southwest of Denver (Figure 14). Two types of sandstone bodies comprising the J Sandstone in the Denver basin were described by MacKenzie (1965) from outcrops in the Fort Collins area (Figure 15). One type, named the Fort Collins Member by MacKenzie, is a very fine-grained to fine-grained sandstone containing numerous marine trace fossils and is interpreted to be delta front, shoreline, and marine bar sandstone that was deposited during rapid regression of the shoreline of the Skull Creek sea. A second type is fine- to medium-grained, well-sorted, cross-stratified sandstone (channels) containing carbonized wood fragments and associated shales and siltstones. These lithologies were named the Horsetooth Member by MacKenzie. Valleys of an extensive drainage system were incised into the Fort Collins Member or the underlying Skull Creek Shale and contain a

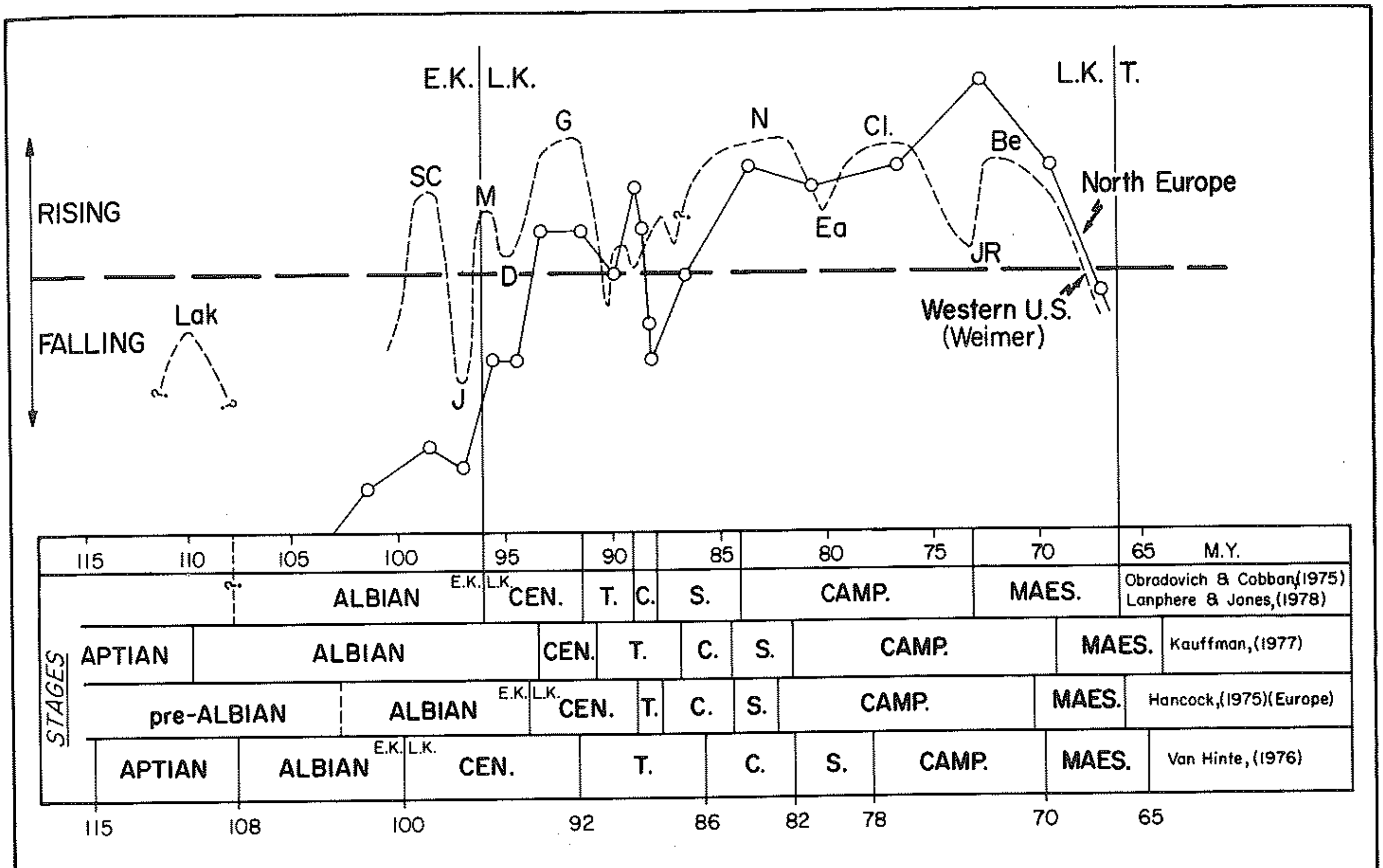


Figure 11—Sea level curves for the United States and Europe. Letters designate the same formations as on Figure 10. Abbreviations for stages: Cen., Cenomanian; T., Turonian; C., Coniacian; S., Santonian; Camp., Campanian; Maes., Maestrichtian; E.K., Early Cretaceous; L.K., Late Cretaceous; T., Tertiary.

fill of sandstone, siltstone, and claystone varying in origin from alluvial plain to shoreline deposits (Horsetooth Member). The J varies in thickness from 6 to 46 m (Figures 15 and 16).

The thick dominantly fresh to brackish water J Sandstone facies in the Golden area was interpreted by Waage (1953), Haun (1963), MacKenzie (1971), and Matuszczak (1976) to be laterally equivalent to the thin marine sandstone facies north of Boulder. This interpretation led to the concept of a northwest-trending marine basin in the area between Boulder and Fort Collins.

The interpretation shown on Figure 15 correlates the Golden area sections (Weimer and Land, 1972) with the Horsetooth Member. The Kassler Sandstone, the lower unit of the J, where present, rests on an erosional surface cut into the Skull Creek Shale. Sandstone of the Fort Collins Member is interpreted as having been removed by erosion prior to deposition of the Kassler. Root zones are found in the Kassler only a few feet above the base. In addition, conglomeratic sandstones with chert pebbles up to 1 cm in diameter are sporadically present in the Kassler (Poleschook, 1978). Thus, lower J Sandstone is interpreted as a valley-fill complex of a major drainage system. Cross strata in the Kassler Sandstone (lower J) indicate a dominantly southeast transport direction (Poleschook, 1978; Lindstrom, 1979) (Figure 17). The drainage patterns are interpreted as tributary rather than distributary as previously described.

A north–south electric log section east of the outcrop across the Wattenberg field shows a similar interpretation of the J Sandstone (Figure 16). The widespread gas-bearing sandstone at Wattenberg is the Fort Collins Member of the J, which is transitional with the underlying Skull Creek. Major channel sandstones of the Horsetooth Member are present to the north and south of Wattenberg (Figures 16 and 17). In the Third Creek field (sec. 19, T. 2 S., R. 67 W.) (Figure 16), root zones are preserved below the J channel sandstone and above the erosional surface on top of the marine Fort Collins Member. Based on core interpretation of facies, at least 10 m of the Fort Collins Member was eroded prior to deposition of the fluvial channel sandstone that is oil-productive. Previous interpretations have shown the channel sandstone to be the lateral equivalent of the Fort Collins Member at Wattenberg. Since the channel sandstone can be demonstrated to be younger than the erosional surface cut on the Fort Collins Member, such a facies interpretation is in error.

Tectonics and Sedimentation Model for J Sandstone, Denver Basin

The following model for tectonic influence on J Sandstone sedimentation is proposed for the Denver basin. At the end

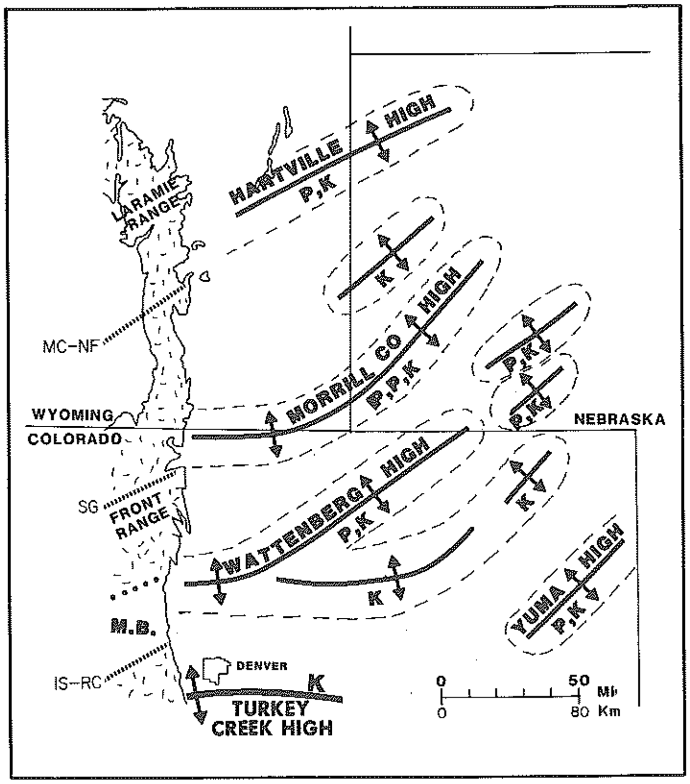


Figure 12—Summary diagram of east-northeast trending paleostructures (basement fault blocks) in northern Denver basin. Times of dominant movement are IP, Pennsylvanian; P, Permian; K, Cretaceous. Outcrop of Precambrian with major shear zones along left side of diagram. MC-NF, Mullen Creek-Nash Fork; SG, Skin Gulch; IS-RC, Idaho Springs-Ralston Creek; M.B., Colorado mineral belt.

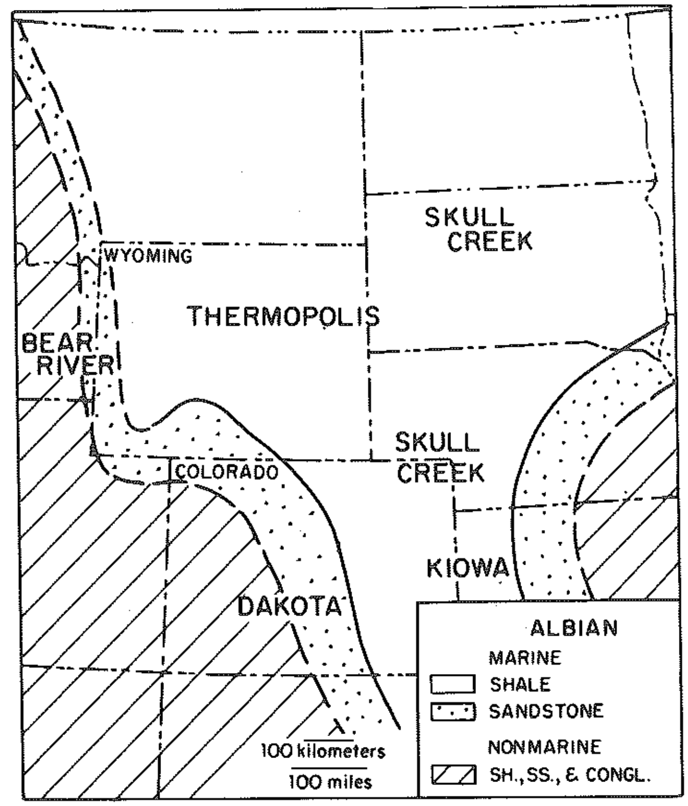


Figure 13—Outline of Cretaceous seaway during Albian time.

of Skull Creek deposition (T_1, Figure 18), a regressive event began that deposited shoreline and shallow-marine sandstones with a transitional contact with underlying Skull Creek Shale. Depositional patterns over basement fault blocks, where slight fault block movement influenced sedimentation, are illustrated. Rivers and associated deltas positioned themselves in structural and topographically low areas, grabens, whereas delta margin or interdeltaic sedimentation occurred along an embayed coast over structural horst blocks. Delta front and shoreface sands extended seaward from the shoreline to a distance controlled by effective wave base. The shoreline prograded seaward to position T_2 and a sheetlike sand body was deposited over a large area (Wattenberg pay sandstone or Fort Collins Member).

A drop in sea level occurred (T_3) during which all, or a large portion, of the depositional basin (Skull Creek seaway) was drained (Figure 19). River drainages were incised into marine shales and/or the regressive shoreline sandstones in topographic lows which generally correspond to the graben fault block area. Over much of the Denver basin the base of the incisement is on the Fort Collins Member (T_1 or T_2 sand complex). Only locally did the erosional surface cut into the Skull Creek Shale.

A rise in sea level occurred during which the incised valleys were probably modified and filled with fluvial and estuarine sandstone, siltstone, and shale. Vertically, the valley fill has a wide variety of fluvial environments in the lowermost part and estuarine or deltaic environments in the upper part (Figure 20). With a rising sea level the earliest fluvial deposits were deposited in narrow valleys as upper meander belt sandstones. As sea level increased, the lower meander belt environments shifted landward and channel meandering widened the valley by scour. These sandstones may overlie either the upper meander belt sandstone or the Fort Collins Member. The final deposits of the J are transitional estuarine, deltaic, or shoreline deposits. After the valleys filled, deposition covered the interstream divide areas. With a continued rise in sea level (T_4, Figure 21) and minor renewed fault block movement, strata were eroded from the top of the horst blocks and an extensive thin transgressive-lag deposit of conglomeratic or coarser grained sandstone formed over the horst blocks on a surface of erosion. Following T_4 the entire region received marine siltstone and shale (Mowry or Graneros shales).

In the above model, an important unconformity separates T_1 and T_2 deposits from T_4 deposits. This basinwide unconformity (T_3, Figure 19) may be within sandstone deposits (i.e., valley-fill sandstones rest on older regressive sandstones), or between sandstone and marine shale deposits (i.e., valley-fill sandstones rest on Skull Creek Shale). In portions of the Wattenberg field, the

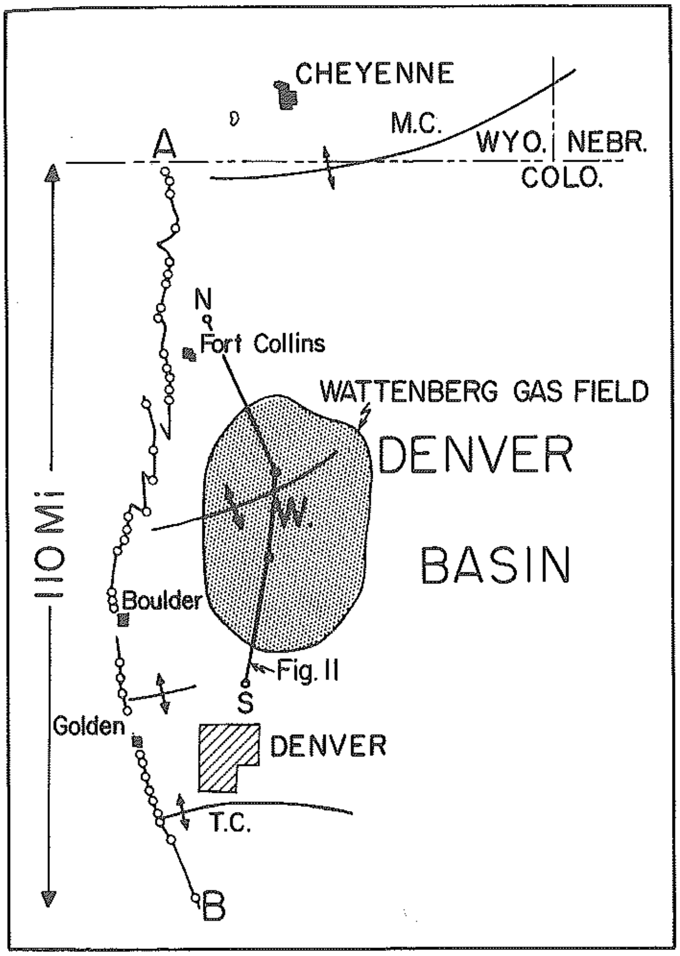


Figure 14—Map of Denver basin showing outcrop sections of Dakota Group and paleotectonic elements: M.C., Morrill Co. High; W., Wattenberg; T.C., Turkey Creek. Locations of measured surface sections indicated by O.

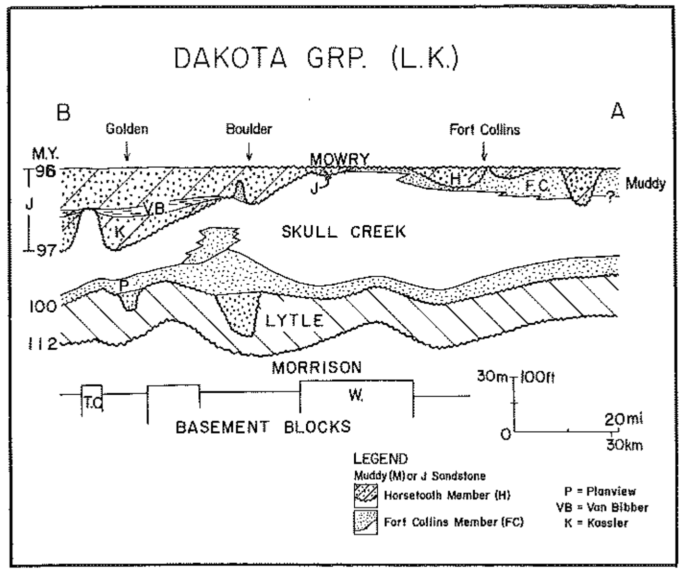


Figure 15—Stratigraphic restored section A–B through the Dakota Group (Lower Cretaceous) (location on Figure 14). Modified after MacKenzie (1971).

unconformity is at the base of the Mowry Shale or top of the regressive sandstone.

Previous correlations which show the J Sandstone to be deposited across the basin during one major regressive event need to be modified. Sandstones above the unconformity (Horsetooth Member) are younger than the regressive sandstone at the top of the Skull Creek (Fort Collins Member), although because of tectonic movement the older sandstones are now at a stratigraphic high position (Figures 15 and 16). This model has important implications for future petroleum exploration in the Denver basin.

A relation exists between major northeast-trending Precambrian shear zones mapped in the Front Range and paleostructure in the northern Denver basin (Figure 12) (Sonnenberg and Weimer, 1981). Recurrent movement on these old fault zones has controlled thickness variations and depositional facies in Paleozoic and Mesozoic strata. Five major east-northeast-trending paleostructures occur in the northern Denver basin which had recurrent movement during the Cretaceous and some have documented movement during the Permian. The major paleostructures are the Wattenberg high, the Morrill County high, the Hartville high, the Turkey Creek high, and the Yuma high (Figure 12). These paleohighs vary in width from 32 to 40 km and in length from 80 to 290 km. Several important northwest- and north-trending paleostructures are omitted from Figure 12 (Sonnenberg and Weimer, 1981). Each structural paleohigh should be investigated to determine if recurrent movement influenced sedimentation as documented in the Wattenberg area.

Recurrent movement on paleostructural elements affected the Cretaceous seaway in a broader sense. The five paleostructural elements (Figure 12) collectively have been grouped together as a broad structural arch referred to as the Transcontinental arch (Weimer, 1978). Structural movement on this broad arch during the time of J or Muddy Sandstone deposition created a topographic high which divided the drainage in the Cretaceous basin during the low sea level stand (T_3; Figure 19). A general south-flowing drainage developed in southwest Wyoming and eastern Colorado (Figure 22), whereas a north-flowing system developed in northern Wyoming (Powder River basin; Weimer et al., 1982).

EROSION OF SHELF STRATA DURING SEA LEVEL CHANGE (90 M.Y. AGO)

Unconformities within marine strata have been described in the Cretaceous by Reeside (1944, 1957), McGookey (1972), and Merewether and Cobban (1972, 1973), Merewether et al. (1976), and Merewether et al. (1979). The stratigraphic positions of the documented unconformities are shown on Figure 10. Uncertainty exists as to the cause of

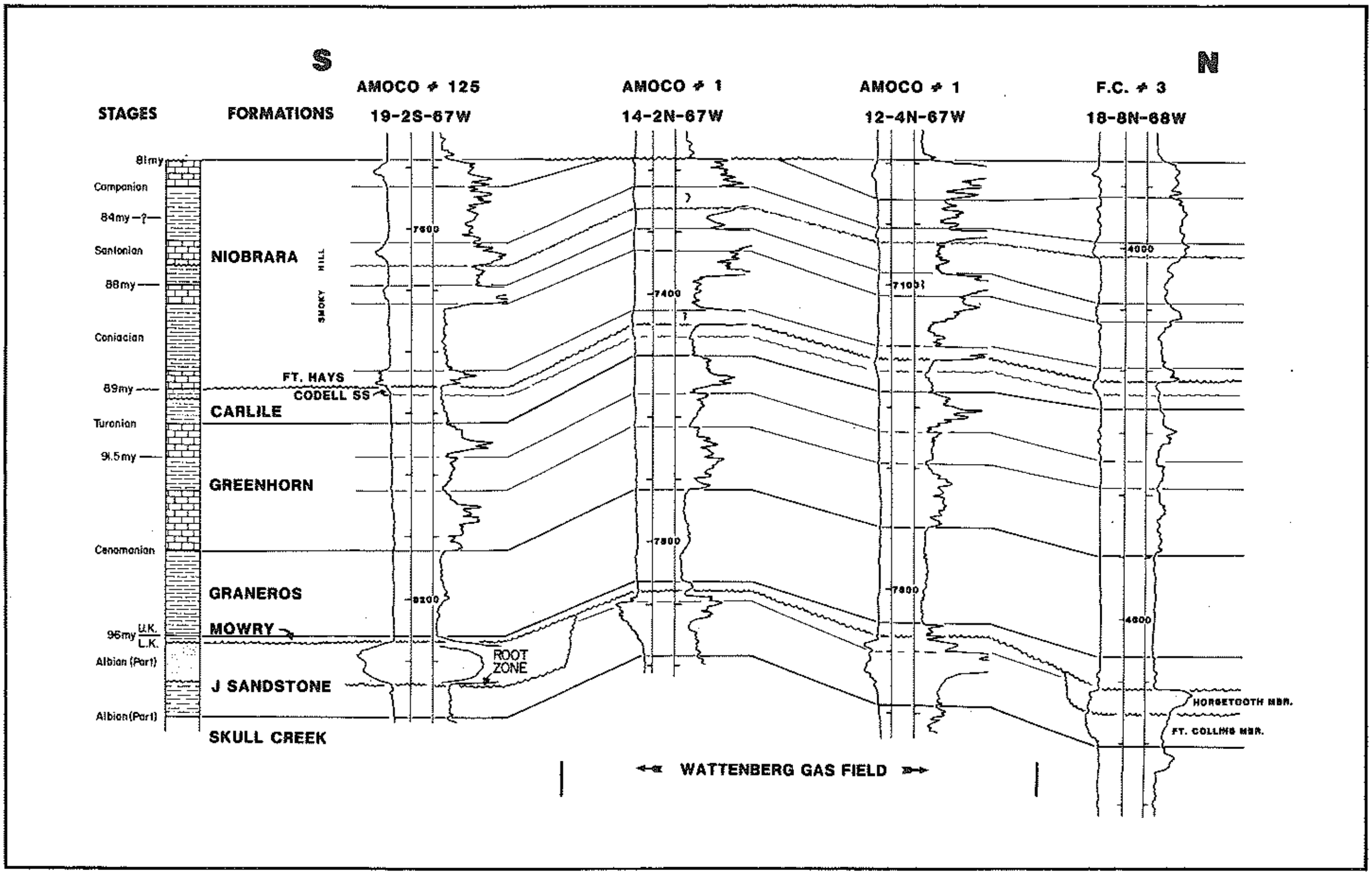


Figure 16—Electric log section across Wattenberg field from Fort Collins to Denver (location on Figure 14).

the marine unconformities: Are they the result of sea level change with subaerial or submarine erosion? Do they result from submarine erosion associated with tectonic movement, nondeposition, or a combination of these processes? To what extent is the geographic distribution of the unconformities influenced by depositional topography, which in turn is controlled by the interplay of rates of sedimentation and oceanic processes?

Model for Depositional Topography

Depositional topography commonly developed in ancient basins which had a high input of terrigenous sediment. Asquith (1970) described depositional topography in the Western Interior Cretaceous basin for Campanian and Maestrichtian strata in Wyoming. A modified model from Asquith for highstand sea level depositional topography includes environments of deposition related to coastal plain, shoreline, shallow marine/shelf, slope, and basin (Figure 23A). Because of high rate of sedimentation and lateral accretion (progradation), higher than normal depositional dip formed in two areas: the delta front–prodelta, and the slope. The primary dips (clinoforms) in these areas of dominantly clay and silt deposition are generally less than 1°, as determined from closely spaced well log correlations (Figure 23B). Because of their low dip, the clinoforms are not generally recognized on seismic sections or on outcrop.

The slowest rates of sedimentation existed in deeper water areas (basin, Figure 23A) where sedimentation of organic rich chalk and clay, related to pelagic sedimentation, was dominant. Water depths are difficult to reconstruct but, in general, shelf depths are estimated to vary from 30 to 90 m. Depths for chalk sedimentation in the basin are controversial but estimates range from 60 to 490 m (Kent, 1967; Eicher, 1969; Hattin, 1975a; Kauffman, 1977). On the basis of the physical evidence for the shelf, slope, and basin model (Figure 25), I favor basin water depths in the range of 180 to 300 m during sea level highstands.

Water depths greatly influenced sedimentation or erosion during sea level changes. During lowstand events erosion by wave energy or by subaerial processes may have removed shelf and slope deposits, depending on the magnitude of the sea level drop (Figure 23C). Sand normally confined to the coastal plain and shoreline areas was transported to the shelf area. During a subsequent sea level rise, the sand may have been reworked into marine shelf complexes, either as narrow linear marine bars, as thin transgressive sheet sands, or as a final fill of incised drainages. The shelf deposits of the Gulf of Mexico illustrate these types of sand bodies and were discussed previously (Figures 5, 6, and 7).

Although the above model applies generally to interpreting all strata in the Cretaceous basin, an example illustrating the components in the marine phase of the

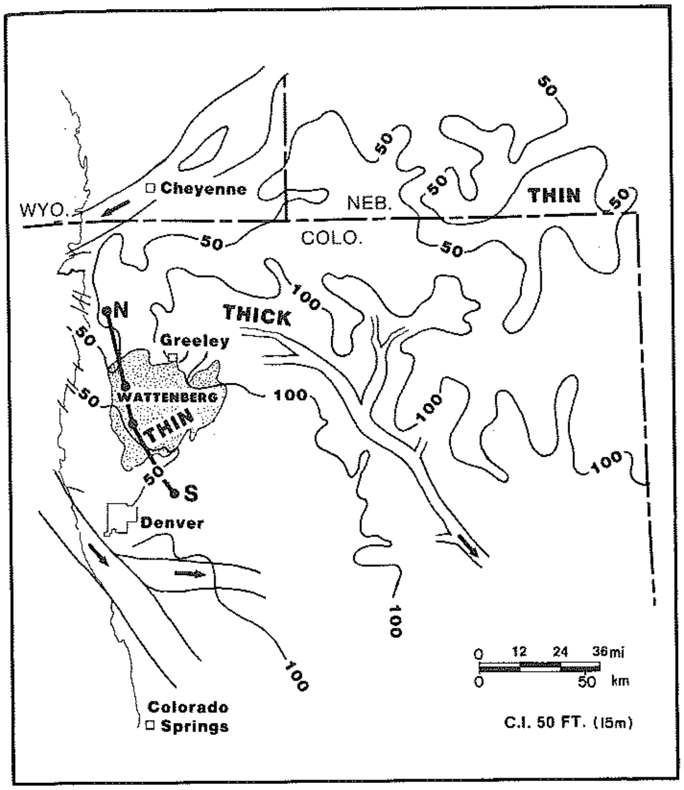


Figure 17—Isopach map of J Sandstone (includes Fort Collins and Horsetooth Members) with location of major incised valleys as indicated by lower J (equivalent of Kassler Sandstone of outcrop on Figure 15). Stippled pattern is area of gas production from J Sandstone. Modified from Haun (1963) and Matuszczak (1976).

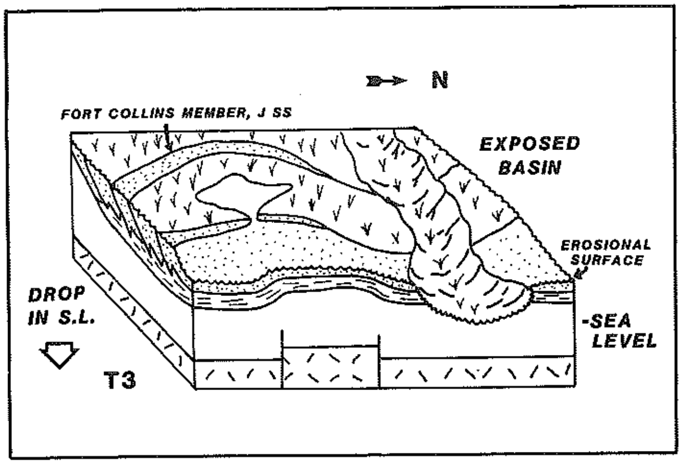


Figure 19—Lowstand sea level (time 3, T_3) recorded as basin-wide erosional surface resulting from subaerial exposure. Root zones form on exposed marine shales and sandstones.

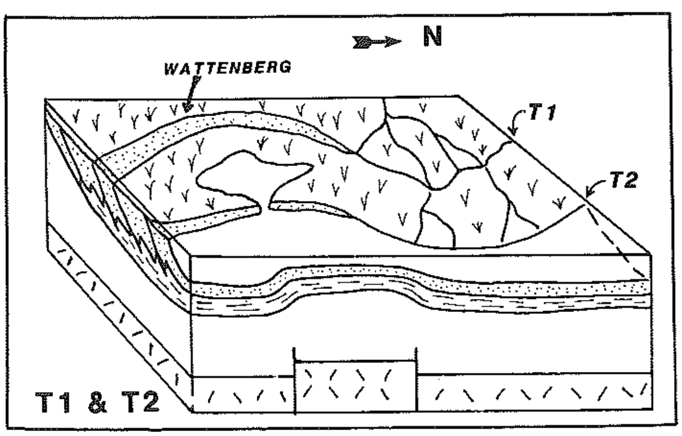


Figure 18—Depositional and tectonic model for Fort Collins Member of J Sandstone showing highstand regression over basement fault blocks (Wattenberg high) with penecontemporaneous movement. T_1, time 1; T_2, time 2. Rate of sediment supply exceeds rate of subsidence or submergence.

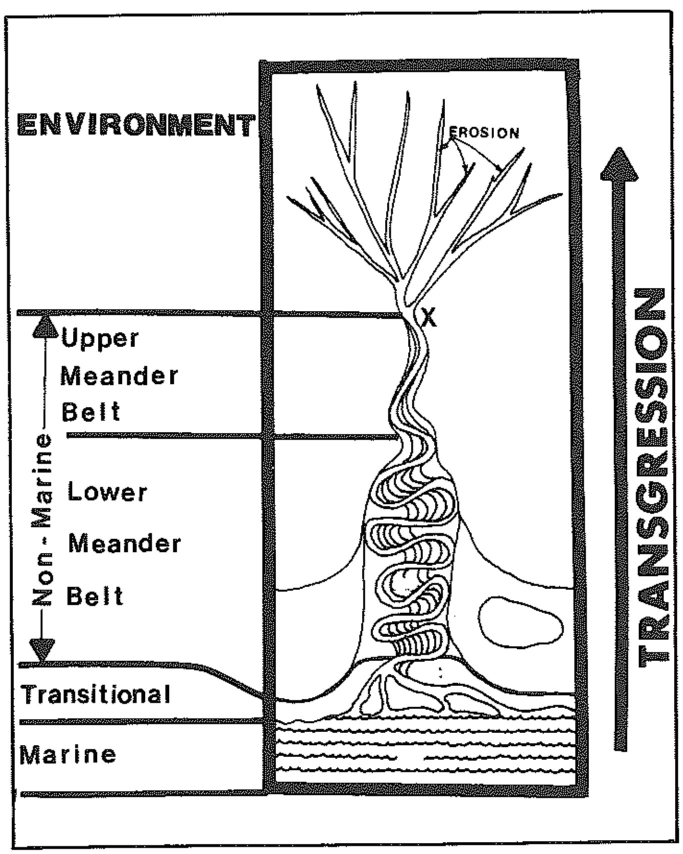


Figure 20—Environments of deposition in an alluvial valley and shoreline setting. X marks reference point for vertical changes in lithology in valley-fill deposits as sea level rises and environments shift landward during transgression.

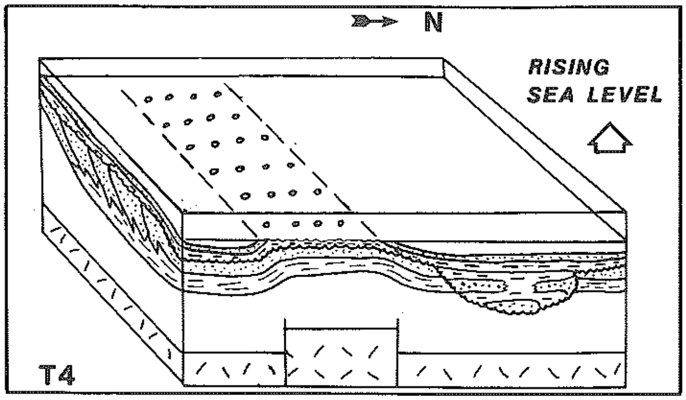


Figure 21—Rising sea level during Time 4 (T_4) with fill of incised valley and deposition of marine shale and sandstones. A thin transgressive lag (generally less than 0.3 m thick) of conglomeratic sandstone (indicated by circles) occurs in association with basement-controlled horst block.

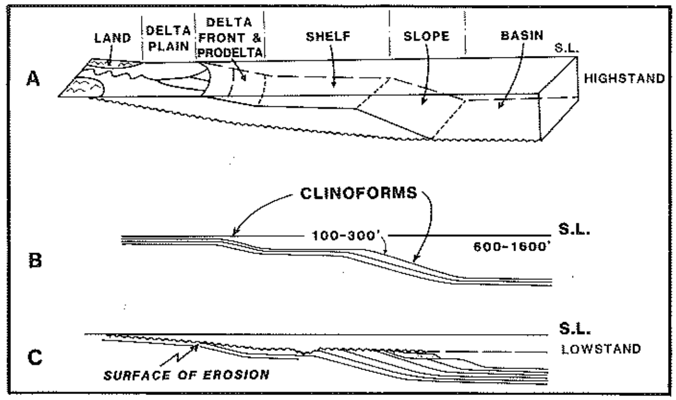


Figure 23—Cross section showing depositional topography in Cretaceous basin during highstand of sea level (A). Areas of depositional dip (clinoforms) develop by lateral accretion during deposition (B). Erosional surface develops across shelf during lowstand of sea. S.L., sea level; numbers give water depth in feet.

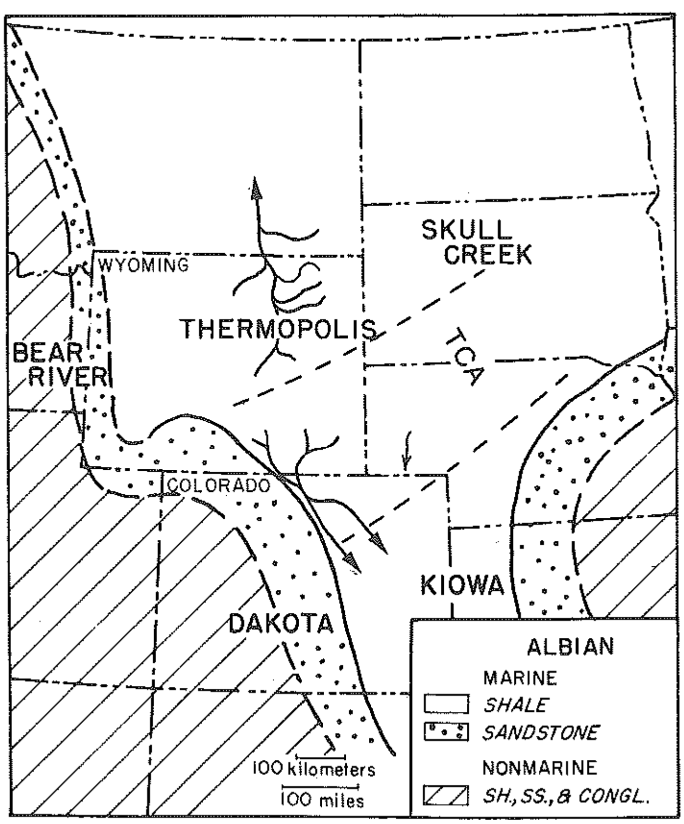


Figure 22—Map showing shoreline trends during high stand of sea level during Skull Creek deposition with direction of flow of incised drainage during subsequent sea level drop (lines within marine area). A drainage divide developed across the basin in the area of the Transcontinental arch (TCA).

model has been developed for Cenomanian and Turonian strata in the Denver basin and adjacent areas. A stratigraphic section from near Hays, Kansas, to central Wyoming incorporates surface and subsurface data (Figures 24 and 25). Ages of formations at each end of the section are based on ammonite correlations. Elsewhere subsurface correlations are by stratal continuity of bentonite layers in shale units, and thin limestones (chalks) identified in thousands of well logs in the Denver basin. Cobban and associates have developed faunal zones (Table 1) for the Cenomanian, Turonian, and Coniacian stages (Merewether et al., 1979). These faunal zones have been related to lithologic markers and traced over a large area as time-stratigraphic units (Weimer, 1978, 1983; Sonnenberg and Weimer, 1981). Shelf sedimentation for the Cenomanian and Turonian is well illustrated by the interbedded sandstones and shales of the Frontier Formation (Figure 25) in central Wyoming (Merewether et al., 1979). They estimate water depths on the shelf of less than 130 m. Synchronous basin sedimentation is represented by chalks of the Greenhorn and Fairport of Kansas (Figure 25). A major unconformity associated with shelf sedimentation (90 m.y. lowstand) is present within the Carlile and Frontier formations.

Carlile Formation

The Carlile Formation in the Great Plains province consists of four widespread members which in ascending order are the Fairport chalk, the Blue Hill Shale, the Codell Sandstone, and the Juana Lopez. A fifth member, the Sage Breaks Shale, is present as the upper Carlile in the northern Denver basin and Powder River basin area. The Juana Lopez member is a lenticular limestone unit that is locally conspicuous in outcrop along the west flank of the Denver basin but is generally too thin (less than 1 m) to map in the subsurface. The unit is ubiquitous in outcrop along the southern margin of the Denver basin and adjacent areas to the south. The unit is absent in outcrop (Figure 25) over most of central Kansas (Hattin, 1975b).

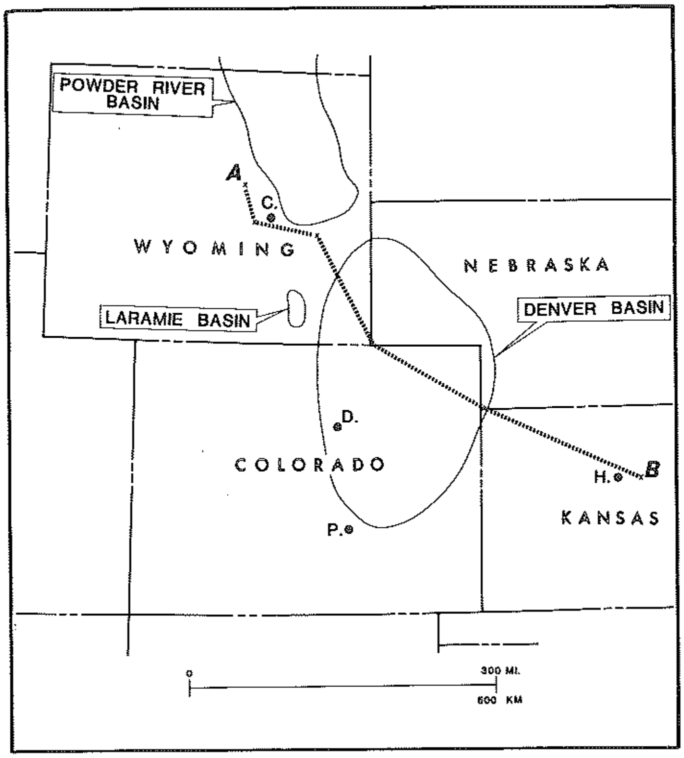


Figure 24—Index map for stratigraphic section from central Wyoming to central Kansas (Figure 25). C, Casper; D, Denver; P, Pueblo; H, Hays.

The Carlile contains one or more unconformities in the upper portion which play a significant role in the thickness and depositional patterns. The thickness of the Carlile varies from less than 15 m to more than 60 m (Figures 25 and 26). The Fairport and Blue Hill members in Kansas are progressively cut out westward by an unconformity at the base of the Codell Sandstone, or in its absence the unconformity at the base of the Fort Hays Limestone (Figure 25). A similar relationship was observed in north–south correlations from the more complete Pueblo, Colorado, section (similar to central Kansas) with the strata in the northern Denver basin (Weimer, 1978).

If a model for a shelf, slope, and basin is used for deposition of the Carlile (Figure 23), the associated regional unconformities can be easily explained by a combination of eustatic changes and tectonic movement. Several important stratigraphic relations in the area from central Wyoming to Kansas support this model.

The Fairport chalk of Kansas (basin deposit) thickens westward and changes across the Denver basin to siltstone and shale with the well-developed clinoforms of slope deposits (Figure 25), especially in southeastern Wyoming and western Nebraska.

The Codell Sandstone in portions of central Kansas and in the Pueblo, Colorado, area has a transitional contact with the underlying Blue Hill Shale (Hattin, 1962; Merriam, 1957, 1963; Pinel, 1977). However, over much of the Denver basin the Codell is sporadically developed, and where present, an unconformity is observed at the base, which has a hiatus increasing in magnitude to the west (Figure 25). A subcrop map of formations beneath the surface of erosion illustrates these relationships (Figure 26). In the northern Front Range area and the Laramie basin, the Codell Sandstone rests on strata equivalent to the middle Greenhorn (faunal zone 8 or 9).

The regional subcrop pattern of the Fairport and Greenhorn beneath the unconformity shows a broad eastward bulge in southern Wyoming and northern Colorado (Figure 27). This feature is related to a structural doming with the beveling of faunal zones 9 through 13 from central Wyoming to Kansas. The regional distribution of regressive sandstone during faunal zone 14 (*Prionocyclus hyatti*) suggests a major sea level drop of short time duration (Table 1). The scour and fill pattern in central Wyoming (Figure 25), showing remnants of faunal zones 12 and 13 (Fairport equivalents) on faunal zone 8 (lower Greenhorn equivalents), suggests movement of local tectonic elements superimposed on the broad doming. Structural movement with erosion started during or after the deposition of faunal zones 12 and 13 (the unnamed member of the Frontier Formation of Merewether et al., 1979). Units 12 and 13 were either deposited over the entire area and subsequently removed by erosion, or they were deposited only in topographic (structural) low areas. Regional correlations suggest that sea level remained high during faunal zones 9 through 13 (Table 1) so the erosion is thought to be related to structural movement and submarine scour. The clinoform pattern of slope and basin deposits in the upper Greenhorn and Fairport formations (Figure 25) may be the result of rapid deposition because of sediment recycling by erosion on the top and deposition on the margin of the broad structural element.

Erosion by subaerial or submarine processes on the shelf during a sea level drop (faunal zone 14) removed strata and erosional depressions (valleys?) were cut into shelf deposits as base level was lowered. Chert pebbles and fine- to coarse-grained sand were transported across the shelf by streams and currents. These scours are observed mainly in the northernmost Denver basin.

With the subsequent rise in sea level (the time of either late faunal zone 14 or zone 15) three types of sandstone were deposited above the surface of erosion: (1) thick sand deposits of fresh or brackish water origin accumulated in the scour depressions, (2) thin widespread fine-grained bioturbated shelf sand, and (3) coarsening upward fine- to medium-grained sand reworked into marine bar complexes. These sands are best preserved in the northern Denver basin. These types of sand occurrences, deposited during a changing sea level, are believed similar to those observed on the modern shelf of the Gulf of Mexico (Figures 5, 6, and 7) as described by Nelson and Bray (1970).

In the southern Denver basin and Kansas, where sedimentation was continuous from the underlying Blue Hill through the Codell, the sand was deposited either as a shallow marine bar sequence or along a regressing shoreline during the lowstand of sea level. These sands are slightly older than the sands above the surface of erosion in the central and northern Denver basin (Figure 25).

The Juana Lopez in Colorado, a thin relict or palimpsest deposit, rests on an erosional surface with chert and

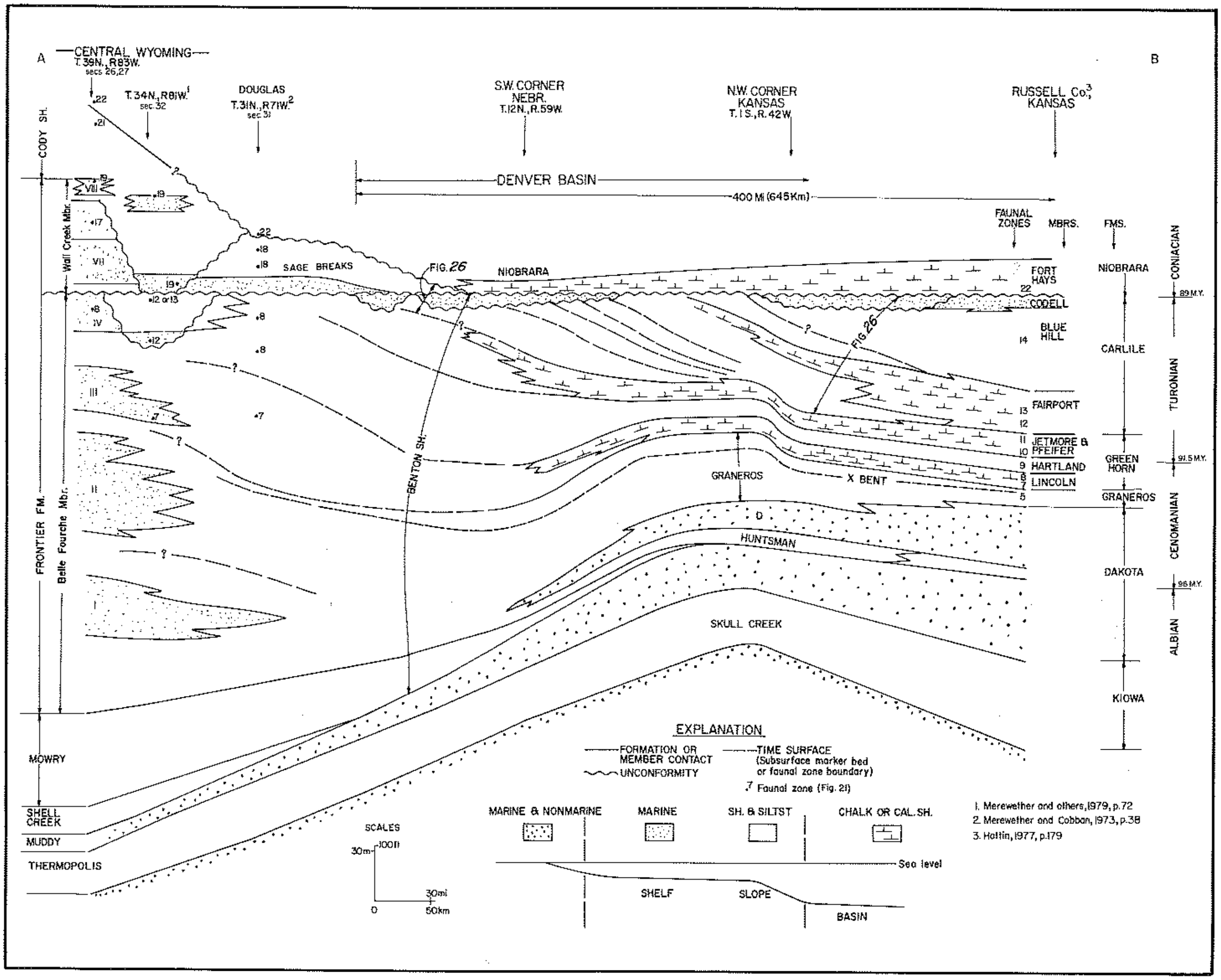


Figure 25—Restored stratigraphic section for lower part of Cretaceous from central Wyoming to central Kansas. Unconformities associated with J and D sandstones are not shown.

phosphate pebbles and coarse sand occurring as a lag in the lower portion. Bioclastic recrystallized limestone with shark teeth occurs in the upper portion. This unit, where well developed (for example, southern Colorado and northern New Mexico), contains faunal zones 15, 16, and 17 (Kauffman, 1977; Hook and Cobban, 1979). The Frontier units 6 and 7 (Wall Creek Member) (Figure 25) record this highstand in central Wyoming.

Erosion in central Wyoming described by Merewether et al. (1979) developed during or near the end of faunal zone 18 and removed sandstone and shale containing zones 16 and 17. The scour was filled by marine deposits containing faunal zone 19 (Figure 25). These relations are interpreted to result from tectonic movement and submarine scour similar to those previously described in the same area for faunal zones 8 through 13. However, an alternative interpretation is for erosion to have occurred on the shelf during minor sea level drops at the times of faunal zones 10 or 11 and 18 or 19. Some regional evidence supports a possible drop during 18 or 19.

Over much of the central Denver basin and eastward into Kansas (Figure 25) a widespread surface of erosion is also present above the Codell Sandstone with the upper part of the Fort Hays Member of the Niobrara Formation (either faunal zone 21 or 22) resting on the surface of erosion. This unconformity has been related by Weimer (1978) to result from erosion and then marine onlap on a broad northeast-trending structural element called the Transcontinental arch. Sparse faunal evidence suggests that the hiatus represents the time of faunal zones 15 through 21 or 22. The erosion may have been associated with the possible sea level drops during faunal zones 18 or 19.

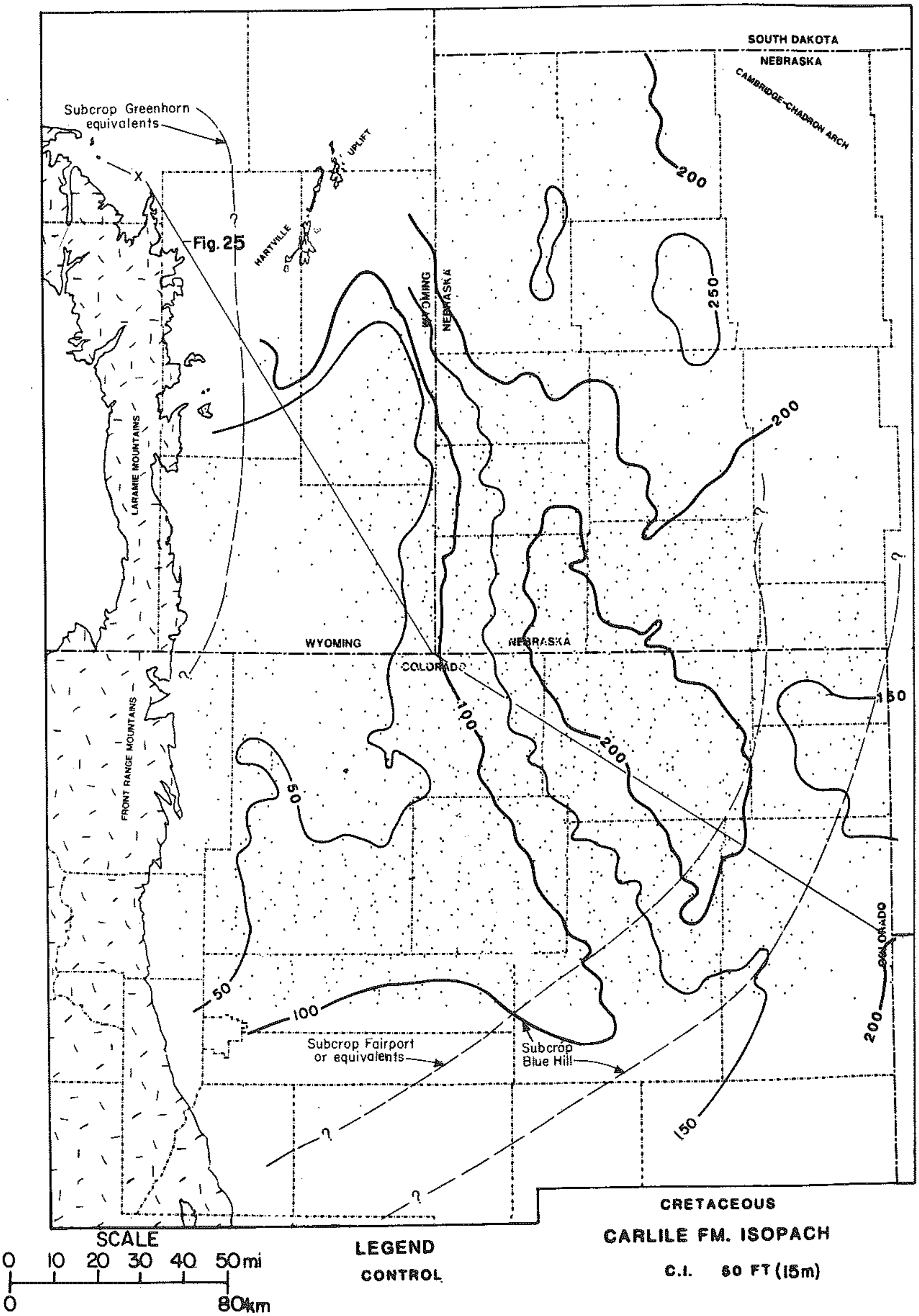


Figure 26—Isopach map of Carlile Formation with areas of subcrop of Fairport, Blue Hill, and Greenhorn beneath erosional surface at base of Codell Sandstone or Fort Hays Limestone (see Figure 25).

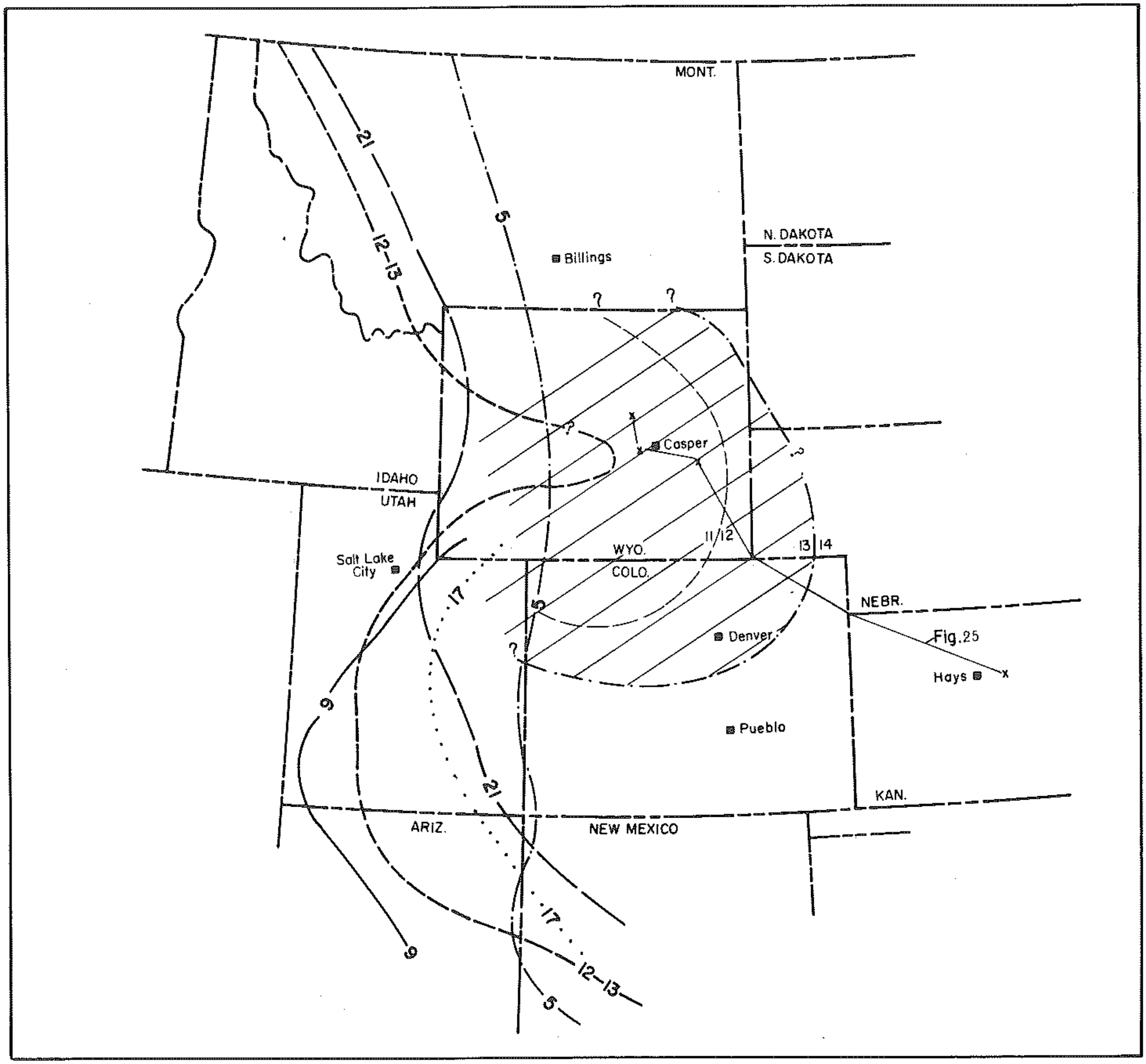


Figure 27—Regional distribution of faunal zones indicating geographic position of shoreline during highstands of sea level. Faunal zones 5 and 12-13, after Cobban and Hook (1979, 1980); faunal zones 9, 17, and 21, after Hook and Cobban (1977, 1979, 1980). Diagonal ruling indicates area of erosion because of structural movement and a low stand of sea level (faunal zone 14).

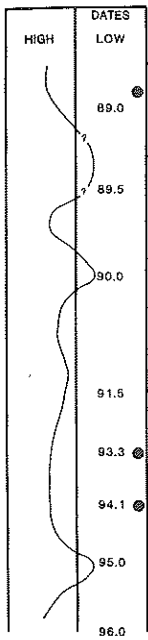
The approximate positions of the western shoreline of the basin for highstands during faunal zones 5, 9, 12, 13, 17, and 21 (Figure 27) have been mapped by Hook and Cobban (1977, 1979, 1981a) and Cobban and Hook (1979, 1981). Because of the lack of detailed faunal data on a regional basis, the pattern of deposition and erosion is preliminary in nature and no attempt has been made to change shoreline trends. Some of these shorelines must be significantly modified because of the erosion of faunal zones from the paleohigh (Figure 25), especially for faunal zones 9 through 14.

EXAMPLE OF TECTONIC MOVEMENT AND SEA LEVEL CHANGES AFFECTING BASIN DEPOSITS (80-81 M.Y. AGO)

Niobrara Formation

Following the late Turonian (Carlile and equivalents of previous section) depositional patterns changed significantly. During the Coniacian, the Niobrara Formation (composed of chalk and organic rich shale deposition, similar in lithology to the Greenhorn) was deposited over eastern Colorado, Kansas, and adjacent areas (Figures 10 and

Table 1—Faunal zones in lower part of Upper Cretaceous. After Merewether et al. (1979). Dots are faunal zones with radiometric dates. After Obradovich and Cobban (1975); modified by Fouch (1983).



DATES	STAGE	FAUNAL ZONES	FORMATIONS
	SANT.	25 CLIOSCAPHITES SAXITONIANUS	
	SANT.	24 SCAPHITES DEPRESSUS	
	CONIACIAN	23 SCAPHITES VENTRICOSUS	NIOBRARA
●	CONIACIAN	22 INOCERAMUS DEFORMIS	NIOBRARA
89.0	CONIACIAN	21 INOCERAMUS ERECTUS	NIOBRARA
	CONIACIAN	20 INOCERAMUS WALTERSDORFENSIS	NIOBRARA
	TURONIAN	19 PRIONOCYCLUS QUADRATUS	CARLILE
89.5	TURONIAN	18 SCAPHITES NIGRICOLLENSIS	CARLILE
	TURONIAN	17 SCAPHITES WHITFIELDI	CARLILE
	TURONIAN	16 SCAPHITES WARRENI	CARLILE
	TURONIAN	15 PRIONOCYCLUS MACOMBI	CARLILE
90.0	TURONIAN	14 PRIONOCYCLUS HYATTI	CARLILE
	TURONIAN	13 COLLIGNONICERAS WOOLLGARI (LATE FORM)	CARLILE
	TURONIAN	12 COLLIGNONICERAS WOOLLGARI (EARLY FORM)	CARLILE
	TURONIAN	11 MAMMITES NODOSOIDES	GREENHORN
	TURONIAN	10 WATINOCERAS COLORADOENSE	GREENHORN
91.5	CENOMANIAN	9 SCIPONOCERAS GRACILE	GREENHORN
	CENOMANIAN	8 DUNVEGANOCERAS ALBERTENSE	GREENHORN
93.3 ●	CENOMANIAN	7 DUNVEGANOCERAS PONDI	GREENHORN
	CENOMANIAN	6 PLESIACANTHOCERAS WYOMINGENSE	GRANEROS
94.1 ●	CENOMANIAN	5 ACANTHOCERAS AMPHIBOLUM	GRANEROS
	CENOMANIAN	4 ACANTHOCERAS ALVARADOENSE	GRANEROS
	CENOMANIAN	3 ACANTHOCERAS MULDOONENSE	GRANEROS
95.0	CENOMANIAN	2 ACANTHOCERAS GRANEROSENSE	GRANEROS
	CENOMANIAN	1 CALYCOCERAS GILBERTI	GRANEROS
	CENOMANIAN	NO MOLLUSKAN FOSSIL RECORD	
96.0			MOWRY

28). This lithologic change from Carlile to Niobrara was the result of a significant increase in water depth as the shoreline zone shifted to western Wyoming and Utah (highstand 21, Figure 27). The shelf–slope break shifted westward in a corresponding manner to central Wyoming (Figure 29). Thus, the northern Denver basin, where shelf and slope deposits were dominant in the Carlile, became an area of chalk and shale deposits of the basin setting.

Whereas thickness changes associated with the Greenhorn chalks follow a regional pattern (Sonnenberg and Weimer, 1981), the Niobrara shows many thickness anomalies of a more local distribution (Figure 28). The Niobrara Formation in the northern Denver basin varies in thickness from 75 m to more than 150 m. The formation or equivalent strata are thicker to the south in the Pueblo area and to the north in the Powder River basin (Figure 28).

Within the Niobrara, four limestone intervals and three intervening shale intervals occur regionally and are easily recognized on geophysical logs (Figure 16). The lower limestone is named the Fort Hays and the overlying units are grouped together as the Smoky Hill Member (Scott and Cobban, 1964). The lower boundary is an erosional surface where the limestone is in contact with either Carlile Shale or, in some places, strata as old as the Greenhorn Formation. The upper boundary of the Niobrara is placed at the contact with the noncalcareous black shales of the Pierre Shale. Locally, the contact is an erosional surface; elsewhere the contact is transitional.

Regionally, the northern Denver basin has a thin Niobrara section that is related to structural movement on the Transcontinental arch (Weimer, 1978) and depositional thinning because of slow rates of deposition. Superimposed on the broad pattern are the major northeast–southwest axes of thinning (Figure 28), which are related to second-order paleotectonic elements (Sonnenberg and Weimer, 1981). Thinning over the paleohighs results from erosion of the upper chalk and underlying shale (Figure 16), whereas these strata are preserved in structural and topographic lows between the structural highs (Weimer, 1980).

The time of major movement on the paleohighs was near the end of Niobrara deposition or early in the deposition of the Pierre Shale. The maximum thinning occurs over the Wattenberg paleostructure where up to 30 m of Upper Niobrara was removed by sea floor erosion prior to deposition of the overlying Pierre (Figure 28).

Minor thinning also occurs at the base of each of the four limestones of the Niobrara in local areas. Regional unconformities can be mapped at the base of the Fort Hays and the base of the second chalk from the top of the Niobrara (Figure 16). Because these breaks occur within the deep water sediments generally during highstand conditions, the breaks may be associated with marine onlap processes as diagrammed by Vail et al. (1977).

A major question is what changed the pattern of structural movement from a broad regional uplift centered in Wyoming during Carlile deposition (Figures 26 and 27) to the movement on northeast structural trends centered in Colorado during late Niobrara and early Pierre deposition (Figure 28). The answer may be related to the direction and rate of movement of the American plate. Normally the plate had western movement to establish the tectonic framework shown on Figures 9 and 29. Either a more rapid rate of westward movement, or a more northwesterly movement may have caused vertical movement on northeast-trending basement faults with submarine erosion recurring over the higher standing blocks.

At approximately the same time as fault blocks were reactivated in the northern Denver basin, volcanic activity on the sea floor, during deposition of the Austin chalk, occurred in Texas (Figure 29) (Simmons, 1967). Ancient submarine volcanoes occur along a northeast trend across central Texas. The lithology of the igneous material is ultrabasic to basic in composition and the features are referred to as "serpentine plugs" altered from igneous rocks rich in olivine. Carbonate reefs are found fringing or capping the volcanoes. Depth of the sea during deposition of the upper Austin is estimated to have been between 60 to 245 m (Simmons, 1967).

The northeast trend of the volcanoes was related by Simmons (1967) to extrusion above basement fault systems. Tension along the Balcones fault zone opened the crust to allow mantle-derived material to be intruded in the strata or to be erupted on the sea floor as volcanoes.

The Austin chalk of Texas is correlated with the Niobrara Formation of eastern Colorado and Kansas. Thus, at the time of the volcanic events in Texas, basement fault block movement occurred on second order structures along the ancestral Transcontinental arch (Figure 29). Moreover, major thrusting was in progress along the Meade–Crawford thrust sheets in western Wyoming and Utah (Royse et al., 1975; Jordan, 1981). The timing of these events is approximately 80–81 m.y. ago.

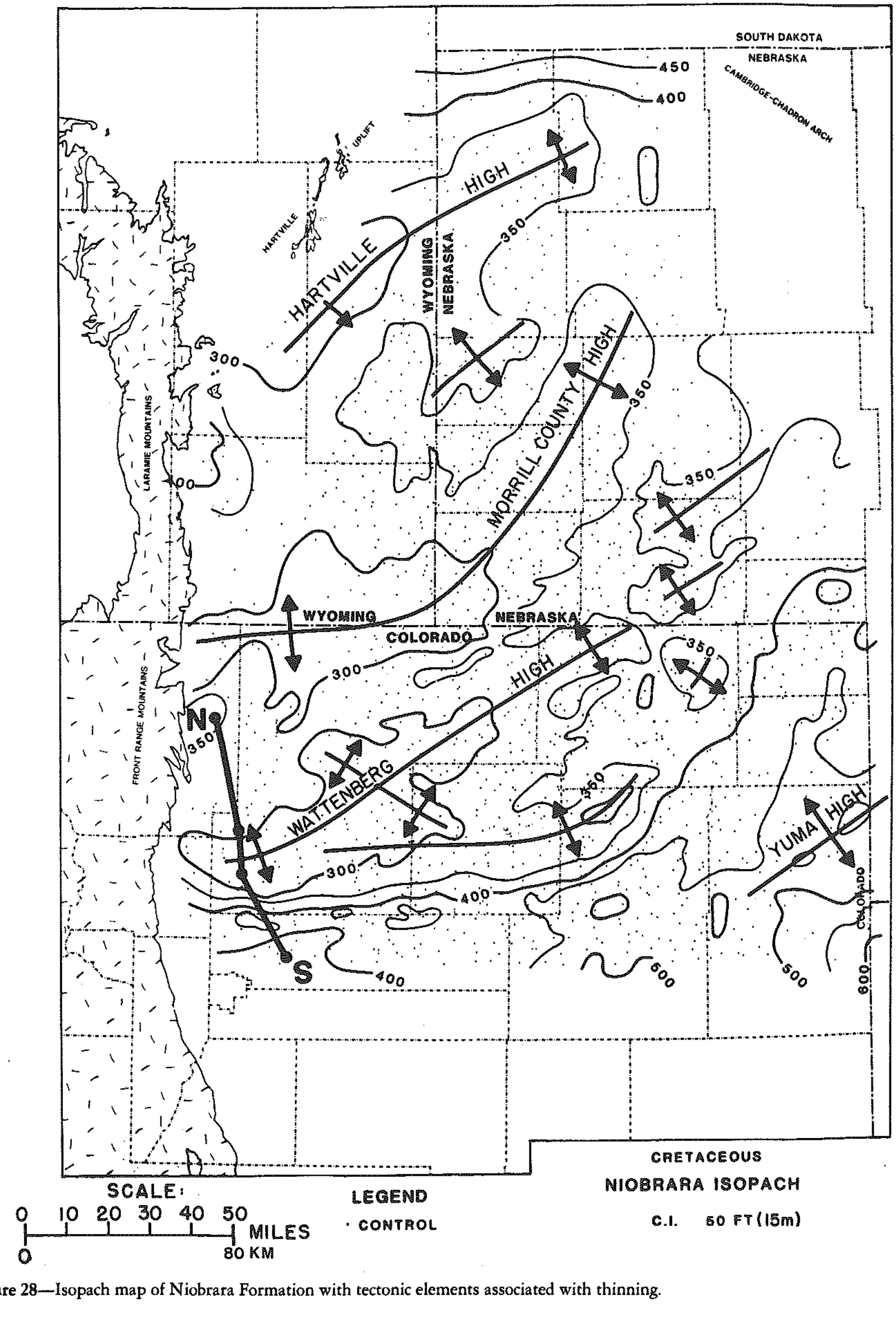


Figure 28—Isopach map of Niobrara Formation with tectonic elements associated with thinning.

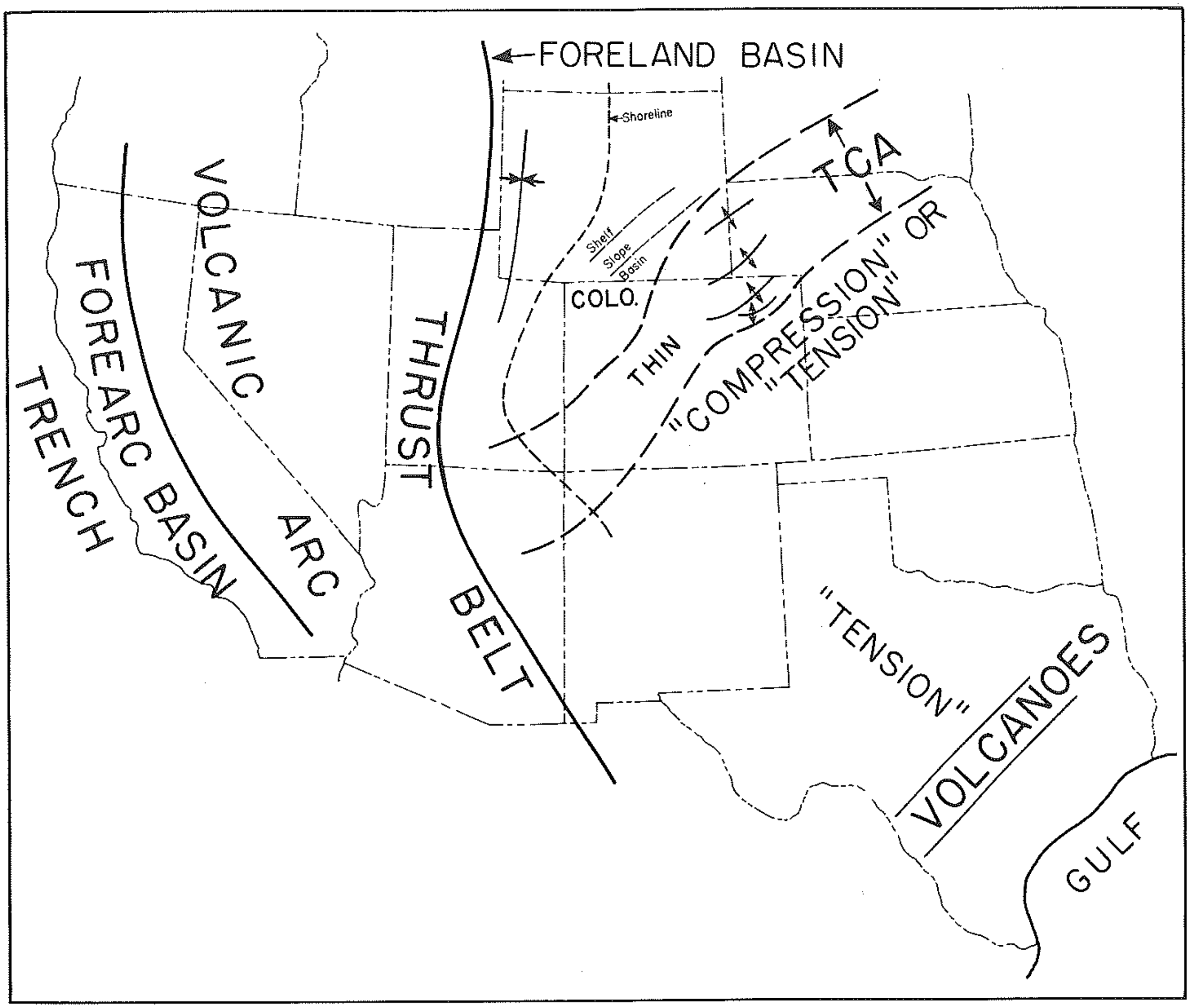


Figure 29—Map of western United States showing events in Cretaceous foreland basin during deposition of upper Niobrara and Austin strata (80–81 m.y. ago).

Uplift of the fault blocks on the sea floor in the northern Denver basin could have resulted from compression with the blocks forming topographic and structural highs; or, a broad arch related to compression may have been modified by tension with some blocks subsiding to lower structural positions than adjacent more positive blocks.

The structural movement was synchronous with a possible sea level drop. The upper Niobrara chalk is a basin facies equivalent of the Eagle and Shannon sandstones of Montana and Wyoming. The wide distribution of these shelf sandstones may have been related to events similar to the processes described previously for the Carlile Formation. A lower sea level would have affected storm wave base and associated scour. By a lowering of storm wave base, strata were removed by erosion over the topographic (structural) highs but not in the intervening structural and topographic lows. Thus, the Niobrara isopach pattern and associated unconformities are interpreted to result from a northwest direction of plate motion, the development of compression to uplift parts of the sea floor, and submarine scour during a contemporaneous sea level drop. Following these events, a normal pattern of tectonics and sedimentation for the Western Interior Cretaceous was resumed for the time of lower Pierre sedimentation.

PETROLEUM OCCURRENCE

Modern petroleum exploration integrates geologic factors that relate to origin, migration, and accumulation of oil and gas. The factors are source beds, generation area, migration paths, reservoir, seal, time of formation, and preservation of trap.

The principal source beds in the Denver basin have been identified as the Benton Group (Graneros, Greenhorn, and Carlile) by Clayton and Swetland (1980). They believe that oil was generated in the deeper parts of the Denver basin and that migration occurred from these organically rich layers into the J (Muddy) Sandstone. In the proposed depositional model (Figures 23 and 25), the organic-rich source beds originated as basin and slope deposits. These are deeper water deposits where anoxic conditions favored preservation of organic matter.

Reservoir rocks in the J (Muddy) Sandstone are of two main types: one is the widespread marine delta front sandstone (Fort Collins Member) illustrated by the Wattenberg field. The second is the fluvial channel sandstone facies of the valley-fill deposits (Horsetooth Member). Because most of the individual sand bars within the channel complex are small in geographic distribution, the oil fields are small (generally less than 2 million bbl of reserves per field).

The trap for petroleum may be either facies changes within the valley fill from reservoir to nonreservoir rock, or the unconformity surface. In the latter case, wedge out of sandstone against an impermeable valley wall occurred, or erosion of porous sandstone with impermeable shales placed in the scour forming a trap.

Reservoir rocks in the Frontier Formation in central Wyoming are lenticular marine shelf sandstones which occur both above and below the major surface of unconformity (Figure 25). Petroleum occurs where offshore marine sandstones are in favorable structural condition for entrapment. Over 400 million bbl of oil have been produced from the Second Wall Creek Sandstone at the Salt Creek field, Wyoming (Barlow and Haun, 1966). This sandstone is shown as Unit 3 of the Frontier Formation on Figure 25 (Merewether et al., 1979). Many other fields in central Wyoming also produce from the Frontier Formation.

CONCLUSIONS

Stratigraphic evaluation of ancient sequences has been directed principally toward the construction of a depositional model to explain the origin and distribution of formations, facies, and time-stratigraphic units. For some sequences, little attention has been given to the possible influence of intrabasin deformation on sedimentation and the development of unconformities, especially during times of major eustatic changes.

This paper presents data and concepts that illustrate unconformities associated with the 97, 90, and 80–81 m.y. sea level changes. During these times, complex relationships existed among the following: sea level fluctuations and related changes in base level of erosion and deposition; tectonic movements and/or climatic changes in the source area that influenced the rate of sediment supply to the basin; unconformities within the basin; distribution of sandstone reservoirs related to environments of the shelf, shoreline, and alluvial valleys; and the influence of intrabasin recurrent movement of basement fault blocks. The stratigraphic record from studies of inland cratonic basins should be coordinated with studies of plate margin areas and of other continents.

By evaluating the above factors, a more complete geologic model can be constructed and used as a powerful predictive tool in stratigraphic trap exploration for petroleum. Improved modeling will aid significantly in the interpretation and use of seismic data both in the older mature areas of exploration and in frontier areas.

ACKNOWLEDGMENTS

I appreciate S. A. Sonnenberg's assistance in compiling and interpreting subsurface data, and am grateful to the Getty Oil Company for making the research possible by generous financial support. Barbara Brockman typed the manuscript and Craig Corbin drafted many of the illustrations. I thank M. Reynolds, T. D. Fouch, and P. C. Weimer for helpful suggestions in improving the manuscript.

REFERENCES CITED

Asquith, D. O., 1970, Depositional topography and major marine environments, Late Cretaceous, Wyoming: AAPG Bulletin, v. 54, n. 7, p. 1184–1224.

Barlow, J. A., Jr., and J. D. Haun, 1966, Regional stratigraphy of Frontier Formation and relation to Salt Creek field, Wyoming: AAPG Bulletin, v. 50, n. 10, p. 2185–2196.

Blackwelder, E., 1909, The valuation of unconformities: Journal of Geology, v. 17, p. 289–300.

Clark, B. A., 1978, Stratigraphy of the Lower Cretaceous J Sandstone, Boulder County, Colorado—a deltaic model, *in* J. D. Pruit, and P. E. Coffin, eds., Proceedings, Symposium on mineral resources of the Denver basin: Rocky Mountain Association of Geologists, p. 237–246.

Clayton, J. L., and P. J. Swetland, 1980, Petroleum generation and migration in Denver basin: AAPG Bulletin, v. 64, p. 1613–1634.

Cobban, W. A., and S. C. Hook, 1979, *Collignoniceras woollgari woollgari* (Mantell) ammonite fauna from Upper Cretaceous of Western Interior, United States: New Mexico State Bureau of Mines and Mineral Resources Memoir 37, p. 5–51.

———, 1980, Occurrence of *Ostrea beloiti* Logan in Cenomanian rocks of Trans-Pecos Texas: New Mexico Geological Society 31st Field Conference Guidebook, p. 169–172.

———, 1981, New turrilitid ammonite from mid-Cretaceous (Cenomanian) of southwest New Mexico: New Mexico State Bureau of Mines and Mineral Resources Circular 180, p. 22–35.

Curray, J. R., 1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico, *in* F. P. Shepard, F. B. Phleger, and T. J. van Andel, eds., Recent sediments, northwest Gulf of Mexico: AAPG Special Publication, p. 221–266.

———, 1975, Marine sediments, geosynclines and orogeny *in* A. G. Fischer, and S. Judson, eds., Petroleum and global tectonics: Princeton University Press, Princeton, New Jersey, p. 157–217.

Dickinson, W. R., 1976, Plate tectonic evolution: AAPG Continuing Education Course Note Series 1, p. 46.

Eicher, D. L., 1969, Paleobathymetry of Cretaceous Greenhorn sea in eastern Colorado: AAPG Bulletin, v. 53, n. 5, p. 1075–1090.

Fisk, H. N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: Vicksburg, Mississippi, U. S. Corps of Engineers, Waterway Experiment Station, 98 p.

Fouch, T. D., 1983, Patterns of synorogenic sedimentation in Upper Cretaceous rocks of central and northeastern Utah, *in* M. Reynolds, and E. Dolly, eds., Mesozoic paleogeography of west-central United States: Denver, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section Special Publication, p. 305–336.

Hancock, J. M., 1975, The sequence of facies in the Upper Cretaceous of northern Europe compared with that in the Western Interior, *in* W. G. C. Caldwell, ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper No. 13, p. 82–118.

———, and E. G. Kauffman, 1979, The great transgressions of the Late Cretaceous: Geological Society of London Journal, v. 136, p. 175–186.

Hattin, D. E., 1962, Stratigraphy of the Carlile Shale (Upper Cretaceous) in Kansas: Kansas Geological Survey Bulletin, n. 156, 155 p.

———, 1975a, Stratigraphy and depositional environment of Greenhorn Limestone (Upper Cretaceous) of Kansas: Kansas Geological Survey Bulletin, n. 209, 128 p.

———, 1975b, Stratigraphic study of the Carlile-Niobrara (Upper Cretaceous) unconformity in Kansas and northeastern Nebraska: Geological Association of Canada Special Paper No. 13, p. 195–210.

Haun, J. D., 1963, Stratigraphy of Dakota Group and relationship to petroleum occurrence, northern Denver basin, *in* P. J. Katich, and D. W. Bolyard, eds., Geology of the northern Denver basin and adjacent uplifts: Rocky Mountain Association of Geologists Guidebook, p. 119–134.

Hook, S. C., and W. A. Cobban, 1977, *Pycnodonte newberryi* (Stanton)—common guide fossil in Upper Cretaceous of New Mexico: New Mexico State Bureau of Mines and Mineral Resources Annual Report, p. 48–54.

———, 1979, *Prionocyclus novimexicanus* (Marcou)—common Upper Cretaceous guide fossil in New Mexico: New Mexico State Bureau of Mines and Mineral Resources Annual Report, p. 35–42.

———, 1980, Some guide fossils in Upper Cretaceous Juana Lopez member of Mancos and Carlile shales, New Mexico: New Mexico State Bureau of Mines and Mineral Resources Annual Report, p. 38–49.

———, 1981b, Late Greenhorn (mid-Cretaceous) discontinuity surfaces, southwest New Mexico, *in* S. C. Hook, compiler, Contributions to mid-Cretaceous paleontology and stratigraphy of New Mexico: New Mexico State Bureau of Mines and Mineral Resources Circular 180, p. 5–36.

Jeletzky, J. A., 1978, Causes of Cretaceous oscillations of sea level in western and arctic Canada and some general geotectonic implications: Geological Survey of Canada Paper 77-18, 38 p.

Jordan, T. E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: AAPG Bulletin, v. 65, p. 2506–2520.

Kauffman, E. G., 1977, Upper Cretaceous cyclothems, biotas, and environments, Rock Canyon anticline, Pueblo, Colorado: The Mountain Geologist, v. 14, n. 3 and 4, p. 129–152.

Kent, H. C., 1967, Microfossils from the Niobrara Formation (Cretaceous) and equivalent strata in northern and western Colorado: Journal of Paleontology, v. 41, n. 6, p. 1433–1456.

Lanphere, M. A., and D. L. Jones, 1978, Cretaceous time scale from North America, *in* G. V. Cohee, and M. F. Glaessner, eds., The geologic time scale: AAPG Studies in Geology, n. 6, p. 259–268.

Lindstrom, L. J., 1979, Stratigraphy of the South Platte Formation (Lower Cretaceous), Eldorado Springs to Golden, Colorado, and channel sandstone distribution of J Member: Master's thesis, Colorado School of Mines, Golden, Colorado, 142 p.

MacKenzie, D. B., 1965, Depositional environments of Muddy Sandstone, Western Denver basin, Colorado: AAPG Bulletin, v. 49, p. 186–206.

———, 1971, Post-Lytle Dakota Group on west flank of Denver basin, Colorado: The Mountain Geologist, v. 8, n. 3, p. 91–131.

Matuszczak, R. A., 1976, Wattenberg Field: a review, *in* R. C. Epis, and R. J. Weimer, eds., Studies in Colorado field geology: Golden, Colorado, Colorado School of Mines Professional Contribution 8, p. 275–279.

McGookey, D. P., 1972, Cretaceous system, *in* W. W. Mallory, ed., Geologic atlas Rocky Mountain region: Rocky Mountain Association of Geologists Special Publication, p. 190–228.

Merewether, E. A., and W. A. Cobban, 1972, Unconformities within the Frontier Formation, northwestern Carbon County, Wyoming: U.S. Geological Survey Professional Paper 800-D, p. D57–D66.

Merewether, E. A., and W. A. Cobban, 1973, Stratigraphic sections of the Upper Cretaceous Frontier Formation near Casper and Douglas, Wyoming: Wyoming Geological Association Earth Science Bulletin, v. 6, n. 4, p. 38–39.

Merewether, E. A., W. A. Cobban, and C. W. Spencer, 1976, The Upper Cretaceous Frontier Formation in the Kaycee-Tisdale Mountain area, Johnson County, Wyoming: Wyoming Geological Association 28th Annual Field Conference Guidebook, p. 33–44.

Merewether, E. A., W. A. Cobban, and E. T. Cavanaugh, 1979, Frontier Formation and equivalent rocks in eastern Wyoming: The Mountain Geologist, v. 16, n. 3, p. 67–101.

Merriam, D. F., 1957, Subsurface correlation and stratigraphic relation of rocks of Mesozoic age in Kansas: Kansas Geological Survey Oil and Gas Investigations n. 14, 25 p.

———, 1963, The geologic history of Kansas: Kansas Geological Survey Bulletin, n. 162, 309 p.

Nelson, H. F., and E. E. Bray, 1970, Stratigraphy and history of the Holocene sediment in the Sabine-High Island area, Gulf of Mexico, *in* J. P. Morgan, and R. H. Shaver, eds., Deltaic sedimentation modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication, n. 15, p. 48–77.

Obradovich, J. D., and W. A. Cobban, 1975, A time scale for the Late Cretaceous of the Western Interior of North America, *in* W. G. A. Caldwell, ed., The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper, n. 13, p. 31–54.

Peterson, W. L., and S. D. Janes, 1978, A refined interpretation of depositional environments of Wattenberg Field, Colorado, *in* J. D. Pruit, and P. E. Coffin, eds., Rocky Mountain Association of Geologists Symposium, Energy Resources of the Denver Basin: Denver, Rocky Mountain Association of Geologists, p. 141–147.

Pinel, M. J., 1977, Stratigraphy of the upper Carlile and lower Niobrara formations (Upper Cretaceous), Fremont and Pueblo counties, Colorado: Master's thesis, Colorado School of Mines, Golden, Colorado, 111 p.

Poleschook, D., Jr., 1978, Stratigraphy and channel discrimination, J Sandstone, Lower Cretaceous group, south and west of Denver, Colorado: Master's thesis, Colorado School of Mines, Golden, Colorado, 226 p.

Reeside, J. B., Jr., 1944, Map showing thickness and general character of the Cretaceous deposits in the Western Interior of the United States: U.S. Geological Survey Oil and Gas Investigations Map OM-10.

______, 1957, Paleoecology of the Cretaceous seas of the Western Interior of the United States: Geological Society of America Memoir 67, p. 505–542.

Royse, F., Jr., M. A. Warner, and D. L. Reese, 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-northern Utah, *in* D. W. Bolyard, ed., Deep drilling frontiers of the central Rocky Mountains: Denver, Rocky Mountain Association of Geologists, p. 41–55.

Scott, G. R., and W. A. Cobban, 1964, Stratigraphy of the Niobrara Formation at Pueblo, Colorado: U.S. Geological Survey Professional Paper 454-L, p. L1–L30.

Simmons, K. A., 1967, A primer on "serpentine plugs" in south Texas, *in* W. G. Ellis, ed., Contributions to the geology of south Texas: San Antonio, South Texas Geological Society, v. 7, n. 2, p. 125–132.

Sonnenberg, S. A., and R. J. Weimer, 1981, Tectonics, sedimentation, and petroleum potential, northern Denver basin, Colorado, Wyoming, and Nebraska: Colorado School of Mines Quarterly, v. 76, n. 2, 45 p.

Suryanto, U., 1979, Stratigraphy and petroleum geology of the J Sandstone in portions of Boulder, Larimer, and Weld Counties, Colorado: Master's thesis, Colorado School of Mines, Golden, Colorado, 173 p.

Vail, P. R., R. M. Mitchum, Jr., and S. Thompson, III, 1977, Seismic stratigraphy and global sea-level changes, part 3: AAPG Memoir 26, p. 63–82.

Van Hinte, J. E., 1976, A Cretaceous time scale: AAPG Bulletin, v. 60, n. 4, p. 498–516.

Waage, K. M., 1953, Dakota group in northern Front Range foothills, Colorado: U. S. Geological Survey Professional Paper 274-B, p. 15–51.

Weimer, R. J., 1978, Influence of transcontinental arch on Cretaceous marine sedimentation: a preliminary report, *in* J. D. Pruit, and P. E. Coffin, eds., Energy resources of the Denver Basin: Denver, Rocky Mountain Association of Geologists Symposium, p. 211–222.

______, 1980, Recurrent movement on basement faults, a tectonic style for Colorado and adjacent areas, *in* H. C. Kent, and K. W. Porter, eds., Colorado geology: Denver, Rocky Mountain Association of Geologists Symposium, p. 23–35.

______, 1982, Tectonic influence on sedimentation, Early Cretaceous, east flank, Powder River basin, Wyoming and South Dakota: Colorado School of Mines Quarterly, v. 77, n. 4.

______, 1983, Relation of unconformities, tectonics, and sea-level changes, Cretaceous of Denver basin and adjacent area, *in* M. Reynolds, and E. Dolly, eds., Mesozoic paleogeography of west-central United States: Denver, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section Special Publication, p. 359–376.

Weimer, R. J., and C. B. Land, Jr., 1972, Field guide to Dakota Group (Cretaceous) stratigraphy Golden-Morrison area, Colorado: The Mountain Geologist, v. 9, n. 2 and 3, p. 241–267.

Weimer, R. J., and S. A. Sonnenberg, 1982, Wattenberg field, paleostructure-stratigraphic trap, Denver basin, Colorado: Oil and Gas Journal, v. 80, n. 12, p. 204–210.

Weimer, R. J., J. J. Emme, C. L. Farmer, L. U. Anna, T. L. Davis, and R. L. Kidney, 1982, Tectonic influence on sedimentation, Early Cretaceous, east flank, Powder River basin, Wyoming and South Dakota: Colorado School of Mines Quarterly, v. 77, n. 4.