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STRATIGRAPHIC SEQUENCES AND HYDROSTRATIGRAPHIC UNITS IN LOWER CRETACEOUS STRATA, KANSAS

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by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

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ABSTRACT

Seaward shifts in facies, evidence of subaerial exposure, and incomplete facies successions are the basis for recognizing three unconformity-bounded sequences, Cheyenne, J and D, on the eastern margin of the Cretaceous Western Interior basin in Kansas. The basal unconformities of these three sequences are equivalent to the unconformities at the bases of the Plainview Formation, J sandstone, and D sandstone in Colorado.

The lower, Cheyenne Sequence, of Kansas onlaps and progressively overlaps Jurassic and Permian strata from west to east. Internally it consists of landward-stepping progradational events of fluvial and shoreface siliciclastics succeeded by open marine shale. Formations included in the sequence are the Cheyenne Sandstone of Kansas (fluvial), the Longford Member of the Kiowa Formation (shoreface), and the Kiowa Formation (open marine). Strata deposited at the top of the sequence during relative sea-level fall are present in westernmost Kansas and Colorado but were removed by erosion in the rest of Kansas prior to deposition of the subsequent sequence.

The J Sequence contains strata between the unconformity at the top of the Kiowa Formation to the unconformity within the middle of the Dakota Formation of Kansas. It is composed of landward-stepping progradational events of fluvial and shoreface siliciclastics. Within the sequence fluvial and shoreface facies in western Kansas are transitional to entirely fluvial facies in central Kansas. Strata deposited at the top of the sequence during relative sea-level fall are present in the subsurface of westernmost Kansas but were removed by erosion in the outcrop of central Kansas prior to deposition of the subsequent sequence.

The unconformity at the top of the J Sequence is the onlap surface and basal bounding surface of the D Sequence which extends upsection to an unconformity in the upper Carlile Shale. Basal fluvial and shoreface strata of this sequence (upper Dakota Formation) occur in landward-stepping progradational events.These are succeeded by open marine shale in the last preserved landward-stepping progradational event in Kansas. The lower unconformity of this sequence is reported as Upper Cretaceous age in eastern Colorado. Therefore the upper one half of the Dakota Formation in Kansas, including all of the Janssen Clay Member and the upper part of the Terra Cotta Clay Member, is Upper Cretaceous.

Facies distributions within these sequences were used to define three hydrostratigraphic units. The lower, aquifer unit, is composed of the Cheyenne Sandstone and Longford Member of the Kiowa Formation. The middle, aquitard unit, is composed of Kiowa Formation shale. The upper, aquifer unit, is composed of the Dakota Formation. Shale of the middle aquitard unit decreases in thickness eastward due to lateral facies changes into Longford Member shoreline deposits and from erosional truncation at the base of the Dakota Formation. In central Kansas, where the shale is not present, the two aquifer units are amalgamated and hydraulically connected.

Regional sequence stratigraphic relations were used to identify stratigraphic units in a local area in central Kansas. Sandstones within the Dakota Formation in this area are lens-shaped in cross section and elongated in an west to east direction. Individual sandstones are about 30 ft thick and up to 1/4 mi wide. Large sandstone bodies over 100 ft thick and up to 2 mi wide are an amalgamation of several individual channel sandstones. Channel localization was controlled by west-east trending faults. Interconnectedness of sandstone bodies was evaluated from isopach maps of the sandstones and the sequences that contain them. Sandstone bodies are connected laterally and vertically throughout the Dakota Formation in this area.

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I would like to thank my parents, James and Frances Hamilton, and my many friends for their moral support.

Introduction

The Cheyenne Sandstone, Kiowa Formation and Dakota Formation (Albian and early Cenomanian) outcrop in a northeast-southwest band across central Kansas and in an east-west band across southern Kansas (Fig. 1). To the north and west of the outcrop they subcrop beneath the Graneros Shale. These strata were deposited along the eastern, cratonal side of the Cretaceous Western Interior seaway, far from the Sevier orogenic belt that caused greater subsidence and thicker time-equivalent stratigraphic units along the western side of the seaway. Cretaceous strata along the western margin of the seaway in Colorado, Wyoming and Utah, are far more extensively and recently studied than time-equivalent strata in Kansas. Consequently, sequence stratigraphic relations have been documented there by relating previously recognized transgressive-regressive cycles, and their internal facies architecture, to sequences and sequence-bounding unconformities. This conceptual and methodological approach has proven valuable in understanding and predicting positions of potential reservoirs, migration routes and trapping mechanisms of petroleum in Cretaceous strata. Sequence stratigraphic concepts and methods have not been applied to time-equivalent strata in Kansas. Yet, it is likely that this approach should be equally valuable to understanding the stratigraphic architecture and its control of fluid movement through subsurface strata in Kansas.

There are three principal objectives of this project. The first is to establish the sequence stratigraphic relations of Cretaceous Albian and early Cenomanian strata in Kansas and correlate these with sequences of similar age defined by Weimer (1984) in Colorado. The second is to map the sequences and lithologic units within them in the subsurface in a geographically limited area. The third is to determine hydrostratigraphic units within the sequences and suggest how they may control ground-water flow within a portion of the regional study area. These objectives are part of the Kansas Geological Survey's ongoing Dakota aquifer study (MacFarlane, ed., 1988). This study describes the stratigraphic framework that will be used to understand regional ground-water flow and ground-water quality within the Dakota aquifer.

Sequence stratigraphic relations of these Cretaceous strata were established by identifying unconformities through facies analysis and consequent recognition of seaward shifts of facies tracts. By applying this procedure, using outcrop, core and well-log data,

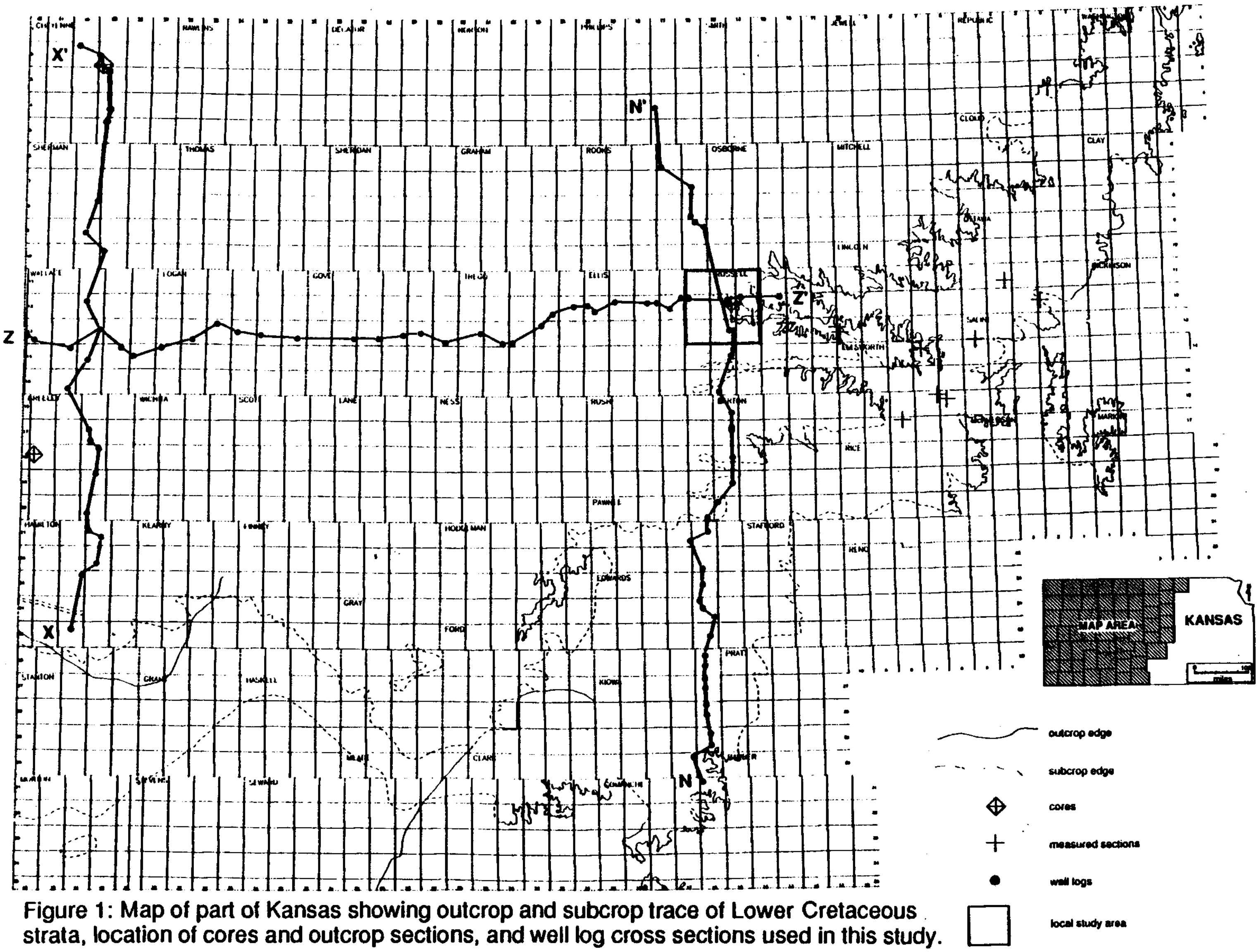


Figure 1: Map of part of Kansas showing outcrop and subcrop trace of Lower Cretaceous strata, location of cores and outcrop sections, and well log cross sections used in this study.

at multiple localities across Kansas, the positions of regionally significant unconformities were described. These unconformities constitute time-significant boundaries that separate strata into sequences which are independent of facies variations or established lithostratigraphic units. Because these unconformity-bounded sequences are regionally extensive and represent the products of sea-level change, tectonic movement and variations in sediment supply, they should correlate with sequences recognized in Colorado. They also should possess some of the internal stratigraphic architecture and facies variations described in time-equivalent sequences along the western margin of the Cretaceous seaway. However, because subsidence and sediment supply rates were far less in Kansas than in Colorado, Utah and Wyoming, some differences in the internal characteristics of sequences are expected. Description and analysis of these differences may prove generically applicable. That is, comparison of the stratal geometries and facies distributions within identical sequences deposited under markedly different conditions of subsidence and sediment supply rates may provide a data base from which the sedimentologic effects of these interdependent controls may be assessed.

For the first objective of this study, two major questions are specifically addressed. How do subsurface strata in Kansas correlate with strata in Colorado, where the sequence stratigraphy has been defined by Weimer (1984)? What is the correlation of subsurface to surface strata in Kansas? By answering these questions the geometries of these unconformity-bounded sequences and the relation of stratigraphic formations to the sequences are identified.

The second objective is to demonstrate how the sequence framework can be applied to understanding the geometry and time relations of strata in a local area. This part of the study demonstrates a methodology for understanding local stratigraphy, lithologic distributions, and aquifer geometries and interconnections. Part of this objective includes determining mappable units external and internal to the sequences, and defining geometries and trends of sandstones that may be most important in controlling movement of ground water. Another part of this objective is to determine where sandstone facies are connected to each other and to underlying and overlying formations or sequences. A final part of this objective is to determine how the sequences and lithostratigraphic units are related to structural elements. Structures may control positions of particular facies and may localize fracturing which would provide hydraulic connections between sequences and with older strata.

Sequences divide the stratigraphic record into genetically related, time-bounded stratigraphic units. By placing facies within this time-space framework, it is possible to determine how depositional environments shifted through time and space. From this framework the spatial distribution and interconnections of lithologies of varying hydraulic conductivities can be found and hydrostratigraphic units identified. The third objective of this study is to identify hydrostratigraphic units within sequences, and determine how they may be connected or isolated from hydrostratigraphic units in underlying strata. A hydrostratigraphic unit is defined as a formation, portion of a formation, or group of formations which have similar hydrologic properties and can be grouped into aquifers, aquitards, or aquicludes (Fetter, 1988). Applied to the Lower Cretaceous, aquifers consists of laterally continuous sandstone facies within sequences and as connections of sandy facies between sequences and with underlying and overlying strata. This information can be used to understand regional ground-water flow, determine quantity and quality of ground water available for future use, and aid in the assessment of anthropogenic effects on the regional ground-water flow system.

The major contributions of this study are that it provides a sequence stratigraphic framework in which time and facies relations of formations are understood, and establishes correlations for recognizing hydrostratigraphic units. Furthermore, this study correlates stratigraphic sequences in Kansas to those described by Weimer (1984) in the rest of the Cretaceous Western Interior basin.

Stratigraphic Framework

Lower Cretaceous strata in Kansas and Colorado were deposited in the Western Interior Seaway, a foreland basin adjacent to the Sevier orogenic belt in Utah (Kauffman, 1977). Subsidence and sediment supply rates along the western margin of the seaway were much higher than those along the eastern margin, resulting in a westward thickening wedge of strata. Because of these differences in tectonic subsidence and sediment supply rates, it is likely that sea-level variations should be more prominently expressed along the eastern margin than along the western margin of the seaway. Identification of relative sea-level variations, regardless of subsidence and sediment supply rates, requires a sequence stratigraphic approach to analysis of strata.

Cretaceous strata in Kansas are divided into lithostratigraphic units, rather than into time-significant, unconformity-bounded stratigraphic sequences. By contrast, owing to more recent and extensive stratigraphic studies in the Denver basin, time-equivalent Cretaceous strata in Colorado have been interpreted within a sequence stratigraphic framework (Weimer, 1984). Because of these different philosophical approaches, this discussion on the stratigraphic framework is organized into three sections. The first treats stratigraphic nomenclature, age relations, lithologies and inferred depositional environments for strata in Kansas. The second section addresses the sequences and their lithologic components in Colorado. The third section discusses the differences and problems of correlation between Kansas and Colorado.

Cretaceous strata of this study in Kansas include the Cheyenne Sandstone, Kiowa Formation, Dakota Formation, and Graneros Shale (Fig. 2). These are unconformable on the Jurassic Morrison Formation in most of the subsurface. East and south of the Morrison Formation subcrop, Cretaceous strata rest with angular unconformity on Permian strata in the subsurface and outcrop.

Kansas Stratigraphy

Stratigraphic studies of Lower Cretaceous outcrops in Kansas began in the late 1800s with initial age determination from fossil collections (Meek and Hayden, 1859; Lesquereux, 1874). General stratigraphic and additional paleontologic descriptions were given by Logan (1897), Prosser (1897), Twenhofel (1924) and Rubey and Bass (1925).

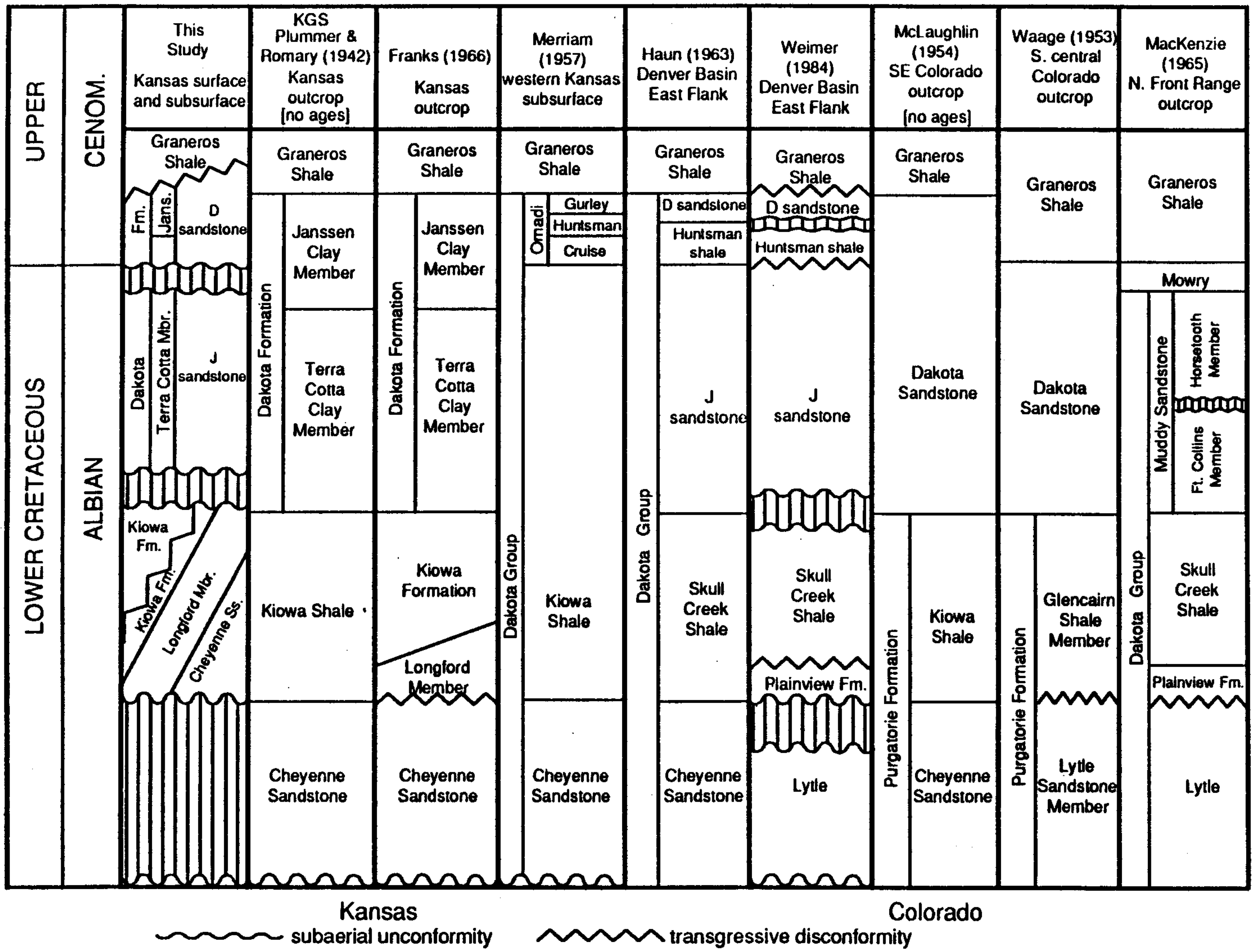


Figure 2: Stratigraphic nomenclature chart showing correlations between formation names based on their position with respect to the Upper/Lower Cretaceous boundary.

Agreement on lithostratigraphic nomenclature was not reached by early workers. However, after an extensive state-wide study, Plummer and Romary (1942) divided Lower Cretaceous strata into three formations: the Cheyenne Sandstone, the Kiowa Shale and the Dakota Formation. Except for the change of Kiowa Shale to Kiowa Formation by Zeller (1968), this is the official classification of the Kansas Geological Survey. Reviews of stratigraphic nomenclatural history are given by Waite (1942), and in other reports on geology and ground-water resources (e.g., Moore, 1940; Latta, 1941).

There are only a few post-1942 studies of Cretaceous strata in Kansas. The first subsurface studies of Lower Cretaceous strata in Kansas were by Frye and Brazil (1943) and Swineford and Williams (1945). These petrographic studies of well cuttings from Ellis and Russell counties in central Kansas distinguished the different Permian and Cretaceous formations, and evaluated their potential as ground-water aquifers or brine-disposal zones. Regional studies of Mesozoic strata in Kansas by Merriam (1957a,b), Lee and Merriam (1954), and Lee (1953), provided more extensive descriptions of lithology distributions in the subsurface.

Franks (1966) described and mapped outcropping Kiowa and Dakota Formations in north-central Kansas. Scott (1967) studied the paleoecological significance of fossils within the Kiowa Formation. Siemers (1971) defined depositional environments within the uppermost part of the Dakota Formation in central Kansas. Franks (1966,1979, 1980) defined the Longford Member of the Kiowa Shale as a separate lithostratigraphic unit. Scott (1970) examined Lower Cretaceous strata throughout the Western Interior including Kansas. Combining surface and subsurface data, he established faunal zones as a basis for time-rock correlations and described a transgressive-regressive cycle model for deposition.

Cheyenne Sandstone

The Cheyenne Sandstone was first described by Cragin in 1885 and named by Cragin (1889) after Cheyenne Rock at the type section near the town of Belvidere in southeast Kiowa County, Kansas. Cragin (1889) assigned the Cheyenne to the Comanchean Series. Because it lacks marine fossils, its age is constrained as older than the overlying Kiowa Formation which is Upper Albian (Scott, 1970). Early interpretations of the Cheyenne suggested that it was deposited in a fluviatile coastal plain near the strandline of the northward advancing Cretaceous sea (Twenhofel, 1924; Plummer and Romary, 1942; Scott, 1970).

The Cheyenne Sandstone is unconformable upon either Permian strata or the Jurassic Morrison Formation in both the outcrop and subsurface (Twenhofel, 1924; Swineford and Williams, 1945; Merriam, 1957a). The unconformity on the Permian has as much as 50 ft of relief (Plummer and Romary, 1942). The contact with the overlying Kiowa Formation has been reported as both conformable (Latta, 1946; Scott, 1970) and unconformable (Franks, 1975).

In outcrop the Cheyenne Sandstone consists predominantly of light-colored, fine- to medium-grained, friable cross-bedded sandstone. Lenses of conglomerate, and sandy to silty carbonaceous shale containing lignite and plant fossils are also common in the upper part of the formation (Latta, 1946). Exposures of the Cheyenne Sandstone occur only in southern Kansas in areas near the type section. Fent (1950) reported inliers of a sandstone and a cobble zone at the base of the Kiowa Formation in Rice County which he thought may be Cheyenne Sandstone. The thickness of the formation in outcrop ranges from 32 ft to 94 ft (Latta, 1946). However, because of lithologic variations and absence of fossils in the Cheyenne, its presence and thickness have been variously interpreted in both outcrops and in the subsurface.

In the subsurface the Cheyenne is commonly described as white, fine- to medium-grained sandstone composed of subrounded, frosted quartz grains that are unconsolidated or cemented with pyrite or calcium carbonate (Merriam, 1957a). Swineford and Williams (1945) identified two types of mineralogy, Permian-like and Kiowa-like, within the Cheyenne, and noted thickness variations ranging from 0 to 62 ft in Russell County of central Kansas. Frye and Brazil (1943) reported 0 to 200 ft in Russell and Ellis Counties. Merriam (1957a) identified the Cheyenne throughout the Kansas subsurface, and recorded a maximum thickness of 260 ft. He also noted that the thickness is variable and that the formation thins to the east and south. Scott (1970) reported the Cheyenne Sandstone as absent in central Kansas subsurface.

Kiowa Formation

The Kiowa Formation was first described by Cragin in 1885 and was named by Cragin (1895) as the Kiowa Shale at the type section near Belvidere, Kiowa County, Kansas. It was defined by Plummer and Romary (1942) as marine shale, sandstone and fossiliferous limestone above the Cheyenne Sandstone and below the Dakota Formation. The top of the formation was more specifically defined by Franks (1966) as occurring at the base of the red-mottled mudstones and claystones of the Dakota Formation.

The Kiowa Formation is exposed throughout the entire outcrop belt and subsurface, except in the northeast part of the state where it pinches out beneath the Dakota Formation in Ottawa and Clay Counties (Plummer and Romary, 1942). The Kiowa Formation rests on Cheyenne Sandstone and Permian strata in outcrop (Scott, 1970). The contact with the Permian is an angular unconformity with commonly 50 ft, and sometimes 100 ft, of relief (Franks, 1966; Fig. 3). The contact with the Cheyenne Sandstone is reported as both conformable (Latta, 1946) and unconformable (Franks, 1975). Twenhofel (1924) described the contact as, "The Kiowa shales rest unconformably on the Cheyenne Sandstone. The contact is sharply defined and abrupt and is thought to represent the change from continental to marine conditions. The plane of contact is the strandline surface of erosion made by the transgressing sea." The contact with the overlying Dakota Formation is reported as conformable and gradational (Latta, 1946), and conformable and disconformable (Latta, 1948; Franks, 1979).

The lithology of the Kiowa Formation is variable as reported by different authors, and includes shale, thin sandstone, and fossiliferous limestone. It has a thickness of 300 ft in the type area (Latta, 1946). In the subsurface of Russell and Ellis Counties it is between 100 ft and 125 ft thick (Frye and Brazil, 1943), and Merriam (1957a) reported a maximum thickness of 380 ft in the subsurface of western Kansas. Depositional environments of the Kiowa Formation have been interpreted as sublittoral to open marine (Scott, 1970), reflecting the variability in lithologies. Sandstones within the formation are interpreted as delta-front sands, barrier bars, offshore bars, and tidal-current bars deposited near the margin of the Kiowa sea (Franks, 1966, 1975). The age of the formation is Upper Albian, *Venezoliceras kiowanum* to *Inoceramus bellvuensis* zones (Scott, 1970). It is reported as the lithologic and temporal equivalent of the Skull Creek Shale (Cobban and Reeside, 1952; Haun, 1963).

Longford Member of the Kiowa Formation

Franks (1966) separated white siltstones, lenticular sandstones and red-mottled

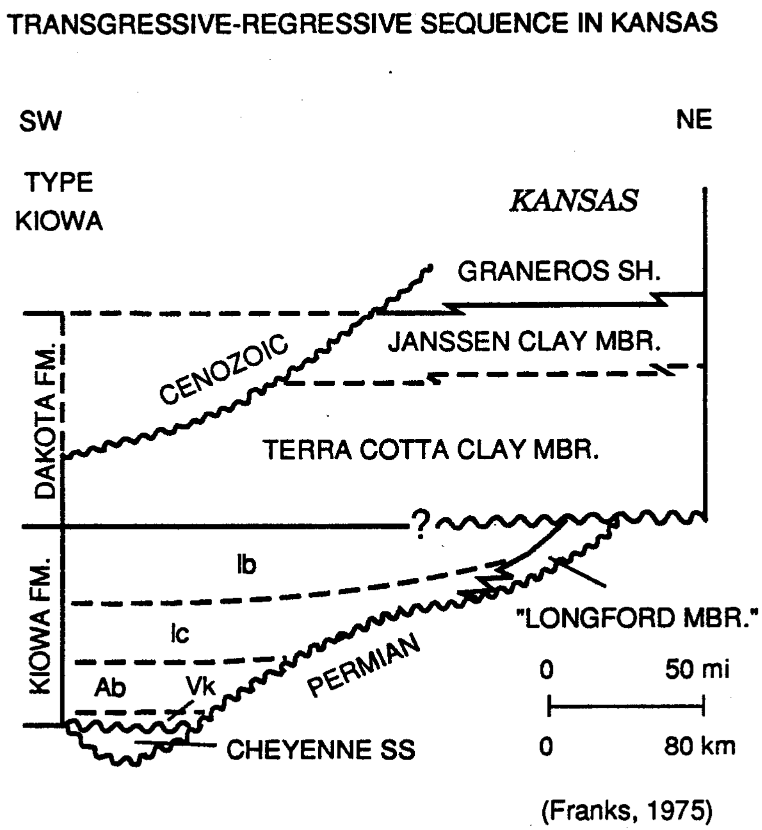


Figure 3: Stratigraphic and age relations along the outcrop belt in Kansas.

siltstones and mudstones at the base of the Kiowa Formation into the Longford Member. Subsequently he determined that the Longford Member rests with transgressive disconformity on the Permian, and is conformably overlain by the Kiowa Formation (Franks, 1980).

The Longford Member outcrops in a north-south trending band at the base of the Kiowa Formation along the eastern edge of the outcrop belt in central Kansas, where it is up to 100 ft thick (Franks, 1979). It is not present in southern Kansas outcrops, but has been reported in the subsurface of Barton County (Latta, 1950). Franks (1980) interpreted the Longford Member as a variety of nonmarine and paralic deposits including fluvial, estuarine, lagoonal, and barrier bars.

Dakota Formation

The Dakota Formation was first described by Meek and Hayden (1861) near Dakota City in northeastern Nebraska. In Kansas the formation is defined as nonmarine and littoral clay and sandstone over the Kiowa Formation and below the Graneros Shale, and consists of the Terra Cotta Clay and Janssen Clay Members (Plummer and Romary, 1942). The type sections for both members are located in Ellsworth County in central Kansas. The Dakota Formation is Albian to Cenomanian (Franks, 1975), and the upper part is restricted to the Cenomanian (Hattin, 1965; Franks, 1966). The average thickness of the formation is 250 ft (Siemers, 1971). In Ellis and Russell Counties the thickness is between 200 ft and 300 ft (Frye and Brazil, 1943). Mack (1962) reported a thickness of 350 ft in Ottawa County.

The lithology of the Dakota Formation is highly variable. The upper part generally consists of variegated nonmarine claystone, fluvial sandstone, estuarine sandstone, lignite and shale. The lower part consists of white, grey, brown, red, and tan mudstone, with claystone, siltstone, and sandstone lenses. Sandstones in the formation are dominantly quartz rich (Siemers, 1971), fine- to medium-grained and comprise 25% to 40% of the formation (Mack, 1962). Conglomeratic sandstones are common at the base of the formation (Franks, 1966), and multistory fluvial channel sandstones up to 70 ft thick have been described in outcrop (Franks, 1975). Provenance is to the east and northeast (Franks, 1966).

Depositional environments represented by these lithologic types are mostly nonmarine in central Kansas outcrops. Merriam et al. (1959) interpreted dominantly marine depositional environments in a core from western Kansas. Franks (1966, 1975) interpreted the Dakota Formation as alluvial plain and deltaic complexes deposited during the retreat of the Kiowa Sea. Plummer and Romary (1942) interpreted sandstones in the formation as nearshore sand flat deposits, and claystones as lagoon, swamp, lake, stagnant stream, or delta deposits in a setting similar to the Mississippi delta.

The Rocktown Channel Sandstone is a prominent sandstone body in the upper part of the formation in outcrops of Russell County. It was deposited by meandering streams in a wide floodplain where variegated and carbonaceous mudstones were also deposited (Rubey and Bass, 1925). The uppermost part of the formation in Russell County was deposited in distributary channels, estuaries, and deltas (Siemers, 1976; Fig. 4).

The contact between the Dakota Formation and the underlying Kiowa Formation has been described as conformable, disconformable and unconformable. Unconformable contacts are generally described as erosional surfaces separating grey, massive clay from overlying red, yellow, and red-mottled clay with concretionary iron pellets (Plummer and Romary, 1942). Mack (1962) described an erosional, unconformable contact in Ottawa County where channels in the Kiowa Formation are filled with sandstones of the Dakota Formation. By contrast, the contact in southern Kansas was described by Latta (1946) as occurring within a lithologically homogeneous stratigraphic succession, and therefore interpreted as conformable and gradational. However, Latta (1948) later described the same contact as conformable but locally unconformable. Franks (1966) interpreted the contact in the south-central Kansas outcrops as conformable on regressive deposits of the Kiowa Formation, and unconformable where the Dakota is locally scoured into the Kiowa Formation. Franks (1975) interpreted the contact in the north-central Kansas outcrops as a transgressive disconformity, but suggested that the Dakota Formation intertongues to the west with the Kiowa Formation. Merriam (1957a) also suggested that the two formations intertongued locally but not regionally.

Terra Cotta Clay Member

The Terra Cotta Clay Member is defined as grey claystone and red-mottled massive claystone, siltstone, and sandstone comprising approximately the lower two-thirds of the Dakota Formation (Plummer and Romary, 1942). Thickness of the member ranges from

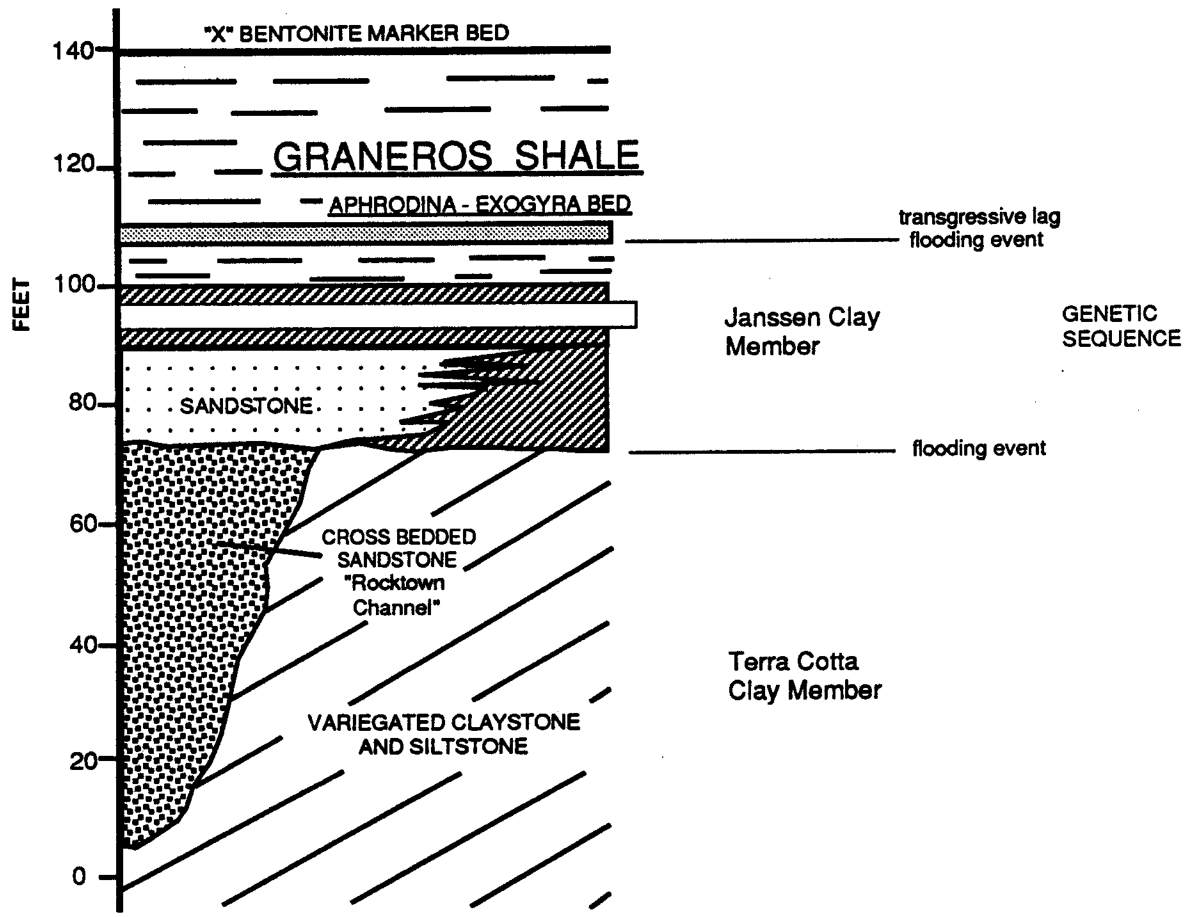


Figure 4: Idealized lithologic units and contacts shown as defined by Siemers (1971). Genetic sequence boundaries and time-significant surfaces shown as described in this study.

150 ft to 250 ft (Franks, 1966).

According to Karl (1976), sandstones in Washington County, Kansas, and southern Nebraska were deposited by low sinuosity bedload streams flowing southwest. The fine-grained facies of this member were deposited in floodplains adjacent to these rivers (Franks, 1975).

The contact with the overlying Janssen Clay Member is gradational and is placed at the top of a concretionary siderite, limonite, or hematite, and/or "quartzite" sandstone which is overlain by a bed of grey, massive clay (Plummer and Romary, 1942). In Russell County, Rubey and Bass (1925) described the grey shale at the top of the Dakota Formation as grading downward and laterally with variegated mudstone. They also recognized that the locally occurring Rocktown channel sandstone in the upper 125 ft of the formation interfingers with and cuts into variegated shale.

Janssen Clay Member

The Janssen Clay Member is defined as lignite, dominantly kaolinitic grey to dark-grey massive claystone, siltstone and some shale above the Terra Cotta Clay Member and below the Graneros Shale (Plummer and Romary, 1942). Other rock types include isolated lignites 2 ft to 28 ft thick, ironstone-bearing or sideritic claystones up to 31 ft thick (Siemers, 1971), and fine-grained, trough and epsilon cross-stratified, lens-shaped sandstones (Karl, 1976).

The Janssen Clay Member constitutes approximately the upper one-third of the Dakota Formation. It varies between 30 ft to 80 ft thick according to Plummer and Romary (1942), and 50 ft to 100 ft according to Franks (1966).

The environment of deposition is largely transitional from nonmarine to marine. Sandstone lenses were deposited in meandering streams (Karl, 1976). Flat-bedded sandstones were deposited in estuaries and deltas, lignites in fresh to brackish water swamps, and iron-bearing claystones in brackish and open marine bays (Siemers, 1971).

The Dakota Formation is described as grading laterally into and intertonguing with the Graneros Shale. Franks (1966, 1975) and (Siemers, 1971) characterized the contact as uneven and transitional. Hattin (1965) also recognized that the Dakota-Graneros contact is transitional through alternating beds of sandy shale, shale and thin sandstone beds. He suggested that the Graneros Shale intertongues with the Dakota.

Graneros Shale

The Upper Cretaceous Graneros Shale is defined in central Kansas outcrop as consisting in the lower part of medium dark-grey, noncalcareous, silty and sandy shale with numerous sandstone beds, and in the upper part of medium dark-grey silty shale with calcareous sandstone and beds of *Inoceramus* prisms (Hattin, 1965). The lower part of the formation was deposited in shallow nearshore marine water of less than normal salinity. The upper part of the formation was deposited in offshore marine water of normal salinity (Hattin, 1965). The Graneros Shale is 25 ft to 40 ft thick in Ellis and Russell Counties (Frye and Brazil, 1943), 24 ft to 40 ft thick in central Kansas outcrop (Hattin, 1965), and 14 ft to 40 ft thick in Russell County (Swineford and Williams, 1945).

Colorado Stratigraphy

Lower Cretaceous strata in Colorado have been studied more extensively and more recently than in Kansas because they contain hydrocarbons in the Denver basin. Sequence stratigraphic studies of Lower Cretaceous strata in Colorado are important to this study because they form the basis for correlating time-equivalent strata from the western to the eastern side of the Western Interior Seaway. Sequence stratigraphic relationships of Cretaceous strata in Colorado were derived from extensive research primarily within exposures along the Front Range around Denver, Colorado (e.g., Waage, 1955; Waage, 1959; Haun and Barlow, 1962; MacKenzie, 1963, 1965, 1971, 1972; Weimer, 1970; Weimer and Land, 1972; Matuszczak, 1973; MacMillan and Weimer, 1976). Weimer (1984) synthesized a comprehensive sequence stratigraphic and tectonic model for the deposition of Cretaceous strata in Colorado and Wyoming and extended this framework of unconformity-bounded sequences into the subsurface of western Kansas.

Weimer (1984) proposed a division of Cretaceous strata into sequences of genetically related strata bound by time-significant surfaces of subaerial unconformity and their correlative conformities (Fig. 5). These unconformities were formed by subaerial erosion during times of lowered sea level, and were enhanced by local and regional tectonics. The unconformities are interregional in extent, and are recognized by incised valleys, missing facies, root zones and paleosols associated with scour surfaces. Four unconformity-bound sequences defined by Weimer (1984) encompass the time during which strata of this

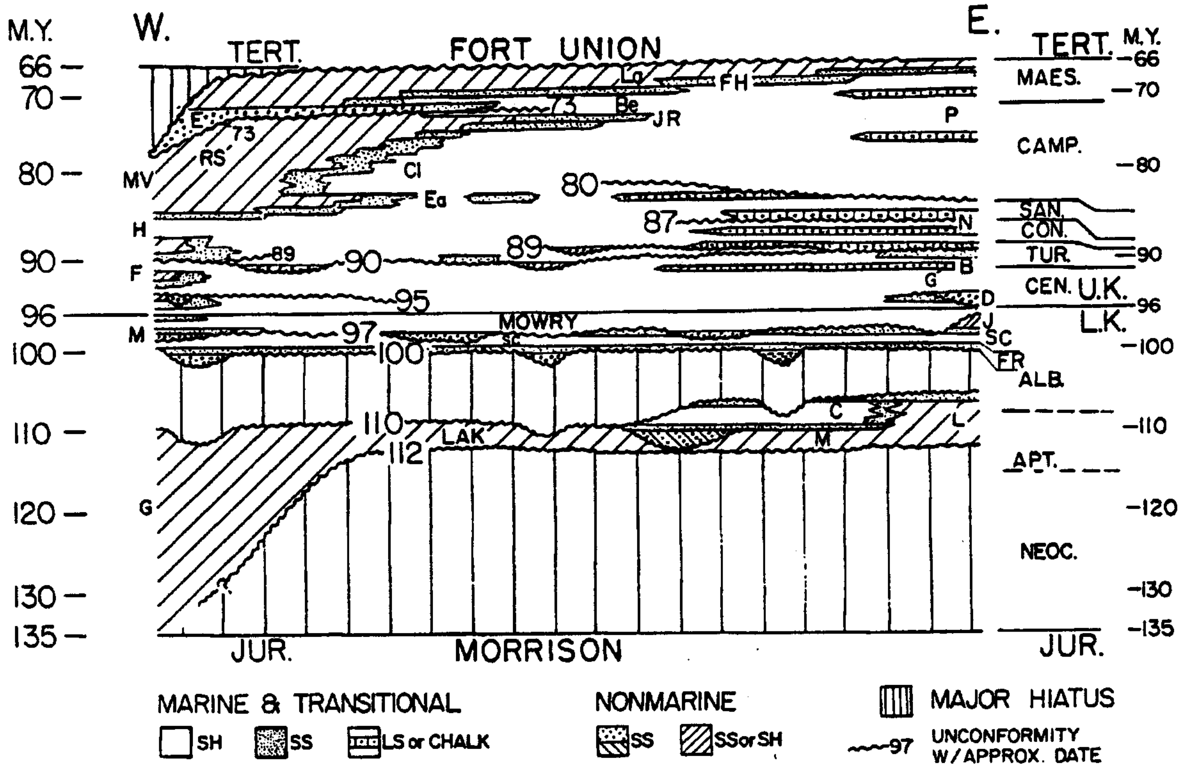


Figure 5: Diagrammatic east-west section across Cretaceous basin showing stratigraphic position and approximate dates of major intrabasin unconformities (modified after McGookey, 1972). Formations or groups to the west are: G=Gannett; SC=Skull Creek; M=Mowry; F=Frontier; H=Hilliard; MV=Mesaverde; RS=Rock 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 the Denver basin; G=Greenhorn; B= Benton; N=Niobrara; P=Pierre; M and C are the 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. From Weimer (1984) without modifications.

study were deposited in Kansas. The ages, facies relations and interpreted depositional environments of these sequences are summarized in stratigraphic order.

Sequence 1 (Lytle Formation)

The first sequence consists wholly of the Lytle Formation, and was deposited between 110 Ma and 112 Ma (Weimer and Land, 1972; Weimer, 1984). In outcrops near Denver, it is 78 ft to 120 ft thick and consists of medium- to coarse-grained, lenticular fluvial sandstone bodies enclosed in floodplain deposits of varicolored siltstones and mudstones (Weimer and Land, 1972). The Lytle Formation is present throughout the Front Range in Colorado (Waage, 1959), the subsurface in Colorado (Sonnenberg and Weimer, 1981), and outcrops in eastern Colorado (McLaughlin, 1954).

This sequence is unconformable on the Jurassic Morrison Formation and is unconformably overlain by the Plainview Formation of the second sequence. The Lytle Formation is time equivalent to the Lakota Formation in Wyoming (Weimer, 1984), and subsurface lithologic equivalents of the Lytle Formation in Colorado are called Cheyenne Sandstone (Haun, 1963). The usage of the name Cheyenne Sandstone in Colorado is based on lithologic similarity to the Cheyenne Sandstone in Kansas. The formations may not be temporally or genetically related, and no physical or temporal correlation of the two formations has been demonstrated (Scott, 1970).

Sequence 2 (Plainview Formation and Skull Creek Shale)

The second unconformity-bounded sequence consists of the Plainview Formation and the Skull Creek Shale. The Plainview consists of grey, carbonaceous claystones and burrowed sandstones, and is 12 ft to 60 ft thick in central Colorado outcrop. It was deposited in marginal marine and coastal plain environments along the edge of the transgressing Early Cretaceous sea. In outcrop the Skull Creek Shale is 50 ft to 70 ft of grey siltstone, shale and clayey sandstone. It was deposited in open bays to open marine environments (Weimer and Land, 1972). In the subsurface the Skull Creek is between 100 ft and 200 ft thick (Weimer, 1984).

The base of this sequence is the erosional unconformity on the top of the Lytle Formation (Sequence 1). The top of Sequence 2 is the erosional unconformity at the base of the J sandstone. The Plainview/Skull Creek sequence was deposited during the time interval between the two unconformities which are dated at 100 Ma and 97 Ma (Weimer, 1984).

The Skull Creek Shale is equivalent to the Kiowa Formation in Kansas and the Thermopolis Shale in Wyoming. These shales are present throughout the basin because the seaway during the Albian was continuous from north to south across the North American continent (Haun, 1963).

Sequence 3 (J sandstone and Huntsman Shale)

The third sequence extends from the unconformity at the top of the Skull Creek Shale to the unconformity at the base of the D sandstone, and contains the J sandstone and Huntsman Shale. The J sandstone consists of lenticular quartzose sandstone and siltstone with grey claystone and shale interbeds (Weimer, 1984; Weimer and Land, 1972). The J sandstone was deposited in diverse environments. From the base up, these are generally upper meander belt, lower meander belt, fluvial-deltaic, estuarine-lagoonal, and then marine (Weimer, 1984). In the Front Range area, the J sandstone has a combined thickness of less than 100 ft (Weimer, 1984). The Huntsman Shale is composed of black, organic-rich, nonburrowed marine shale (Sonnenberg, 1987).

This sequence, as defined above, is present only on the eastern flank of the Denver basin where the D sandstone exists. West of the depositional limit of the D sandstone, the sequence extends upsection to the unconformity at the base of the Codell Sandstone (Weimer, 1984). The J sandstone is present throughout the Western Interior basin. The Huntsman Shale, which separates the J and D sandstones, pinches out to the east before it reaches Kansas (Haun, 1963).

Using the time scale of Obradovich and Cobban (1975), Weimer (1984) assigned a 97 Ma age for the basal bounding unconformity, and a 95 Ma age for the upper bounding unconformity. The J sandstone is lithologically equivalent to the Muddy Sandstone and Newcastle Formation (Haun, 1963).

Sequence 4 (D sandstone, Graneros Shale)

As defined for the eastern part of Colorado, the fourth sequence extends from the unconformity at the base of the D sandstone to the unconformity at the top of the Carlile Formation, base of Niobrara Formation. This sequence includes the D sandstone, Graneros Shale, Greenhorn Limestone, and Carlile Formations (Weimer, 1984).

The D sandstone was transported entirely from eastern sources, and its depositional limit occurs in eastern Colorado and western Nebraska (MacKenzie and Poole, 1962). The D sandstone represents a succession of environments from basal fluvial and estuarine channels, deltaic, shoreline, to open marine mudstones at the top (Sonnenberg, 1987). The Graneros seaway was continuous from the Arctic to the Gulf of Mexico during its deposition (Haun, 1963).

The fourth sequence is bounded by a basal unconformity dated at 95 Ma (early Cenomanian) and an upper unconformity dated at 90 Ma (Turonian) by Weimer (1984). It rests unconformably on the Huntsman Shale. The D sandstone is separated from the Graneros Shale by a transgressive disconformity (Sonnenberg, 1987).

Kansas / Colorado Stratigraphic Differences and Problems

Differences between Kansas and eastern Colorado stratigraphy are the result of differing depositional environments, provenance, sediment supply rates, lithology, depositional slopes and subsidence rates. These differences, in combination with different approaches and philosophies to correlation, account for the use of different stratigraphic nomenclatures in Kansas and Colorado. Traditional correlations from Kansas to Colorado include the following: Cheyenne Sandstone to Lytle Formation; Kiowa Formation to Skull Creek and Glencairn Shales; Dakota Formation to various formations and members of the Dakota Group (Fig. 2).

Depositional environments across (east-west) the seaway varied as a consequence of differential depositional slopes and subsidence rates. Since Colorado was in a more seaward position and closer to the Sevier thrust belt, marine depositional environments were dominant and subsidence rates greater. Fluvial depositional environments were dominant in the landward direction in Kansas. Merriam et al. (1959) observed that a core from the Dakota Formation in northwest Kansas was much more marine in character than outcrops to the east in central Kansas.

Source areas of sediments were mainly from the western and eastern margins of the Western Interior basin (Fig. 6). Sediments in Kansas were transported from the east and northeast, and some were derived locally (Swineford and Williams, 1945; MacKenzie and Poole, 1962; Franks, 1966). Strata in Colorado were transported from the west and

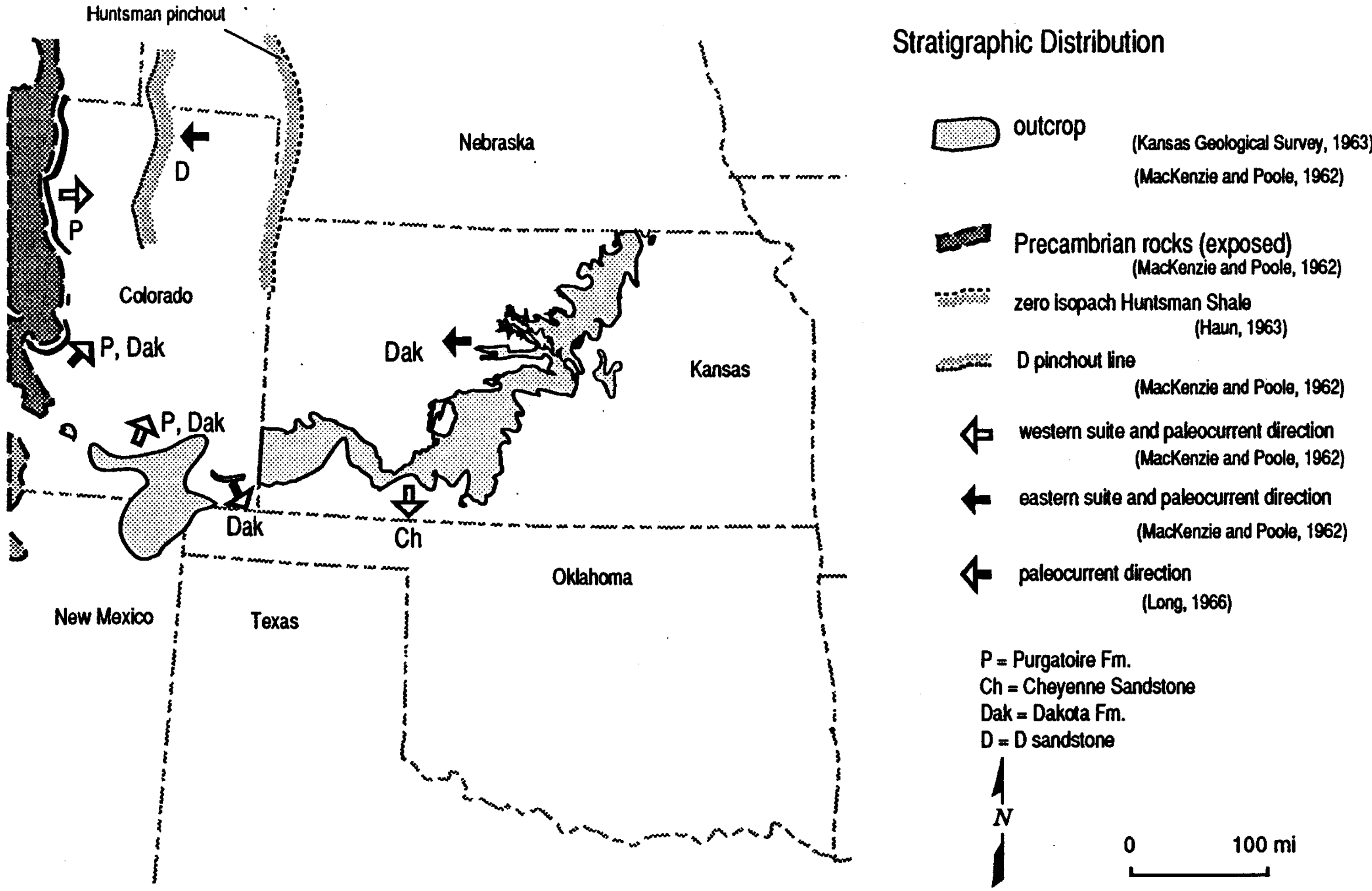


Figure 6: Map showing regional outcrops, provenance, and paleocurrent directions of formations related to this study.

east, with the mineralogical suites interfingering in the central part of the basin in eastern Colorado. The D sandstone of the upper Dakota Group was derived entirely from the northeast (MacKenzie and Poole, 1962).

Basal Cretaceous strata of eastern Colorado and western Kansas subsurface are unconformable on the Jurassic Morrison Formation. Elsewhere in Kansas, they are unconformable on Permian strata of the Custerian and Cimmaronian stages (Merriam, 1963).

The Cheyenne Sandstone outcrops only in southwest Kansas and is not present everywhere in the subsurface. In Colorado, the Cheyenne is recognized on the east flank of the Denver basin, and the Lytle Formation is recognized as the basal Cretaceous unit along the Front Range. The Kiowa Formation is present everywhere in the subsurface and outcrop of Kansas except in north-central Kansas where it pinches out to the east beneath the Dakota Formation. In Colorado, the Skull Creek Shale is recognized across the Denver basin through the Front Range. Formations of the Dakota Group are present everywhere in eastern Colorado outcrop and subsurface with the exception of the D sandstone. The D sandstone, derived from the east, reaches its depositional limit east of the outcrop. The Dakota Formation of Kansas and its equivalents in eastern Colorado are everywhere overlain by the Graneros Shale.

Correlations of the Lytle Formation to the Cheyenne Sandstone, and the upper Dakota Group to the Dakota Formation between Colorado and Kansas are problematic. This is largely due to the absence of fossils in these units and to the gross lithologic similarities of these pairs of formations which have caused them to be treated as temporal equivalents. By contrast, the Kiowa Formation, Skull Creek and Glencairn Shales have been correlated by lithologic and faunal equivalence throughout the Western Interior basin (Cobban and Reeside, 1952; Haun, 1963; Scott, 1970). These formations provide a physically correllable stratigraphic separation between the lower and upper formations of the Dakota Group in Colorado, and between the Cheyenne Sandstone and Dakota Formation in Kansas.

The Cheyenne Sandstone was first described by Cragin (1889) in south-central Kansas. It was correlated on the basis of lithologic similarity by McLaughlin (1954) to the Lytle Formation of the Dakota Group in south-eastern and south-central Colorado outcrop. There are no fossils in either the Lytle Formation or Cheyenne Sandstone, and a physical correlation of the two formations is not possible because the Cheyenne Sandstone pinches out west of its outcrop in Kansas. Haun (1959) demonstrated that the Lytle Formation is physically continuous from the Colorado outcrop into the subsurface of the Denver basin where it is called the Cheyenne Sandstone. The Cheyenne Sandstone in the Colorado subsurface is assumed the temporal equivalent of the Cheyenne Sandstone of Kansas outcrop (Haun, 1963).

Scott (1970) correlated the Lytle Formation in Colorado with the Cheyenne Sandstone in Kansas based on an assumed conformable relationship with the overlying Glencairn Shale and Kiowa Formation, respectively. Scott (1970), following previous workers, interpreted the Cheyenne Sandstone of Kansas as coastal plain deposits adjacent to the transgressing Kiowa sea. From this interpretation, Scott (1970) recognized that the Cheyenne Sandstone is temporally equivalent to the marine shales of the Kiowa. He also assumed an identical relationship between the Lytle Formation and Glencairn Shale of Colorado. This assumed correlation between the Cheyenne Sandstone and Lytle Formation may be incorrect. Weimer (1984) recognized an unconformity at the top of the Lytle Formation, separating it from the Plainview Formation and Glencairn and Skull Creek Shales. Weimer (1984) extended this observation into the subsurface and recognized an interregional unconformity between the Lytle and Plainview Formations and their temporal stratigraphic equivalents. So the Kiowa sits conformably on a sandstone that is younger than the Lytle. Therefore, the Cheyenne Sandstone of Colorado subsurface is probably not correlative to the Cheyenne Sandstone of Kansas outcrop. The significance of these possibilities will be addressed subsequently.

Merriam (1957a) suggested tentative correlations of the Dakota Formation in Kansas with strata in the Colorado and Nebraska portions of the Denver basin. He correlated the Dakota Formation in Kansas with the Omadi Formation of Condra and Reed (1943) in Nebraska. The three members of the Omadi Formation, the Cruise Sandstone, Huntsman Shale and Gurley Sandstone, were correlated to the J sandstone, Huntsman Shale, and D sandstone, respectively. He also correlated the J sandstone to the Janssen Clay Member of the Kansas outcrop, and suggested that there were no stratigraphic equivalents to the D sandstone in the Kansas outcrop. Merriam (1957a) placed the Upper/Lower Cretaceous boundary at the base of the Omadi Formation.

Haun (1963) proposed corrections to the correlations by Merriam (1957a). Haun

(1963) mapped the zero isopach of the Huntsman Shale almost coincident with the Colorado-Kansas state line. This is in direct contradiction to the correlation of the Huntsman Shale throughout the Kansas subsurface by Merriam (1957a). Haun (1963) placed the Upper/Lower Cretaceous boundary at the top of the Omadi Formation.

These contradictions, along with the speculative correlations of the Dakota Formation members into the subsurface, are major hindrances to the correlation of Kansas outcrop with Denver basin strata. However, Weimer (1984) made correlations from Wyoming to western Kansas by classifying formations and members as genetically related parts of unconformity-bound sequences. Weimer (1984) correlated the Dakota Formation of western Kansas to the J sandstone, Huntsman Shale, and D sandstone of Colorado. Weimer (1984) indicated that the Huntsman Shale is not present in Kansas, and that the J and D sandstones are merged as the Dakota Formation of Kansas. He placed the Upper/ Lower Cretaceous boundary at the top of the J sandstone in Colorado. From his correlations this would place the Upper/Lower Cretaceous boundary somewhere in the middle of the Dakota Formation in Kansas. The obscurity of this unconformity, and hence time boundary, within the Dakota Formation continues to make correlations of outcropping Dakota Formation members with Denver basin strata tentative.

Structure

Cretaceous strata in the western United States were deposited in the Western Interior Cretaceous basin of North America. This basin was bordered on the west by the Sevier fold-thrust belt and on the east by the Canadian Shield (Weimer, 1984). Kansas strata were deposited on the distal, cratonic side of the basin. Foreland basin subsidence was initiated around 115 Ma (Jordan, 1981). The basin was subsequently segmented into present-day intermontane basins of the Rocky Mountain region during the Laramide orogeny (Weimer, 1984; Dickinson, et al. 1988). The Denver basin is one of these basins (Fig. 7).

The Central Kansas uplift was a positive structural and topographic feature during the Paleozoic (Merriam, 1963). The Las Animas arch was a positive feature which affected sedimentation during Paleozoic time (Rascoe, 1978). Merriam (1963) suggested that the Central Kansas uplift and the Las Animas arch were positive topographic elements during the Mesozoic. The Las Animas arch along with the Cimmaron arch and the Hugoton embayment of the Anadarko basin may have been tectonically active or topographic features during the Cretaceous. Their effects on sedimentation during the Cretaceous are discussed subsequently.

Numerous faults and folds are present across Kansas (Fig. 8). Berendsen and Blair (1986) studied some of these in central Kansas and concluded that recurrent movement occurred along Precambrian fractures throughout Paleozoic time. It is likely then that movement continued on these and other structures during Mesozoic time. The Fairport anticline/fault and its effect on sedimentation is one such feature that was studied in detail and is discussed subsequently.

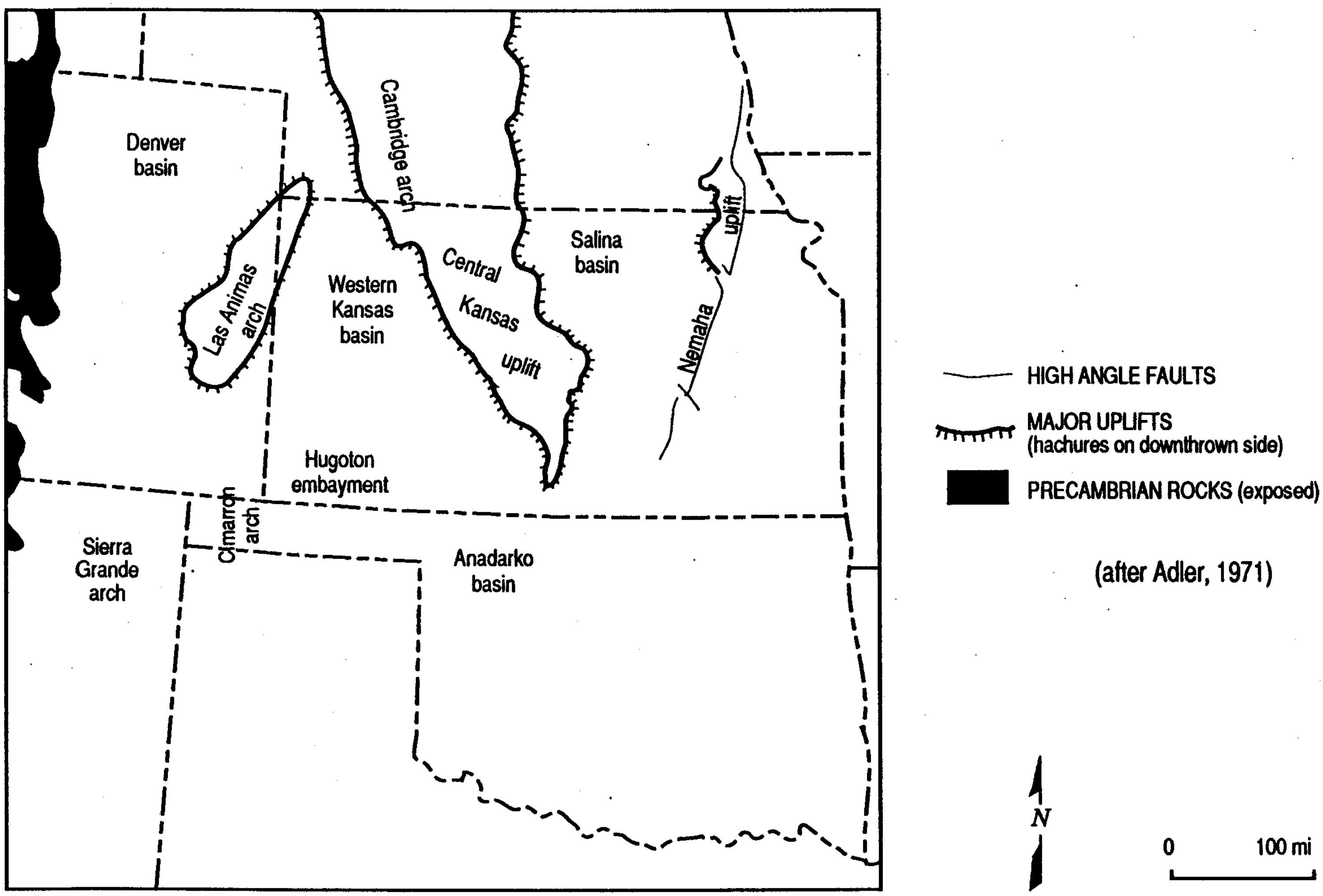


Figure 7: Map showing basement structure of the mid-continent region.

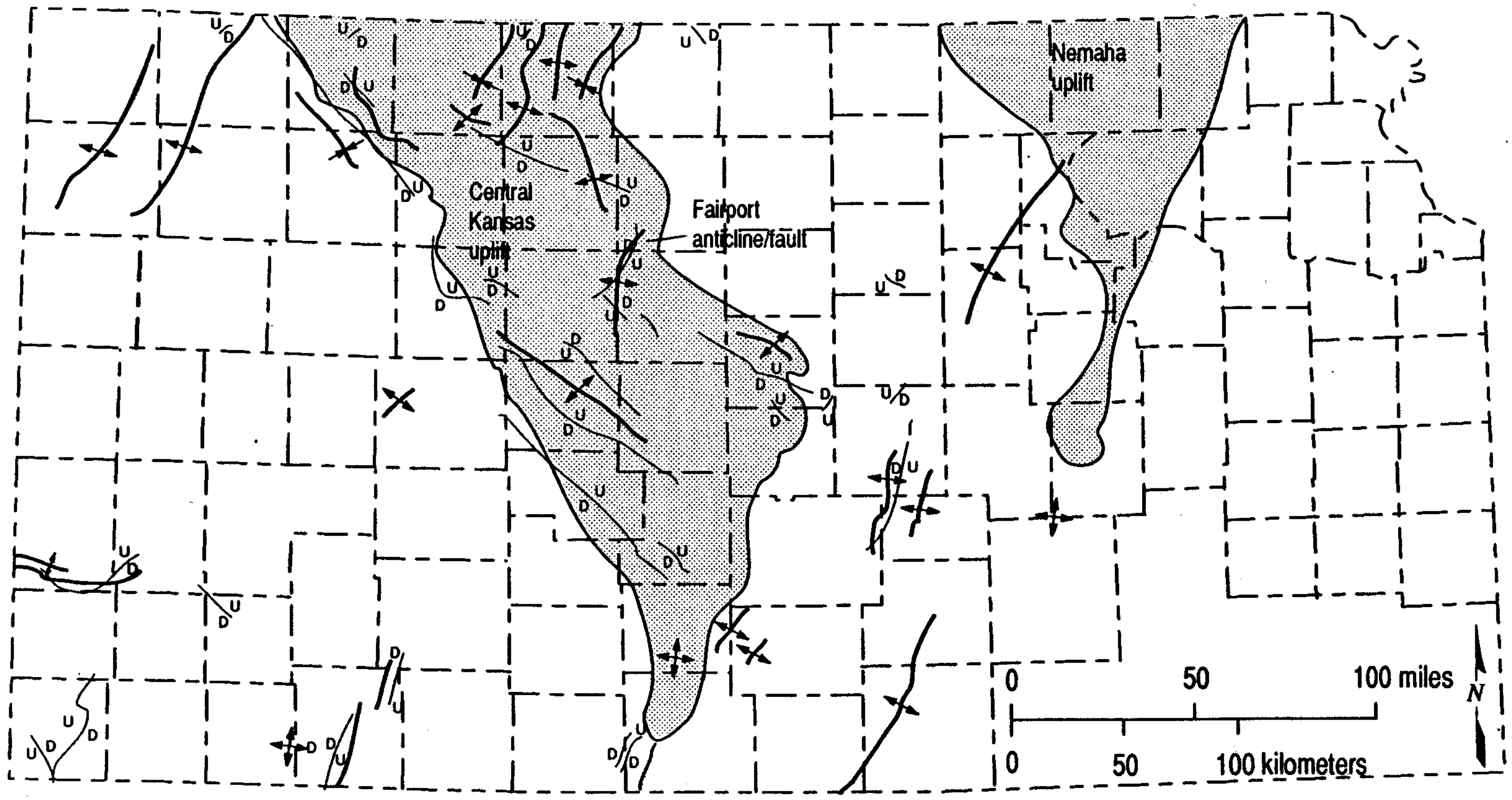


Figure 8: Map of Kansas with location of structural features. From Merriam (1963).

Sedimentology

Sixteen facies were recognized and described in both cores (Beaumeister #1, Plate 1; Haberer, Plate 2; and Bounds #1) and outcrops. The core facies were calibrated to well log signatures (Plates 1, 2 and 3). The location of the cores and outcrops are shown on Figure 1. Columnar sections of outcrop descriptions are in Appendix A. The facies are presented in a vertical succession from nonmarine to nearshore to open marine. This succession and the importance of facies offsets for identifying sequence boundaries is discussed following their description and interpretation.

Facies Descriptions and Interpretations

Facies LTXSS: Large-scale trough cross-stratified sandstone

This facies, described in outcrop, consists of 6 in to 3 ft thick sets of large-scale trough cross-stratified, fine- to medium-grained sandstone (Figs. 9 and 10). Set surfaces dip 2° to 5° in downcurrent direction. Clay clasts and wood chips occur along the basal bounding surfaces of some trough sets. Cross laminations within troughs dip 12° to 27° in a 270° to 337° direction. Some sets are 2 ft to 3 ft thick with troughs 10 ft to 20 ft wide.

This facies was deposited by sinuous-crested megaripples in channelized, unidirectional flow and is interpreted as fluvial channel deposits.

Facies STXSS: Small-scale trough cross-stratified sandstone

This facies, described in core and outcrop, consists of 3 in to 1 ft thick sets of small-scale trough cross-stratified, very fine- to medium-grained, subrounded to rounded sandstone (Figs. 11, 12 and 13). There are two types of trough cross-stratified sets. One type consists of trough cross-stratification sets that are inclined up to 9° in 340° to 45° direction, with foresets dipping 13° to 22° in the same direction. At some localities cross laminae are draped with carbonaceous detritus in which *Skolithos* burrows terminate. Wood chip impressions are present on some of these inclined set surfaces. The other type consists of trough cross-stratification in 1-ft thick horizontal sets that have foreset laminae which dip 21° to 30° in 264° to 301° direction, and have no carbonaceous laminae, wood chip impressions and bioturbation.

This facies was deposited by unidirectional currents, some of which alternated with slack water conditions allowing for carbonaceous matter to settle out. Deposits containing

Figure 9: Facies LTXSS (Large-scale trough cross-stratified sandstone). Location is roadcut in Mullberry Pass, Ellsworth County (sec 21 T14S R6W). Medium-grained LTXSS is overlain by dark colored, coarse-grained PTSS (Planar tabular cross-stratified sandstone).

Figure 10: Facies LTXSS (Large-scale trough cross-stratified sandstone). Note abundance of clay rip-up clasts. This is the contact between the Kiowa and Dakota Formations at Measured Section #12 (sec 8 T16S R6W).

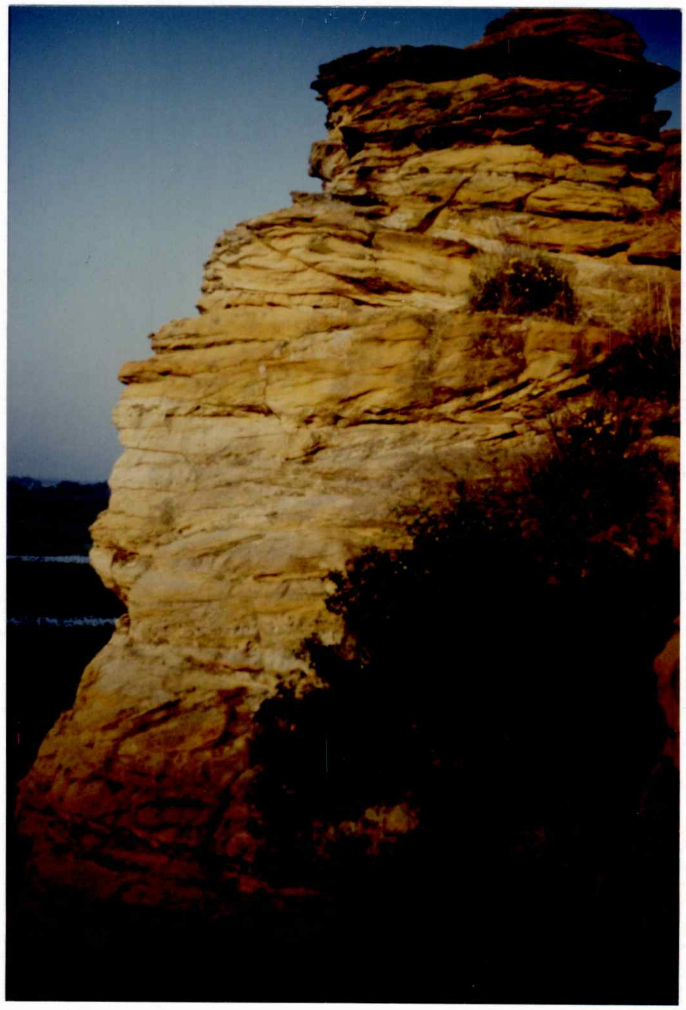


Figure 11: Facies STXSS (Small-scale trough cross-stratified sandstone). LTXSS can also be seen in this photo at Measured Section #12 (sec 8 T16S R6W).

Figure 12: Facies STXSS (Small-scale trough cross-stratified sandstone). Cross stratification seen in this core piece from the Beaumeister core (sec 31 T2S R39W) has flattened wood pieces between laminae. Footage below KB.

Figure 13: Facies STXSS (Small-scale trough cross-stratified sandstone). This piece is from the Haberer core (sec 14 T12S R15W). Footage below KB.

carbonaceous laminae and *Skolithos* bioturbation were deposited in distributary or tidal channels. Troughs with rounded clay rip-up clasts and wood chips, and no carbonaceous laminae or bioturbation are fluvial deposits. Trough sets with inclined bounding surfaces were deposited in a standing body of water, and are interpreted as delta front deposits. These deposits are interpreted as deltaic rather than shoreface deposits because they lack polymodal current indicators, contain no lower shoreface deposits beneath them, and current directions are subparallel to the regional, north-south paleoshoreline trend. Horizontal sets of laterally amalgamated troughs were deposited in fluvial channels.

Facies PTSS: Planar tabular cross-stratified sandstone

This facies, described in outcrop, consists of 8 in to 4 ft thick sets of planar-tabular cross-stratified, medium- to coarse-grained, subangular to rounded sandstone (Figs. 14 and 15). Sandstones contain some rounded granules of chert and quartz, and clay rip-up clasts. Set surfaces are planar, horizontal or dipping slightly in a downcurrent direction. Foreset laminae are 1/8 in to 3 in thick and dip between 22° and 24° in directions ranging from north to west to south. The sandstone is friable but has a surficial iron cementation.

The coarse grain size, presence of clay rip-up clasts, and planar-tabular cross beds indicate deposition by braided streams. The range in current directions may be from deposition by lobate mid-channel bars or by obliquely oriented cross-channel bars.

Facies PSS/SH: Pyritic Interlaminated Sandstone and Shale

This facies, which occurred only near the base of the Haberer core (sec 14 T12S R15W, Plate 2), is white to greenish sandstone with whispy clay laminations (Figs. 16 and 17). Sands are very fine- to fine-grained, subangular to subrounded quartz; and some are frosted medium-sized grains. Blotches of fine pyrite crystals and disseminated pyrite impart a green(ish) color. Sedimentary structure varies from massive to horizontally laminated, to wavy laminated, to low-angle ripple laminated. Trace fossils were not observed.

Thin (1 ft) fining upward intervals are associated with a change from small-scale cross-stratified to horizontally laminated sandstone. It is interpreted as a fluvial deposit. Minor disruption of laminae in places are interpreted as dewatering structures.

Figure 14: Facies PTSS (Planar tabular trough cross-stratified sandstone). This photo is from Measured Section #11 (sec 26 T11S R4W).

Figure 15: Facies PTSS (Planar tabular trough cross-stratified sandstone). Numerous clay rip-up clasts and granules are characteristic of this facies. Photo is from Measured Section #11 (sec 26 T11S R4W).

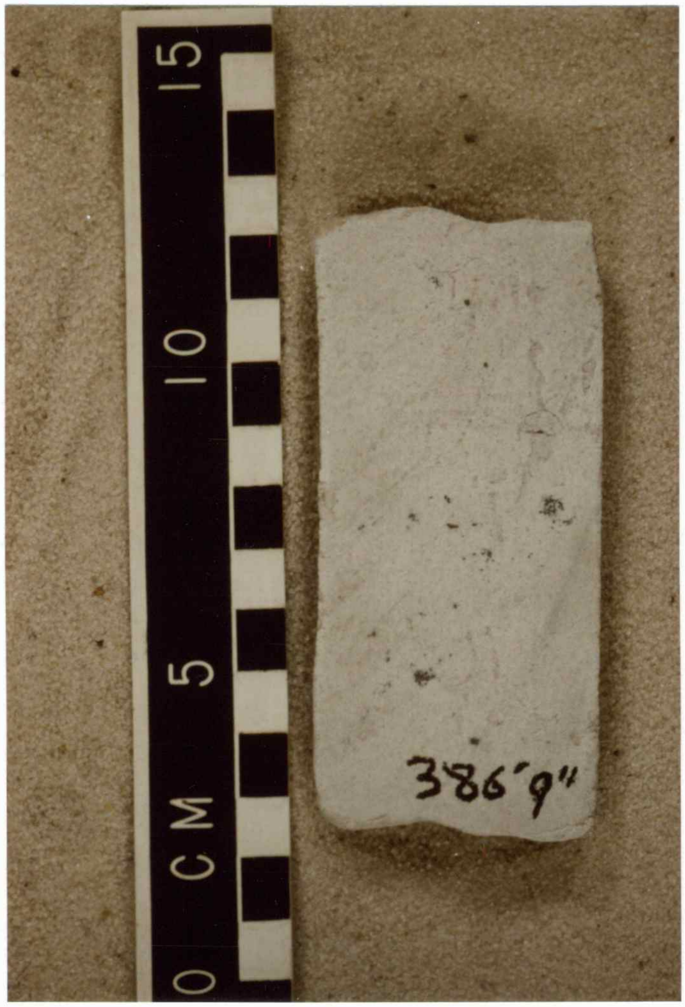


Figure 16: Facies PSS/SH (Pyritic interlaminated sandstone and shale). Few shale laminations are present in this part of the Haberer core (sec 14 T12S R15W). Footage below KB.

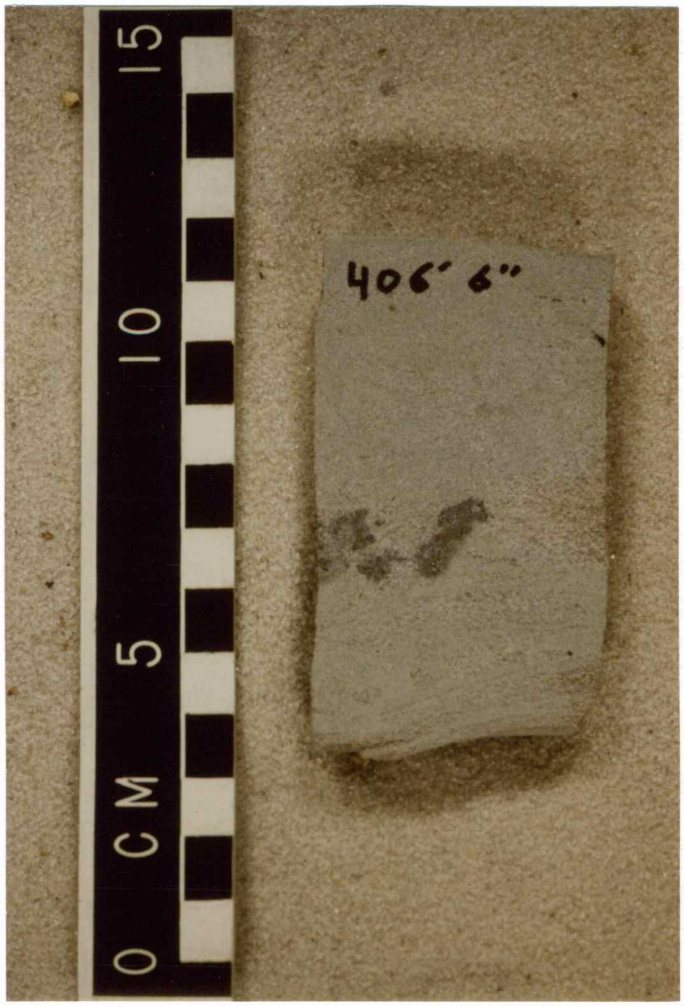


Figure 17: Facies PSS/SH (Pyritic interlaminated sandstone and shale). Pyrite nodules, greenish tint from disseminated pyrite, and cross laminations can be seen in this piece of the Haberer core (sec 14 T12S R15W). Footage below KB.

Facies VGMS: Variegated mudstone

This facies, described in core and outcrop, is grey to tan mudstone that contains numerous red, brown, yellow, and red-brown mottles (Figs. 18, 19 and 20). It is generally massive but has some horizontal laminations. Compaction and dewatering features occur as injection dikes of very fine-grained sandstone, miniature slump features, and brecciation. Sideritic spherulites and pyrite nodules are also present. It weathers to white, red, and yellow in outcrop. Disseminated plant fragments, carbonized wood fragments, and some clay slickensides are present in beds which range from 3.5 ft to 29 ft thick in outcrop.

The plant fragments, variegated colors, and sideritic spherulites indicate nonmarine deposition. This facies is interpreted as an overbank deposit subjected to subaerial exposure and soil formation.

Facies ST: Siltstone

This facies, described in core and outcrop, consists of white, light brown, grey and black siltstone. Secondary components are clay, sand, sideritic spherulites, wood chips, leaves, pyrite nodules, mica, and clay skins (Fig. 21). Sedimentary structure consists of very fine-grained sandstone lenses, horizontal, current- and wave-ripple laminations. In core it is also associated with burrowed sandstones.

The ST facies is interpreted as both overbank and lower shoreface deposits. In marine associations, it contains wave ripples, sandstone senses, and horizontal laminae. In nonmarine associations, it contains leaves, siderite, wood, clay skins, current ripples, and horizontal laminae. In some nonmarine associations, laminations are distorted to brecciated by compaction and dewatering processes.

Facies SS: Massive sandstone

This facies, described in outcrop, is internally massive, clay-rich, grey sandstone with sharp, planar upper and lower contacts. Minor indistinct horizontal laminations are sometimes present in the 2.5 ft to 14 ft thick beds of this facies.

By association with other facies it is interpreted as a fluvial channel deposit. Its massive structure indicates rapid deposition during decreasing flow velocity and turbulence.

Figure 18: Facies VGMS (Variegated mudstone).
Yellow and brown variegations and sideritic spherulites are present in this Haberer core piece (sec 14 T12S R15W). Footage below KB.

Figure 19: Facies VGMS (Variegated mudstone).
Extensive alteration of this Haberer core piece (sec 14 T12S R15W) indicates a soil zone. Footage below KB.

Figure 20: Facies VGMS (Variegated mudstone).
Rust-colored variegations and sideritic spherulites are contained in this piece of the Haberer core (sec 14 T12S R15W). Footage below KB.

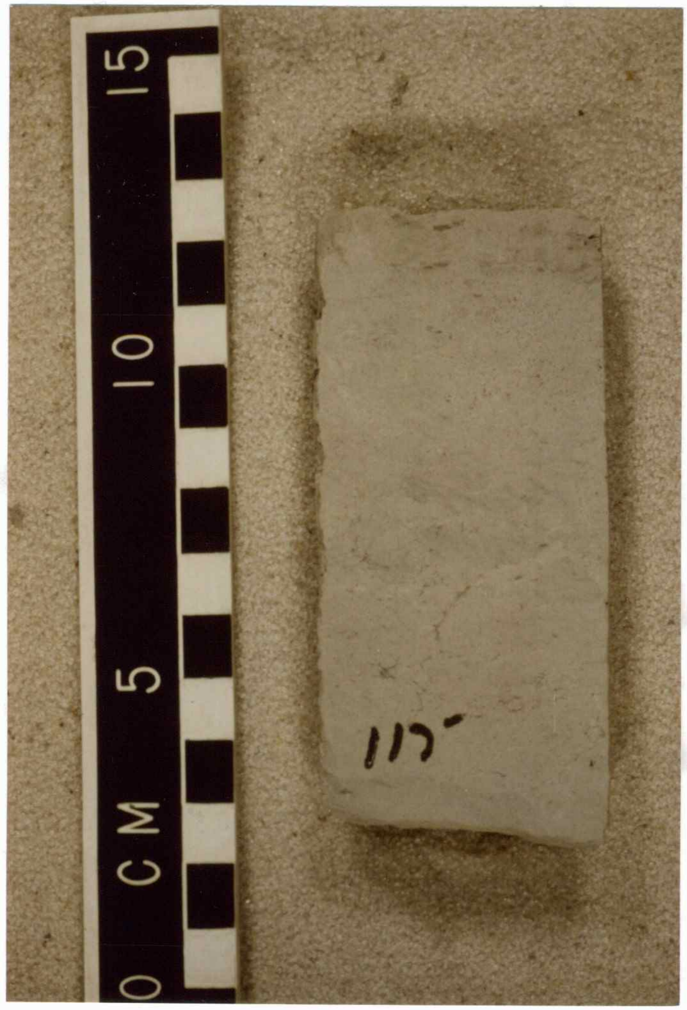


Figure 21: Facies ST (Siltstone).
Note massive texture and mottling in this Haberer core piece (sec 14 T12S R15W). Footage below KB.

Facies MTSS: Mottled Sandstone

This facies, described in core, is tan to grey, very fine-grained sandstone with minor silt and clay (Figs. 22 and 23). It contains sideritic spherulites, pyrite nodules, roots, and carbon flecks. Mottled texture is due to distortion by dewatering and root bioturbation. Some horizontal laminations are present.

The MTSS facies is interpreted as levee and splay deposits with poorly developed soils.

Facies CSH: Carbonaceous shale

The CSH facies, described in core and outcrop, is grey to dark grey, organic rich, silty shale (Fig. 24). It outcrop it occurs as continuous beds and lenses and contains thin lignites.

It is interpreted as abandoned channel fill and swamp deposits.

Facies CSS/SH: Carbonaceous Interlaminated Sandstone and Shale

This facies, described in core and outcrop, comprises interlaminated sandstone and shale (Figs. 25 and 26). The shale is grey to black. Sandstone is clean and well sorted, subrounded to rounded, very fine- to upper fine-grained with some lower medium-sized grains. Present in minor amounts are mica and carbon flecks, leaves and wood fragments, and silt. Laminations are horizontal, wavy, and rippled, and generally 1 mm to 2 mm thick. Ripple forms include climbing, starved and loaded. Transport directions from ripple laminae are bimodal in core. Some laminations are contorted by miniature slump and load features. Bioturbation is minor with some *Planolites* present in lenticular and flaser bedded sandstones. In outcrop it is present in beds less than 4 ft thick some of which dip slightly towards a cutbank.

This facies occurs in lower and middle shoreface and in fluvial environments. Lack of bioturbation and amount of carbonaceous material may be indicative of high sedimentation rates. This facies was also deposited in partially abandoned fluvial channels. Nonmarine occurrences of the facies are recognized by the presence of roots and leaves and by association with other nonmarine facies.

Facies GMS: Grey Mudstone

This facies, described in core and outcrop, is dominantly grey, but is also tan-grey

Figure 22: Facies MTSS (Mottled sandstone).
This Haberer core piece (sec 14 T12S R15W) is mottled and brecciated from compation and dewatering. Footage below KB.

Figure 23: Facies MTSS (Mottled sandstone).
Sideritic spherulites and faint laminations are visible in this piece of the Haberer core (sec 14 T12S R15W). Footage below KB.

FIGURE 3.14—Siltstone (Facies ST). Note the massive texture that can be seen in this piece of the core from the Haberer test well in sec. 14, T. 12 S., R. 15 W. Footage marked on the core piece is the depth below the KB.

FIGURE 3.15—Mottled sandstone (Facies MTSS). In this core piece, the sandstone is mottled and brecciated from compaction and dewatering. The core piece is from the Haberer test well in sec. 14, T. 12 S., R. 15 W. Footage marked on the core piece is the depth below the KB.

Massive Sandstone (Facies SS)

This facies, described in outcrop, is internally massive, clay-rich, gray, fine- to medium-grained sandstone with sharp, planar, upper and lower contacts. Minor indistinct horizontal laminations are sometimes present in the 2.5–14-ft (0.8–4-m)-thick beds of this facies. Facies SS is interpreted as a fluvial channel deposit by its association with other facies. Its massive structure indicates rapid deposition in the waning stages of a high-flow event under conditions of decreasing flow velocity and turbulence.

Mottled Sandstone (Facies MTSS)

This facies, described in core, is tan to gray, very fine grained sandstone with minor silt and clay (figs. 3.15, 3.16). It contains spherosiderite and pyrite nodules, roots, and carbon flakes. Mottled texture is due to distortion by dewatering and root bioturbation. Some horizontal laminations are present. Facies MTSS is interpreted as levee and splay deposits with poorly developed paleosols.

Carbonaceous Shale (Facies CSH)

The CSH facies, described in core and outcrop, is gray to dark-gray, organic-rich, silty shale (fig. 3.17). In outcrop it occurs as continuous beds and lenses and contains thin beds of lignite. This facies is interpreted as abandoned channel-fill and swamp deposits.

FIGURE 3.16—Mottled sandstone (Facies MTSS). Sideritic spherulites and faint laminations are visible in this piece of core from the Haberer test well in sec. 14, T. 12 S., R. 15 W. Footage marked on the core piece is the depth below the KB.

Figure 24: Facies CSH (Carbonaceous shale).
Carbonaceous shale is dark layer in the lower part of this photograph of Measured Section #1 (sec 34 T12S R14W). Facies succession above the carbonaceous shale is VGMS, ST and STXSS. Below the carbonaceous shale are ST and SS (Massive sandstone) facies.

Figure 25: Facies CSS/SH (Carbonaceousinterlaminated sandstone and shale). This piece of the Beaumeister core (sec 31 T2S R39W) exhibits lenticular and flaser bedding, and climbing ripples. Amount of carbonaceous material in fine laminations varies in this facies. Footage below KB.

Figure 26: Facies CSS/SH (Carbonaceousinterlaminated sandstone and shale). This piece of the Haberer core (sec 14 T12S R15W) has carbonaceous-rich laminae. Footage below KB.

and black mudstone (Fig. 27). Secondary components are mica and carbon flecks, roots, sideritic spherulites, pyrite nodules, clay skins, leaves, and wood chips. It is mostly massive with some wavy and horizontal laminations. Other structures include dewatering and miniature slump features. These are expressed as distortion of laminations and brecciation.

This facies is interpreted as an overbank deposit.

Facies HRLSS: Horizontal and ripple-laminated sandstone

This facies, described in core and outcrop, consists of ripple-laminated and horizontal- to wave ripple-laminated, very fine- to fine-grained, tan to white sandstone (Figs. 28, 29 and 30). Ripple-laminated sandstone is composed of asymmetric current ripples with silt and carbonaceous laminae, often modified by *Skolithos*. The horizontal to wave ripple-laminated sandstone is clean, very fine- to fine-grained, and occurs in 1 in- to 2 ft-thick beds with moderate *Skolithos* and minor *Planolites* bioturbation. Some fine carbonaceous detritus is present on laminae and bedset surfaces. Secondary constituents are silt, mica, and glauconite.

The ripple-laminated sandstone was deposited in shallow marine water by unidirectional currents that alternated with periods of slack water, allowing for deposition of carbonaceous material by settling. The horizontal to wave ripple-laminated sandstone was deposited by bimodal currents alternating with slack water conditions in a subtidal marine setting.

Facies BMSS: Burrowed Fine- to Medium-grained Sandstone

Sandstone of this facies, described in core, is fine- to medium-grained. It is generally clean but does contain some mica flecks, carbon flakes, and wood chips. Sedimentary structure is massive to wave ripple laminated with some bidirectional cross laminations all of which are outlined by carbonaceous shale laminae. *Skolithos* and *Planolites* burrows vary in density from minor amounts to thorough destruction of hydrodynamic sedimentary structure.

This facies is interpreted as an upper shoreface deposit.

Facies BSS/SH: Burrowed Interlaminated Sandstone and Shale

Interlaminated sandstone and shale comprise this facies described in core and outcrop

Figure 27: Facies GMS (Grey mudstone).
In this photo from Measured Section #13 (sec 19 T13S R10W), facies GMS is subadjacent to facies CSS/SH. This indicates a change from complete to partial phases of channel abandonment.

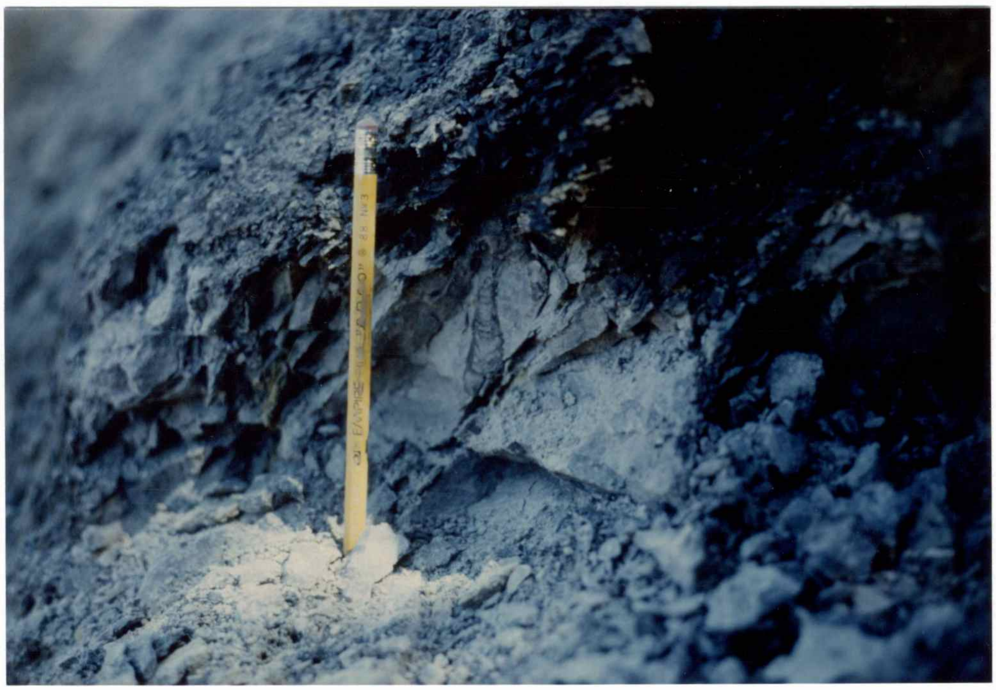


Figure 28: Facies HRLSS (Horizontal and ripple-laminated sandstone). This bed of facies HRLSS is within facies GSH (Grey shale) of the Kiowa Formation at Measured Section #10 (sec 18 T12S R2W). Trace fossil to the side of the pencil is a *Diplocraterion*.

Figure 29: Facies HRLSS (Horizontal and ripple-laminated sandstone).
This Haberer core piece (sec 14 T12S R15W) shows compaction and dewatering distortion of laminae. Footage below KB.

Figure 30: Facies HRLSS (Horizontal and ripple-laminated sandstone). Heavy minerals outline laminations in truncated wave ripples in this Haberer core piece (sec 14 T12S R15W). Footage below KB.

(Figs. 31 and 32). Shale is grey, finely laminated, carbonaceous, and micaceous. Sandstone is white, silty, and very fine- to fine-grained. Laminations are horizontal, wave rippled, and trough cross-stratified. Bioturbation is *Planolites*, *Skolithos* and nondescript. Minor pelecypod shells and shell fragments are present in some beds. Glauconite is associated with some occurrences of this facies.

Deposition of this facies was in lower and middle shoreface environments. Middle shoreface is distinguished by increase in sand content and bioturbation.

Facies FESS: Iron-cemented sandstone

Iron-cemented sandstone, described in outcrop, consists of fine- to coarse-grained quartz sand from 3 in- to 3 ft-thick beds. It contains carbon flecks, wood chips, flattened clay clasts, and some *Thalassinoides* bioturbation.

The thinness, coarse-grain size and bioturbation of this facies indicates that it is a lag deposit.

Facies GSH: Grey Shale

This facies, described in core and outcrop, is grey to black, finely laminated shale. It includes some whispy silt laminations and thin very fine-grained sandstone lenses which are bioturbated by *Planolites* (Figs. 33 and 34) There are a few wave ripples and truncation surfaces present. Fossils of this facies are pelecypod shells and shell fragments. It contains some mica and carbon flakes and pyrite nodules. In outcrop it weathers to light grey and tan in beds 13 to 24 ft thick. This facies makes up the whole Graneros Shale, but also occurs in other formations.

This facies was deposited in offshore marine to brackish water environments.

Facies Succession, Offsets, and Sequence boundaries

Facies analysis of cores and outcrops show distinct and repetitive patterns of vertical facies successions (Fig. 35). In marine facies, the succession, with facies substitutions at three levels, is as follows: Grey shale (GSH), Siltstone (ST); Carbonaceous interlaminated sandstone and shale (CSS/SH), Burrowed interlaminated sandstone and shale (BSS/SH), Horizontal and ripple-laminated sandstone (HRLSS); Burrowed fine- to medium-grained sandstone (BMSS), HRLSS; BSS/SH; HRLSS; ST, and Carbonaceous shale (CSH). This succession comprises

Figure 31: Facies BSS/SH (Burrowed interlaminated sandstone and shale). *Planolites* and *Skolithos* burrows in a piece of the Haberer core (sec 14 T12S R15W). Footage below KB.

Figure 32: Facies BSS/SH (Burrowed interlaminated sandstone and shale). *Planolites* burrows occur in this piece of the Beaumeister core (sec 31 T2S R39W). Footage below KB.

Figure 33: Facies GSH (Grey shale).
Paper-thin laminations are characteristic of this Haberer core piece (sec 14 T12S R15W). Footage below KB.

Figure 34: Facies GSH (Grey shale).
Facies GSH of the Kiowa Formation overlain by facies LTXSS of the Dakota Formation at Measured Section #10 (sec 18 T12S R2W).

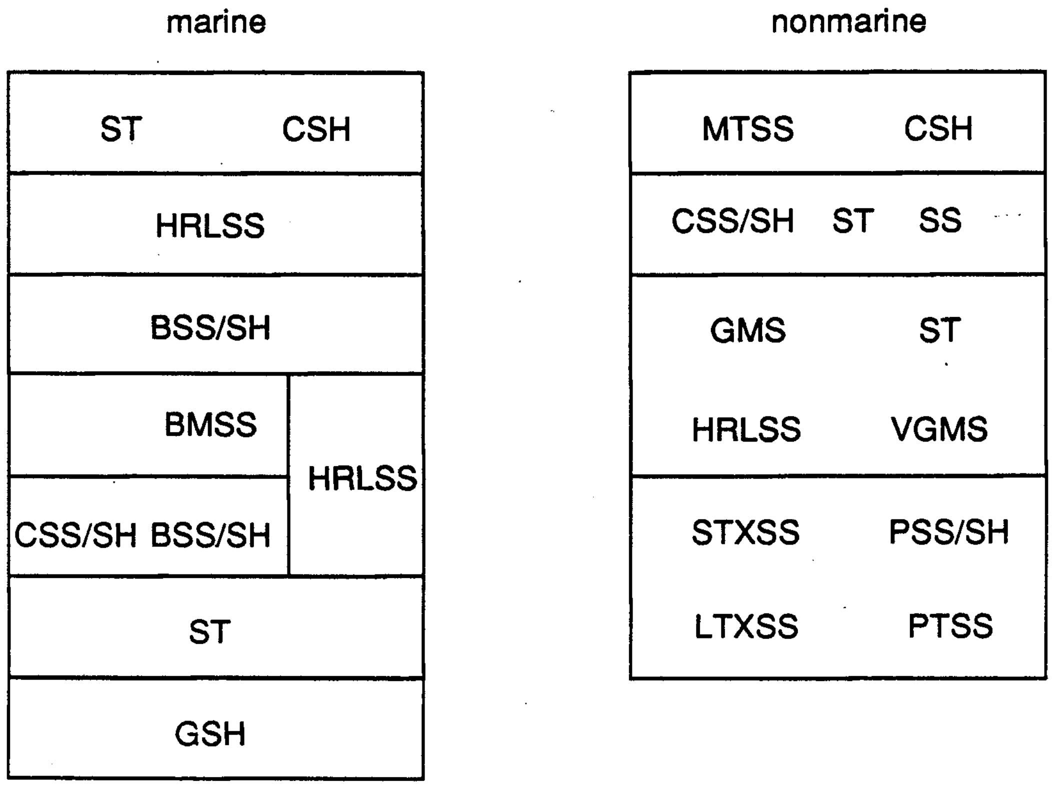


Figure 35: Idealized facies successions in marine and nonmarine strata. Facies within each box substitute for each other. Actual successions range in thickness from 18 ft to 54 ft for marine, and 18 ft to 74 ft for nonmarine.

individual, shoaling-upward, progradational events, with a range of depositional environments from offshore marine to shoreface to coastal plain. One typical succession is 18 ft thick and succeeds from GSH to ST to HRLSS to CSH facies. Another one is 34 ft thick and succeeds from GSH to BSS/SH to BMSS facies. In the nonmarine facies, the succession has substitutions throughout and is as follows: Small-scale trough cross-stratified sandstone (STXSS), Large-scale trough cross-stratified sandstone (LTXSS), Pyritic interlaminated sandstone and shale (PSS/SH), Planar tabular cross-stratified sandstone (PTSS); Grey mudstone (GMS), ST, HRLSS, Variegated mudstone (VGMS); Carbonaceous interlaminated sandstone and shale (CSS/SH), ST, Massive sandstone (SS); Mottled sandstone (MTSS), and CSH. This succession comprises aggradational events, with sandstones at the base followed by vertical accretion deposits. One typical succession is 18 ft thick and succeeds from STXSS to VGMS to ST to MTSS facies. Another is 30 ft thick and succeeds from STXSS to GMS to ST facies.

Upwards from the basal Cretaceous unconformity, nonmarine aggradational events are succeeded by marine progradational events. Facies are offset in a progressively landward direction. The change from nonmarine to marine deposition occurs across an offset of GSH facies over MTSS and CSH facies. Within the marine deposits, facies offsets are shown by GSH facies over ST, CSH, HRLSS, or BSS/SH facies. This succession of nonmarine facies overlain by marine facies, which get progressively deeper, is repeated three times in the strata below the Graneros Shale (Plates 1 and 3).

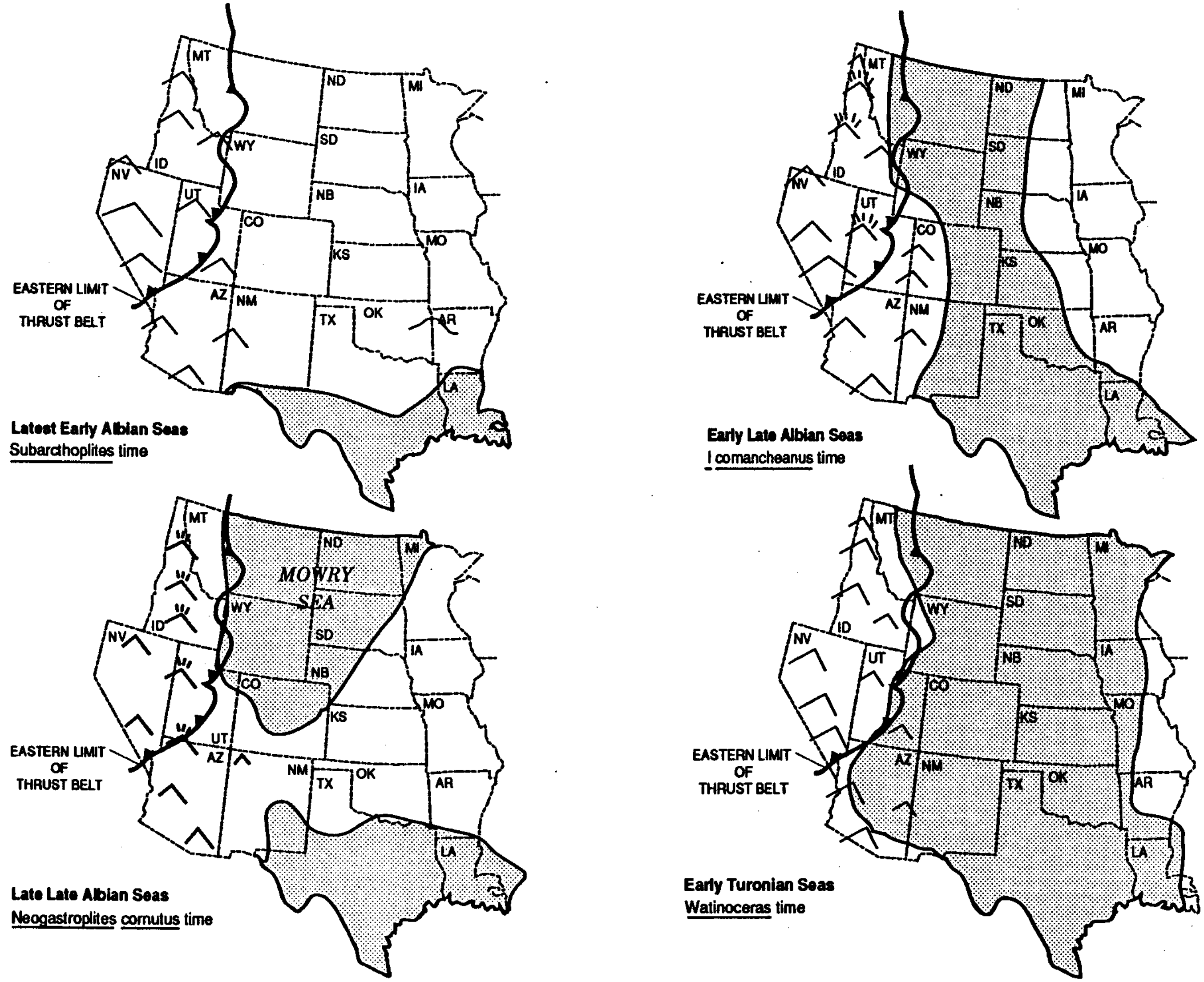
Subaerial unconformities are sequence boundaries and represent a lowering of relative sea level. This lowering is recorded in the stratigraphic section by a seaward shift in facies and evidence of subaerial exposure and erosion. Two sequence boundaries are defined in this study and placed where nonmarine STXSS facies are disconformable on marine GSH facies. In western Kansas cores, where the stratigraphic section is dominantly marine, evidence of subaerial exposure (roots, soils, and kaolinitic zones) and seaward shifts in facies are easily recognized (Plates 1 and 3). This occurs at the base of and in the middle of the Dakota Formation. However, in central Kansas outcrop, where the nonmarine facies dominate, evidence of subaerial exposure is numerous and does not represent sequence boundaries. A seaward shift in facies must be recognized in this case. This shift is recorded by braided stream deposits (PTSS) over meandering stream (STXSS, LTXSS) and vertical accretion deposits (VGMS, GMS, etc). Conventional understanding about braided stream deposits is that they are more proximal to source areas, more distal to base level, and formed on steeper depositional slopes than are meandering stream deposits. Therefore, a sequence boundary is placed at base of laterally continuous PTSS facies in the middle of the Dakota Formation.

Sequence Stratigraphy

The Cretaceous was a time of high global sea level, and much of the Western Interior of North America was periodically flooded. During times of highest sea level, the Western Interior Seaway was continuous from the Gulf of Mexico to the Arctic ocean. During times of lower sea level the Western Interior Seaway was separated by the emergent Transcontinental arch into a northern sea with connection to the Boreal Sea and a southern sea with connection to the Gulf of Mexico. A continuous seaway across the western interior was present at least twice during the Cretaceous (Fig. 36).

Large-scale variations in relative sea level, on the order of 3 to 5 million year periods, formed unconformity-bounded depositional sequences. For the Western Interior Cretaceous basin these interregional surfaces were formed during relative sea level falls and lowstands. During lowstands, deposition was restricted to the basin center and the eastern and western margins were subaerially exposed. Sources of sediment were from the east and west and from the Transcontinental arch. Valleys formed by erosion during lowstands were filled by sediment during subsequent relative rise in sea level. A stratigraphic sequence for this study follows the definition of Weimer (1984) as a package of genetically related strata bound by subaerial erosional unconformities.

Weimer (1984) defined several sequences in Cretaceous strata in Front Range outcrops and in the western Denver basin subsurface (Fig. 5). The basal sequence rests unconformably on Jurassic strata, and consists entirely of the Lytle Formation. The second sequence extends from the unconformity at the base of the Plainview Formation (top of the Lytle Formation) to the top of the Fort Collins Member of the Muddy Sandstone (J 3 unit of the J sandstone), and includes the intervening Skull Creek Shale. The third sequence extends from the unconformity at the base of the Horsetooth Member of the Muddy Sandstone (J 2 unit of the J sandstone) to the base of Codell Sandstone. An erosional unconformity occurs at the base of the D sandstone in the eastern part of the Denver basin, but is not present in the western Denver basin or Front Range outcrop (Fig. 6). The D sandstone was derived from the eastern side of the basin (MacKenzie and Poole, 1962), and its basal unconformity has not been recognized west of its depositional limit in Colorado. Where the D sandstone is present, its basal unconformity forms the upper boundary of the third sequence, and a fourth sequence is contained between it and



(Williams and Stelck, 1975)

Figure 36: Maps showing speculated extents of continental seaways at different time during the Cretaceous.

the unconformity at the base of the Codell Sandstone.

In this study, sequences in Kansas were identified first in the western part of Kansas along the Colorado border, closest to areas in Colorado where Cretaceous sequences have been identified previously. Since Cretaceous strata in western Kansas were deposited in a more basinward position than strata in the rest of the state, they have more marine components in which evidence of subaerial exposure and facies shifts are more readily identified.

The stratigraphic sequences and facies were calibrated to gamma ray well log signatures. Sequences were correlated on three statewide well-log cross sections and then correlated with sequences defined by facies analysis of thirteen measured sections (Fig. 1). Lateral and vertical relations of the sequences and formations are discussed with reference to diagrams constructed from these well-log cross sections (Figs. 37, 38 and 39). Representative gamma ray well logs from the west to east cross section Z-Z' are correlated on Plate 4. The south to north cross section X-X' was hung on the top of the Dakota Formation. The "X" bentonite is contained in the upper part of the Graneros Shale and is approximately parallel to the contact with the overlying Greenhorn Limestone. Since the Graneros is roughly the same thickness across the section, the top of the Dakota approximates a time surface. The west to east Z-Z' cross section was hung on the top of the Graneros. The south to north N-N' cross section was constructed approximately parallel to outcrop in central Kansas. The southern well logs of this section are located in outcrops of Cheyenne and Kiowa Formations. Well log information and top elevations are included in Appendix B.

In Kansas, four sequences of Weimer (1984) are recognized. However, the basal Cretaceous sequence of Weimer (1984) is speculated to occur only in the extreme northwest corner of Kansas. It consists only of the Lytle Formation, which is called Cheyenne Sandstone in the Colorado subsurface, and contains fluvial strata that onlap the basal unconformity and that are truncated by the overlying unconformity (Weimer, 1984). The second, third, and fourth sequences are present in Kansas. Only the part of the fourth sequence which includes the D sandstone and the Graneros Shale were studied in this project. The following discussion defines the boundaries, internal stratal architecture and depositional environments of each sequence, and identifies the lithostratigraphic units

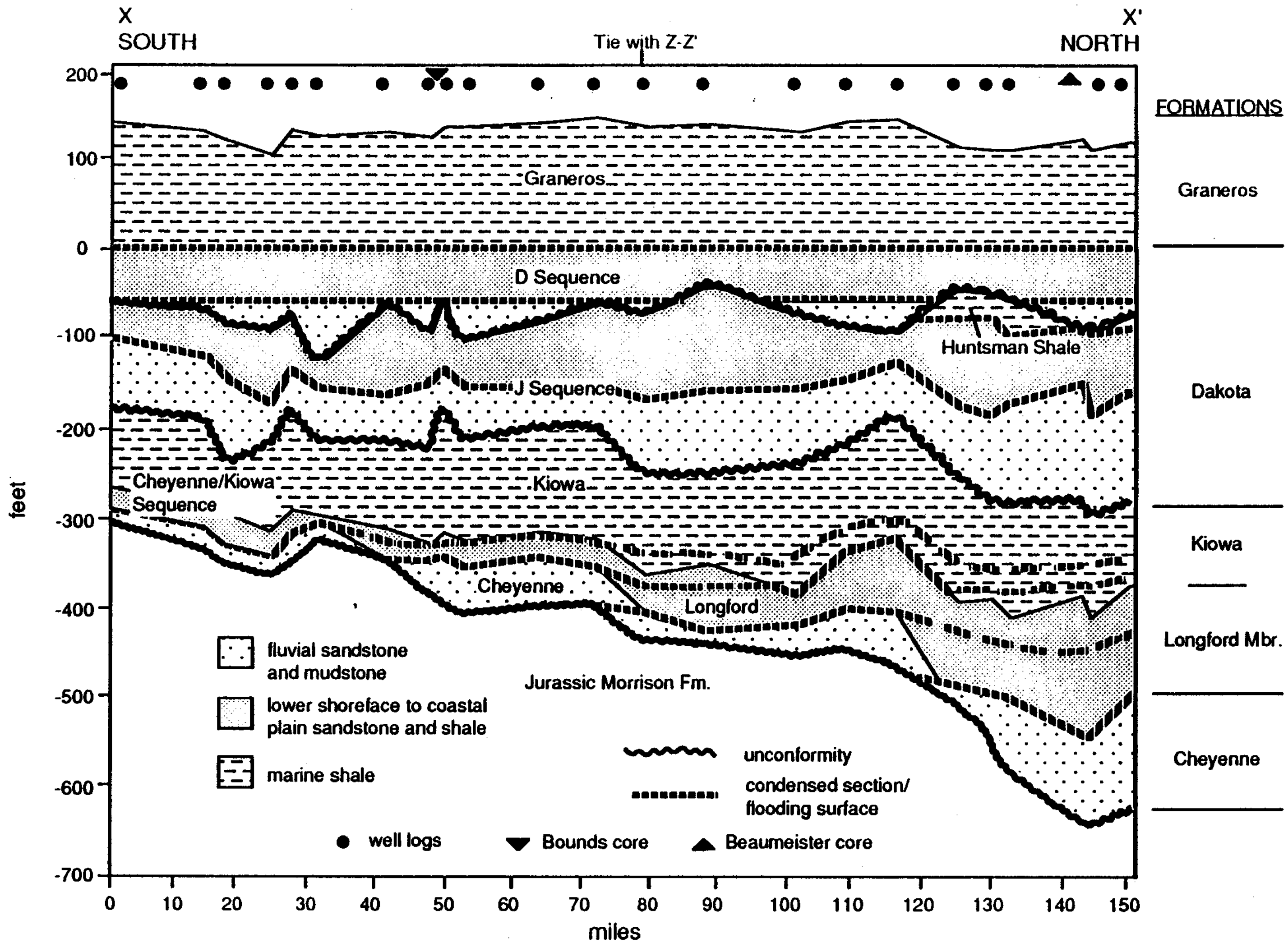


Figure 37: Stratigraphic cross section X-X' showing formations, sequences, progradational events within sequences and facies distributions. Datum is top of Dakota Formation.

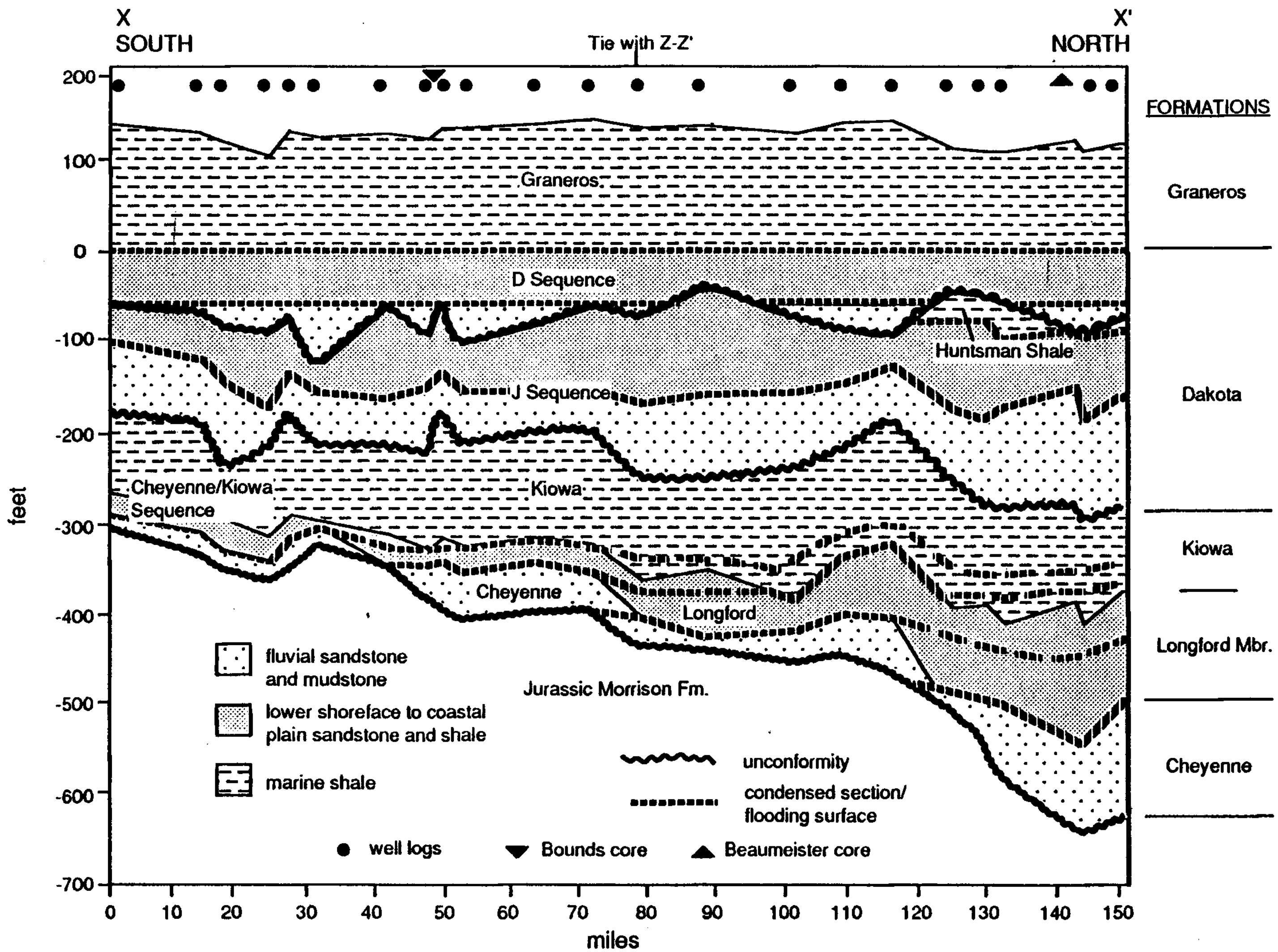


Figure 37: Stratigraphic cross section X-X' showing formations, sequences, progradational events within sequences and facies distributions. Datum is top of Dakota Formation.

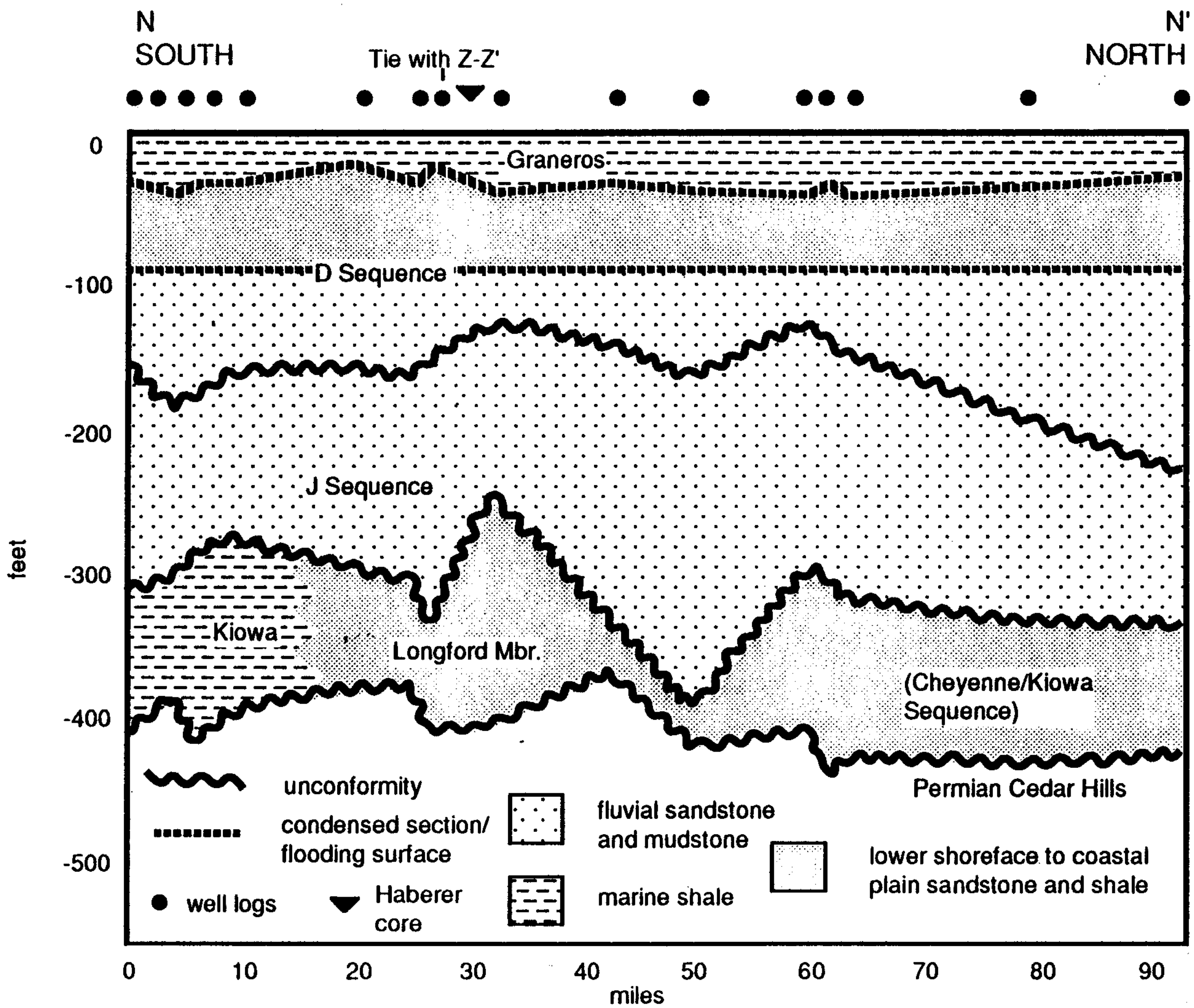


Figure 39: Stratigraphic cross section N-N' showing formations, sequences and facies distributions. Note lateral facies equivalence of Longford Member with Kiowa Shale. Datum is top of Graneros.

contained within each. Names for the sequences in Kansas are proposed as the Cheyenne/ Kiowa, J and D Sequences. It is recommended that these names be adopted as time-stratigraphic classifications. In this way time and facies relations of existing lithostratigraphic formations are better understood. However, no changes in the existing lithostratigraphic names are recommended.

Cheyenne/Kiowa Sequence

The Cheyenne/Kiowa Sequence (perhaps should be called the Cheyowa) in Kansas is defined between the unconformity at the base of Cretaceous strata to the unconformity at the base of the Dakota Formation. Strata within this sequence onlap the basal unconformity in an eastward direction. This sequence progressively overlaps the basal Cretaceous sequence (Lytle Formation) in Colorado, and Jurassic and Permian strata to the east in Kansas. Formations contained within this sequence are the Cheyenne Sandstone of Kansas, Kiowa Formation, and Longford Member of the Kiowa Formation. The bounding unconformities have been dated in Colorado at 100 Ma and 97 Ma (Weimer, 1984). By contrast, Baum and Vail (1988) place an age of 102 Ma on the unconformity at the top of this sequence. Correlations of this and the other sequences to the sea-level curve of Haq et al. (1988) is difficult because of differences in radiometric dates and fauna. Baum and Vail (1988), for example, use the time scale of Van Hinte (1976) instead of the Haq et al. (1988) sea-level curve.

This sequence consists of landward-stepping progradational events. Seaward-stepping progradational events that were deposited at the top of the Kiowa Formation during relative sea-level fall were eroded prior to deposition of the next sequence. These prograding deposits are present to the west in Colorado and are called the J3 unit of the J sandstone.

Typically in western Kansas, most of the progradational events were deposited in lower to upper shoreface environments and consist of, in vertical succession, GSH, CSS/ SH, BSS/SH, HRLSS, CSH facies. Lateral facies changes are interpreted to occur within each progradational event from fluvially deposited sandstones and mudstones (Cheyenne Sandstone) through shoreface sandstones and shales (Longford Member) to open marine shales (Kiowa Formation).

The Cheyenne Sequence is much thinner in the south than north (cross section X-X', Fig. 37). This indicates that there was depositional onlap onto a topographic high that may have been structurally controlled. The landward limit of each progradational event onlaps the basal unconformity to the south and the younger progradational units overlap older units toward the south.

Stratigraphic and paleontologic evidence from the rest of the Western Interior basin show that the seaway advanced from north to south and from south to north across most of the continent (Haun, 1963; Long, 1966). Before the Albian seaway was fully connected from north to south, a drainage divide must have existed. Based on the positions of structural features, provenance information and paleocurrent directions, it is likely that this divide trended northeast-southwest along the Sierra Grande uplift, Cimarron arch, and northern Hugoton embayment (Figs. 6 and 7). Thus, the genetic sequences in southern Kansas prograded southward into the southern sea and the ones in western and central Kansas prograded westward into the northern sea. The seaway was continuous across the continent during Kiowa Formation deposition, *Inoceramus comancheanus* time (Scott, 1970).

The internal architecture of the Cheyenne Sequence in a west to east direction is shown in the Z-Z' cross section (Fig. 38). One way to establish time and facies relations within the Cheyenne Sequence is to use the transgressive disconformity between the Longford and Kiowa as a sloping, rather than horizontal, datum. Assuming that it had a seaward-dipping slope greater than the slope of the coastal plain, a diagram was constructed to show landward to seaward lateral facies changes, and the landward-stepping arrangement of progradational events (Fig. 40). This diagram was constructed from stratigraphic thicknesses taken from well logs uncorrected for compaction. The Longford/Kiowa contact was tilted in a paleoseaward direction at an angle of 0.0768 ° (0.708 ft/mi). This angle was derived from the angle formed by the stratigraphic wedge between the Graneros-Dakota contact and the top of the Graneros, which is parallel to the "X" bentonite. Both surfaces are transgressive disconformities and probably had identical slopes. The depositional systems beneath both transgressive disconformities are also assumed to be similar to each other. Therefore, lateral facies relationships that are observed in the Dakota Formation are inferred for the Cheyenne Sequence. There was sufficient structural deformation by the end of Graneros deposition such that flooding

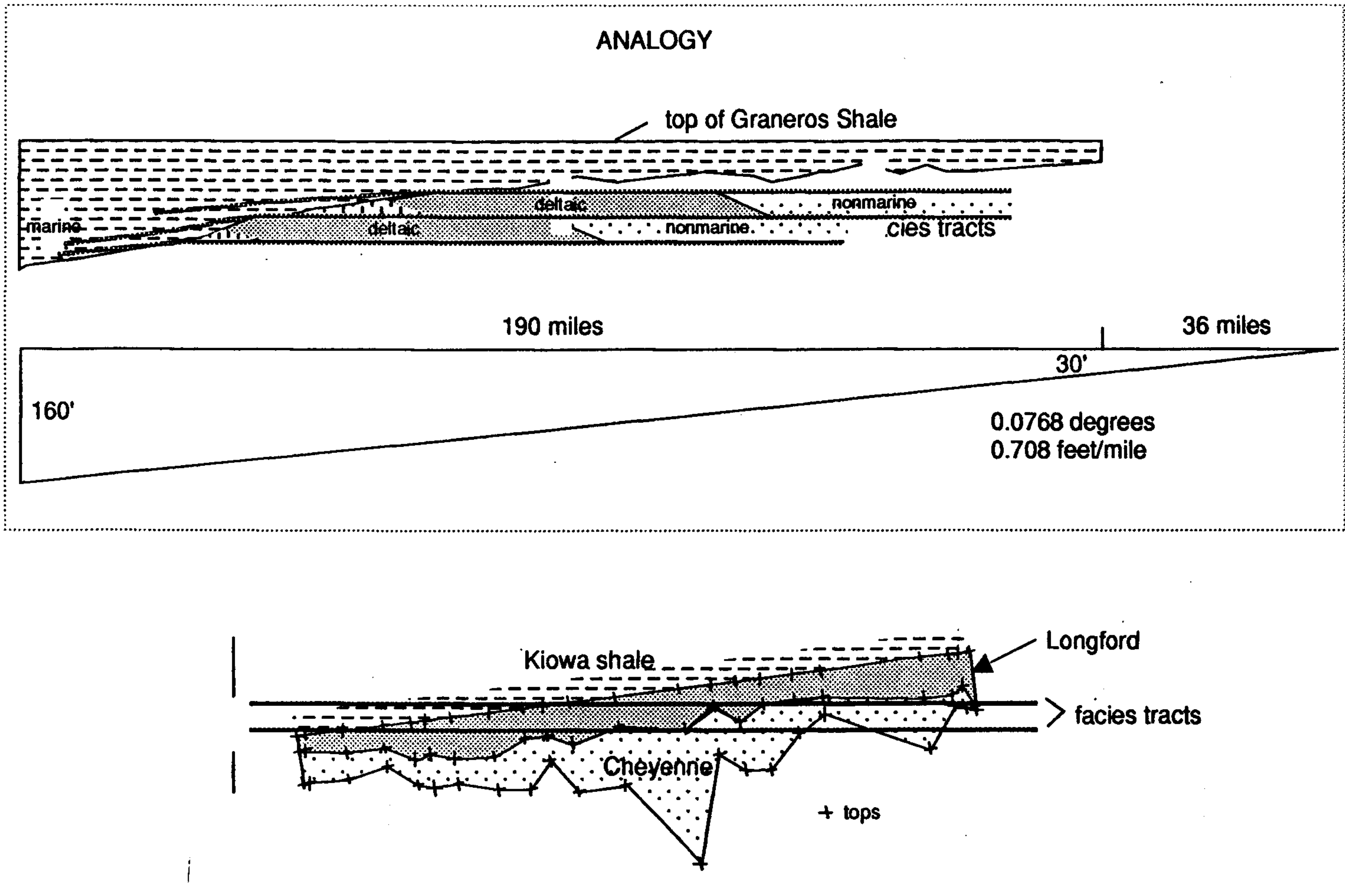


Figure 40: This diagram demonstrates a method for establishing time lines across facies in a sequence without a datum. The Graneros Shale/upper Dakota Formation is used as an analogy. The top of the Graneros Shale is a time line and used as a datum. So the angle of depositional slope between deltaic and open marine facies can be determined with respect to time lines. This angle is then imposed on the same type of facies contact in the lower sequence. These time lines cross formation contacts and show them as lateral facies equivalents.

surfaces appear highly irregular on cross sections hung on the top of the Graneros.

The eastward thinning Cheyenne Sandstone pinches out by onlap at R18W (mile 160, cross section Z-Z', Fig. 38). East of this point the Cheyenne is present as only a thin, locally mappable unit. The Permian Cedar Hills Sandstone subcrop is nearly coincident with the Cheyenne pinchout, suggesting that it may have been a positive topographic feature and sediment source area during Cheyenne deposition. After the time of Cheyenne deposition in this area, a major transgression of the Kiowa sea shifted facies tracts to the east, and drowned the Cedar Hills paleooutcrop.

The Central Kansas uplift may have been a positive topographic feature during the Cretaceous (R21W, mile 130, cross section Z-Z'). The subcrop limit of the Jurassic Morrison Formation against the basal Cretaceous unconformity occurs at about the same location. Cheyenne streams probably flowed parallel to the uplift, eroding the Morrison and forming the unconformity.

In R19W (mile 150, cross section Z-Z'), the Dakota Formation rests directly on the Longford Member. Since the contact between the Kiowa and Longford has been removed by erosion east of this point, the extent of transgression of the Kiowa sea is not known. However, vertical facies successions within the Longford Member in the Haberer core in R15W (mile 170, cross section Z-Z') are interpreted as a basal, landward-stepping geometry then an upper, vertically stacked arrangement of progradational events, suggesting that the maximum extent of the Kiowa sea was at the position where landward-stepping ends (Fig. 41). Seaward-stepping units that must have been deposited during the following relative sea-level fall were removed by subaerial erosion during the lowstand. This trend of top downward truncation of the Kiowa is consistent across the state except in the subsurface near Colorado. Thus, the unconformity at the base of the Dakota Formation cuts down stratigraphically to the east. As seen in the Beaumeister and Bounds cores (sec 8 T2S R39W and sec 17 T18S R42W, Plates 1 and 3), progradational events consisting of lower to middle shoreface deposits are present in the upper part of the Kiowa Formation. These strata must have continued eastward, but they were subsequently removed by erosion. These types of regressive deposits are notably thin throughout the Cretaceous basin (Weimer, 1984).

The anomalously thick section of Cheyenne Sandstone in R30W (mile 80, cross section Z-Z') is the result of dissolution of Permian Flower Pot Salt, as determined from

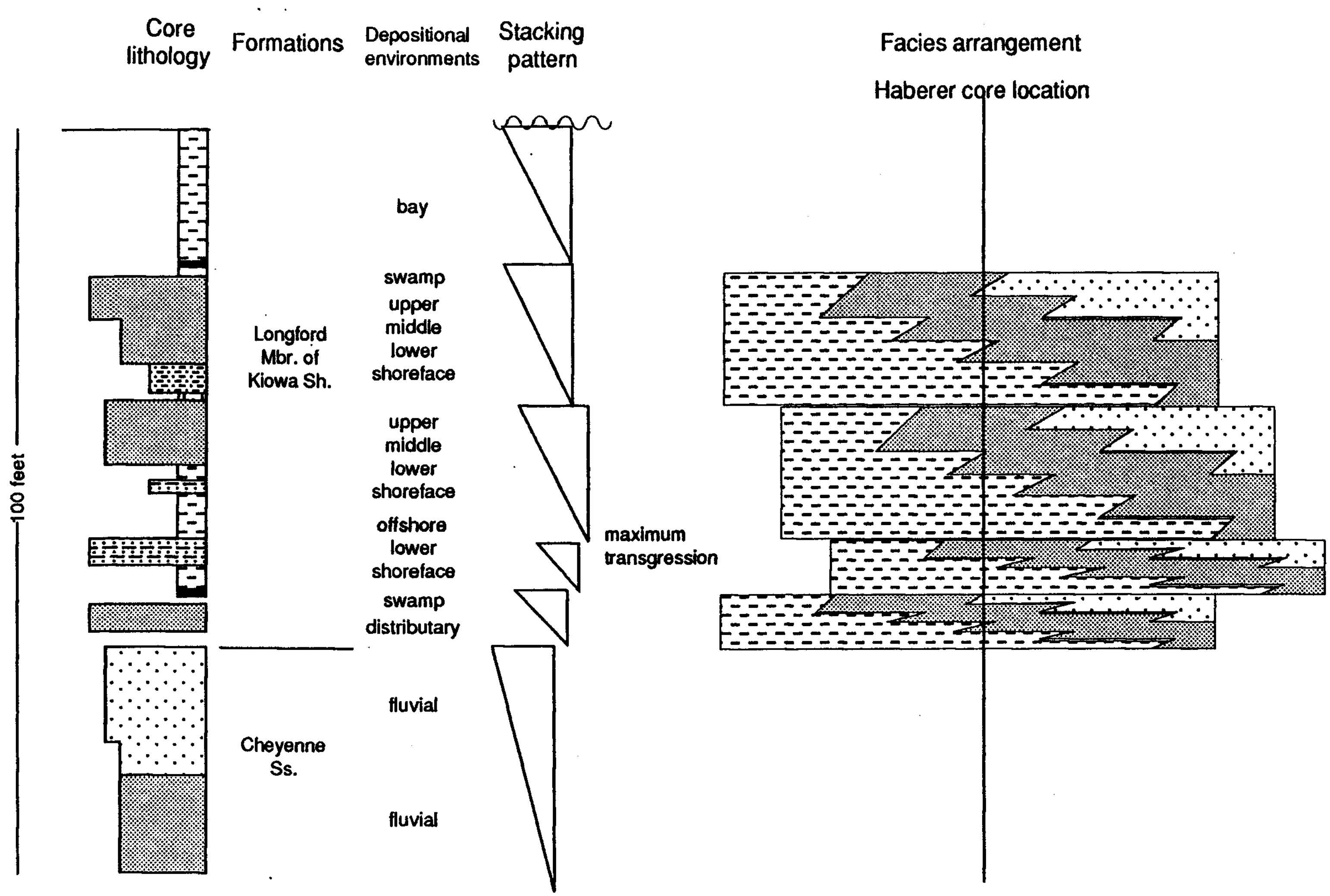


Figure 41: Stacking pattern interpreted within the Kiowa Formation from the Haberer core. Seaward-stepping progradational events reveal maximum transgression position.

correlations of closely-spaced well logs in this area. Because only the Cheyenne Sandstone thickens in this area, the timing of salt dissolution occurred prior to and/or during Cheyenne deposition. This is also the most logical time for salt dissolution to occur since this is a fluvial deposit resting on a subaerial unconformity. The band of dissolution occurs along the depositional edge of the Flower Pot Salt.

The Cheyenne pinches out to the northeast along the N-N' cross section in a similar manner as in the Z-Z' section. A stratigraphic cross section was constructed for the northern part of this section where the Graneros Shale is present (Fig. 39). The Cheyenne pinchout is south of where Graneros Shale is preserved, so it is not shown on the N-N' cross section. The top of the Graneros is the only datum from which to hang the section and evaluate potential depositional relationships in the Cheyenne/Kiowa Sequence. The Kiowa Formation and Longford Member are laterally adjacent to each other in this section and are bounded above and below by identical unconformities. This fact supports their temporal equivalency.

Discussion

The Cheyenne Sandstone at its type locality in southern Kansas consists of fluvial and coastal plain facies. These are laterally and temporally equivalent to the marine Kiowa Formation. Because outcrops are limited and discontinuous, and because the Cheyenne/Kiowa flooding surface is sharp, deposits representing a marine/nonmarine transition between the Kiowa and Cheyenne have not been observed. This contact has been described by previous workers as both a conformity and a transgressive disconformity.

Field observations in this study indicate that the contact is a transgressive disconformity. A landward shift of facies is preserved in the upper part of the Cheyenne Sandstone near the town of Belvidere. Below the transgressive disconformity is a deepening event surface where tidal deposits (Longford Member) are displaced over fluvial deposits (Cheyenne Sandstone). The tidal deposits are represented by a ten foot thick unit of sandstone and shale which contain bimodal paleocurrent indicators and marine bioturbation. These are then overlain by marine shale (Kiowa Formation). The importance of these landward shifts in facies is that the Cheyenne Sandstone, Longford Member, and Kiowa Formation were all deposited in and near the same transgressing sea. In summary, these lithostratigraphic units are temporally equivalent, genetically related facies within the same sequence.

The unconformity at the base of the Cheyenne Sandstone in Kansas must be the same as the one at the base of the Plainview Formation in Colorado (base of second sequence of Weimer, 1984). Both the Cheyenne and the Plainview occur below the same transgressive disconformity, and therefore their basal unconformities are identical, and the Plainview Formation is temporally equivalent to the Longford Member. Some fluvial sandstones occur at the base of the Plainview Formation, incised into the underlying Lytle Formation sequence. These fluvial sandstones are genetically related to the Plainview and not to the underlying fluvial sandstones of the Lytle Formation (Weimer, 1984). These Plainview fluvial sandstones and the Cheyenne Sandstone in Kansas are temporally equivalent. The stratigraphic nomenclature is complicated because the Lytle Sandstone in Colorado is called the Cheyenne Sandstone in the subsurface of Colorado. The Lytle Formation, however, is beneath the unconformity at the base of the Cheyenne Sandstone of Kansas. That is, the Lytle Formation and its lithologic equivalent in the subsurface, Cheyenne Sandstone of Colorado, are in a different, older sequence than the Cheyenne Sandstone of Kansas. No subsurface studies have been done in Colorado to determine what part of the subsurface Colorado Cheyenne Sandstone belongs to the Lytle Formation sequence and what part of it belongs to the Plainview Formation sequence. The Cheyenne Sandstone of Colorado and the Cheyenne Sandstone of Kansas are partially, if not completely, separated by an unconformity.

Independent resolution of this issue is difficult owing to the lack of fossils in these formations upon which age relations might be independently established. Physical correlation is not possible due to westward and northward pinchout in the subsurface of the Cheyenne Sandstone from its type locality in southern Kansas. Cheyenne Sandstone described by McLaughlin (1954) in southeast Colorado may or may not be time equivalent to the Cheyenne Sandstone in Kansas. Correlative strata were removed by Cenozoic erosion east of the Colorado outcrop.

Using macrofossils, Scott (1970) correlated the Kiowa Formation with the Skull Creek and Glencairn Formations in Colorado. The most widespread faunal zone is the *I. comancheanus*, which extends from outcrops in central Kansas to outcrops along the Front Range in Colorado. The oldest fossil zone, *V. kiowanum,* occurs at the base of the Kiowa Formation only in southern Kansas (Scott, 1970). This limited distribution indicates that the Cheyenne Sandstone in this area pinches out by depositional onlap. Furthermore, if transgression occurred from north to south in Colorado, then west to east into Kansas, the oldest fossil would be expected to be found to the north and west from Kansas, not to the south and east. This observation, in combination with the southerly directed paleocurrent of the Cheyenne Sandstone in southern Kansas, leads to the interpretation that a paleodrainage divide, which separated the northern from the southern sea, was located north of the Cheyenne and Kiowa type localities. This divide was probably located north and west from the position were the Cheyenne Sandstone pinches out and where the *V. kiowanum* zone onlaps the basal unconformity.

The Hugoton embayment may have influenced the extent of this southern sea which advanced into southern Kansas at a much earlier time than the northern sea advanced into the rest of Kansas. Franks (1975) noted this age relationship in Kansas outcrop (Fig. 3). It led him to believe that the Kiowa sea advanced in a southwest to northeast direction across Kansas. Franks (1979) mapped the distribution of the Longford Member in central Kansas outcrop. However, on his maps the contact between the Longford and the Kiowa trends in a north to south direction. If the Longford and Kiowa are lateral equivalents, and if the sea advanced from the southwest to the northeast, then the contact between the two should trend northwest-southeast. I believe that once the drainage divide separating the two seas was flooded, the shorelines reoriented to a south-north trend parallel to the basin axis, and transgression occurred mostly in a west to east direction across most of Kansas.

J Sequence (lower Dakota Formation)

The J Sequence in Kansas is defined from the unconformity at the top of the Kiowa Formation (base of Dakota Formation) to an unconformity within the Dakota Formation. The basal unconformity is equivalent to the one described by Weimer (1984) at the top of the Skull Creek Shale (base of J sandstone), top of Fort Collins Member or base of Horsetooth Member of the Muddy Sandstone. The upper unconformity is equivalent to the one at the base of the D sandstone. The unconformities are dated in Colorado at 97 Ma and 95 Ma (Weimer, 1984).

In the Beaumeister and Bounds cores in western Kansas, this sequence consists of landward-stepping progradational events (Plates 1 and 3). In these cores, the lower progradational events are composed entirely of fluvial facies, and the upper progradational units are composed entirely of shoreface facies. The unconformity is recognized here by cross-bedded sandstones with clay rip-up clasts resting on marine shales.

The definition of the upper bounding unconformity relies on recognizing seaward offsets of these progradational events. On the eastern flank of the Denver basin, the unconformity at the base of the D sandstone is easily defined because fluvial sandstone rest directly on open marine deposits of the Huntsman Shale, representing a major seaward displacement of facies tracts (Sonnenberg, 1987). However, in Kansas the Huntsman Shale is absent due to a combination of erosion below the D unconformity and lateral facies change into strata representing shoreface and coastal plain environments. Because much of this sequence in Kansas is represented by coastal plain facies, evidence of subaerial exposure and scour are numerous, and these criteria alone are insufficient to determine the position of an interregional unconformity. However, a seaward displacement of facies, reversing the landward-stepping trend, is sound evidence for identifying the position of the D unconformity.

The deepening-upward (landward-stepping) asymmetry of the J Sequence results from two causes. First, the younger Huntsman Shale and time equivalent strata above it were eroded in Kansas. Second, because the coastal plain facies are deposited aggradationally during relative sea-level rise, and sediment bypass (nondeposition) occurs during falling base level, any sediments deposited in Kansas during regression were probably initially very thin.

Along depositional strike it is possible to correlate the flooding event at the top of the first progradational event within this sequence (Fig. 37). The thickness of strata between this surface and the basal unconformity decreases to the south. Therefore, the lower part of this sequence onlaps to the south.

The correlation of intrasequence flooding surfaces along depositional dip proved difficult (Fig. 38). The interbedded sandstones and shales composing the section create a highly variable gamma ray well-log signature. In addition, flooding surfaces disappear landward into coastal plain facies. For these reasons the landward shift of the coastal plain to shoreface facies transition was approximated as a smooth line.

In the outcrop, facies contained within this sequence were deposited entirely in fluvial environments (Figs. 38 and 39) The maximum eastward extent of the transgression associated with the Huntsman Shale is not possible to determine. This is due to truncation of the turnaround point by the D unconformity. However, given the trend of the facies transition from marine to nonmarine, it probably did not extend much farther east beyond the point where it is presently truncated.

The position of the unconformity in the Haberer core in central Kansas in not known for certain (Plate 2). Core was not recovered from the thick sandstone interval. A major downward shift in facies is not evident in the section of core above this. Based on the position of the unconformity in nearby wells and outcrop, it is assumed to be obscured within the amalgamated sandstones represented by the well log.

Discussion

The unconformity between the Dakota and Kiowa Formations in western Kansas subsurface is the same as the interregional, erosional unconformity between the J sandstone and Skull Creek Shale in Colorado (Weimer, 1984). The nature of contact between the Kiowa and Dakota Formations in outcrop is not well established. Numerous workers confirm that the Kiowa and Dakota Formations were deposited in Kansas along the eastern side of the north-south trending Western Interior Cretaceous Seaway (MacKenzie and Poole, 1962; Haun, 1963; Hattin, 1965; Scott, 1970; Siemers, 1971; Williams and Stelck, 1975; Witzke, 1983; Vuke,1984) (Fig. 36).

Franks', (1966, 1979), conclusions vary only slightly from this viewpoint, in that he suggested that transgression occurred from southwest to northeast across Kansas. This variance can be explained because he worked only in the southwest-northeast trending outcrop along which changes from west to east would appear to have occurred from the southwest to the northeast. Very little of the Dakota outcrops around the Cheyenne and Kiowa type sections in southern Kansas. All interpretations about the contact are from central Kansas outcrops where paleoshoreline trends are north to south. A state-wide isopach map of the Graneros Shale produced by staff at the Kansas Geological Survey shows a distinct north-south paleoshoreline trend.

With this basin configuration in mind, it is only logical to conclude that if the top of the Kiowa Formation was subaerially exposed basinward in eastern Colorado, then the top of the Kiowa Formation was subaerially exposed in Kansas. Thus, the contact between the Kiowa and Dakota Formations in central Kansas outcrop must also be a subaerial erosional unconformity.

Field evidence from the three measured sections confirm the unconformity between the Kiowa and Dakota Formations (Sections 5, 10, and 12 in Appendix A). In each case fine- to coarse-grained sandstones and some conglomeratic sandstones of the Dakota Formation are separated from shales, siltstones and fine-grained sandstones of the underlying Kiowa Formation by a sharp contact. Truncation of underlying beds and the presence of clay rip-up clasts in the overlying beds are evidence for erosion. Wood chips, leaves and unidirectional cross beds and current ripples are present in the Dakota, but absent in the Kiowa Formation.

Scott and Franks (1988) stated: "The Kiowa-Dakota contact accents a major, only locally erosional, regressive episode." This is consistent with Franks' earlier conclusion (1966, 1975) that the Dakota was deposited progradationally as the Kiowa sea retreated. Their interpretation of the nature of the contact is obviously one of conformity. By contrast, Weimer (1984) demonstrated that the Dakota Formation and equivalent strata in Colorado onlap the basal unconformity, and therefore were deposited during a relative sea-level rise. Well log correlations confirm that this onlap continues in an eastward direction in Kansas.

Additional evidence for an unconformity between the Kiowa and Dakota Formations is that the Dakota Formation is unconformable on Permian Sumner Group in Washington County, northeast Kansas. If the Kiowa were formerly present in this part of Kansas, it has certainly been eroded. The existence of an erosional unconformity in the basinward direction has already been established. There is no possible way for the Kiowa-Dakota contact to be unconformable on the basin margin and in the basin center, yet conformable with only local erosion at a position in the basin between these two end points.

Franks (1979, 1980) interpreted sandstones in the Longford Member as barrier bars. Based upon the evidence and reasoning below, and on the previous discussion of the Kiowa-Dakota contact, these sandstones are reinterpreted as fluvial channel deposits in the Dakota Formation. This reinterpretation removes inconsistencies in recent interpretations of facies and stratigraphic ages, and further supports the position and occurrence of the sequence boundary between the Kiowa and Dakota Formations. Franks (1979) described the inferred barrier bars as fine- to medium-grained sandstone containing small- to medium-scale wedge- to planar-tabular and trough cross stratified sets with granules and clay pebbles concentrated on scour surfaces; paleocurrent directions vary from southeast to southwest, parallel to the trend of the sandstone bodies. One vertical section (Section 12 Appendix A) was measured at the locality identified as a barrier bar in a photograph in a report on Ellsworth County (Bayne, et al, 1971). The contact between shales of the Longford Member and the overlying medium-grained sandstones is erosive with large clay rip-up clasts imbricated in the sandstone (Fig. 10). Between this contact and the cross-stratified sandstone are fluvial lateral accretion beds which contain abundant whole fossil leaves and pieces of wood. The overlying cross-stratified sandstone body, interpreted by Franks (1979) as a barrier bar, has a concave-up base. So the sandstone body widens upward from a concave-up erosional scour surface. Lateral to this sandstone body are grey mudstones that I interpret as overbank deposits.

Harms (1966) outlined sedimentologic evidence for distinguishing between valley-fill fluvial sandstones and open marine barrier bars in time-equivalent strata in western Nebraska. He stated that fluvial sandstones widen upward, contain clay rip-up clasts, are medium- to coarse-grained, cross stratified, and are not bioturbated. By contrast, barrier bar sandstones are very fine- to fine-grained, narrow upward, and are ripple-laminated and bioturbated. These lines of evidence lead to the conclusion that the sandstone body in question is a fluvial deposit of the Dakota Formation. This further supports the interpretation of the Kiowa-Dakota contact as an erosional unconformity.

In summary, the J Sequence onlaps and progressively overlaps the Cheyenne Sequence in an eastward direction. It consists of a series of landward-stepping progradational events deposited during a relative sea-level rise. Facies contained in the sequence change from fluvial and marine in the west to entirely fluvial in the east. This sequence comprises approximately the lower half of the Dakota Formation in Kansas. It is bound by the same unconformities that bound the J sandstone and Huntsman Shale in the Denver basin of Colorado. Because the base of the sequence was probably deposited after the basal part of the J sandstone in Colorado, and because any sediment deposited at the top of the sequence during highstand was subsequently eroded, the preserved strata of the sequence in Kansas probably are time equivalent to the middle and upper J sandstone and the lower part of the Huntsman Shale in Colorado.

D Sequence (upper Dakota Formation)

The D Sequence of this study is defined from the unconformity at the top of the J Sequence to the unconformity at the top of the Carlile Shale. Only the Dakota Formation part of this sequence was studied. The base of the D Sequence onlaps the unconformity at the top of the J Sequence. Based on the age of the unconformity of 95 Ma, the sequence is Cenomanian and Turonian (Weimer, 1984).

The internal architecture of the sequence consists of landward-stepping progradational events which are overlain by a transgressive disconformity at the base of the Graneros Shale. The upward succession of depositional environments between the basal unconformity and the base of the Graneros Shale is from fluvial to shoreface. The facies contained within each progradational event differ slightly in the Beaumeister and Bounds cores (Plates 1 and 3). In the Bounds core each progradational event consists of only one or two facies representing coastal plain and/or upper shoreface depositional environments. In the Beaumeister core each progradational event contains several facies deposited in various parts of the coastal plain and shoreface. Facies successions in both show a landward shift of facies tracts with each successive progradational event. Open marine shale of the Graneros sea was deposited above the last progradational event.

Boundaries of progradational events in this sequence proved difficult to correlate, because of sparse well control along the cross sections and because they are dominated by coastal plain and fluvial facies. In the X-X' cross section (Fig. 37), the flooding event which placed facies representing shoreface environments over mudstones and sandstones of coastal plain environments is inferred to be a horizontal plane parallel to the base of the Graneros Shale. Fluvial sandstones and coastal plain mudstones fill the broad valleys formed by erosion on the top of the J Sequence.

In the depositional dip section Z-Z' (Fig. 38), the Graneros Shale thins dramatically in a landward direction. This is the result of facies transition from marine to coastal plain facies through time-equivalent strata. The facies transition from shoreface to coastal plain is shown in its approximate position because of the highly variable well-log signature given by the interbedded sandstones and shales of both environments.

Because all but the upper part of the Dakota Formation in outcrop is represented by fluvial deposits, evidence of scour and subaerial erosion is insufficient to define a sequence boundary. Instead, a seaward shift in environments is the best evidence for recognizing a relative sea-level fall and sequence-bounding unconformity. Such a shift is interpreted within the middle of the Dakota Formation where the facies indicate an abrupt change from a meandering stream system to a braided stream system. This shift is represented by an upward change from variegated mudstone and fine- to medium-grained trough cross-bedded sandstone, to medium- to coarse-grained planar tabular cross-bedded sandstone (Fig. 9, and Sections 7 and 10 in Appendix A). The planar tabular cross-bedded facies consist mostly of medium- to large-scale planar-tabular cross beds composed of medium- to coarse-grained, granule and conglomeratic sandstones with numerous clay rip-up clasts (Figs. 14 and 15). The only other place in the Dakota Formation where such sedimentary structures, coarse grain size, and granules of chert and quartz exist is at the base where the formation is unconformable on Kiowa Formation and Permain formations (Section 10 Appendix A). Given the change from meandering to braided stream depositional environments, abrupt increase in grain size, and similarity to the basal Dakota sandstones, the D Sequence unconformity is interpreted at the base of this facies. A well log signature of this facies shift is illustrated in Figure 42. In outcrop, a distinct change in weathering profile also occurs at the position of the D Sequence unconformity (Figs. 43 and 44). Above this braided stream deposit, facies in the Dakota Formation return to variegated mudstones and fine-grained channel sandstones deposited in a meandering stream system (Section 3, Appendix A, as an example). This represents a rise in base level and deposition of landward-stepping progradational units to the west. A similar upward succession from braided to meandering facies was described by Karl (1971, 1976) in the Dakota Formation in Nebraska. He interpreted the change to result from an eastward transgression of the Graneros sea.

The facies architecture of the upper part of the Dakota was studied in outcrop and shallow subsurface to define a stratigraphic model for the distribution of rock types in the subsurface. An east-west stratigraphic cross section across the outcrop belt was constructed from nine measured sections and one core (Fig. 45), extending Siemers' (1971) correlations and interpretations to the west in the subsurface (Fig. 46) and to the east in the outcrop. Along this cross section the basal part of the sequence consists of nonmarine fluvial and coastal plain strata. These are overlain by two landward-stepping progradational events consisting of progressively more marine strata.

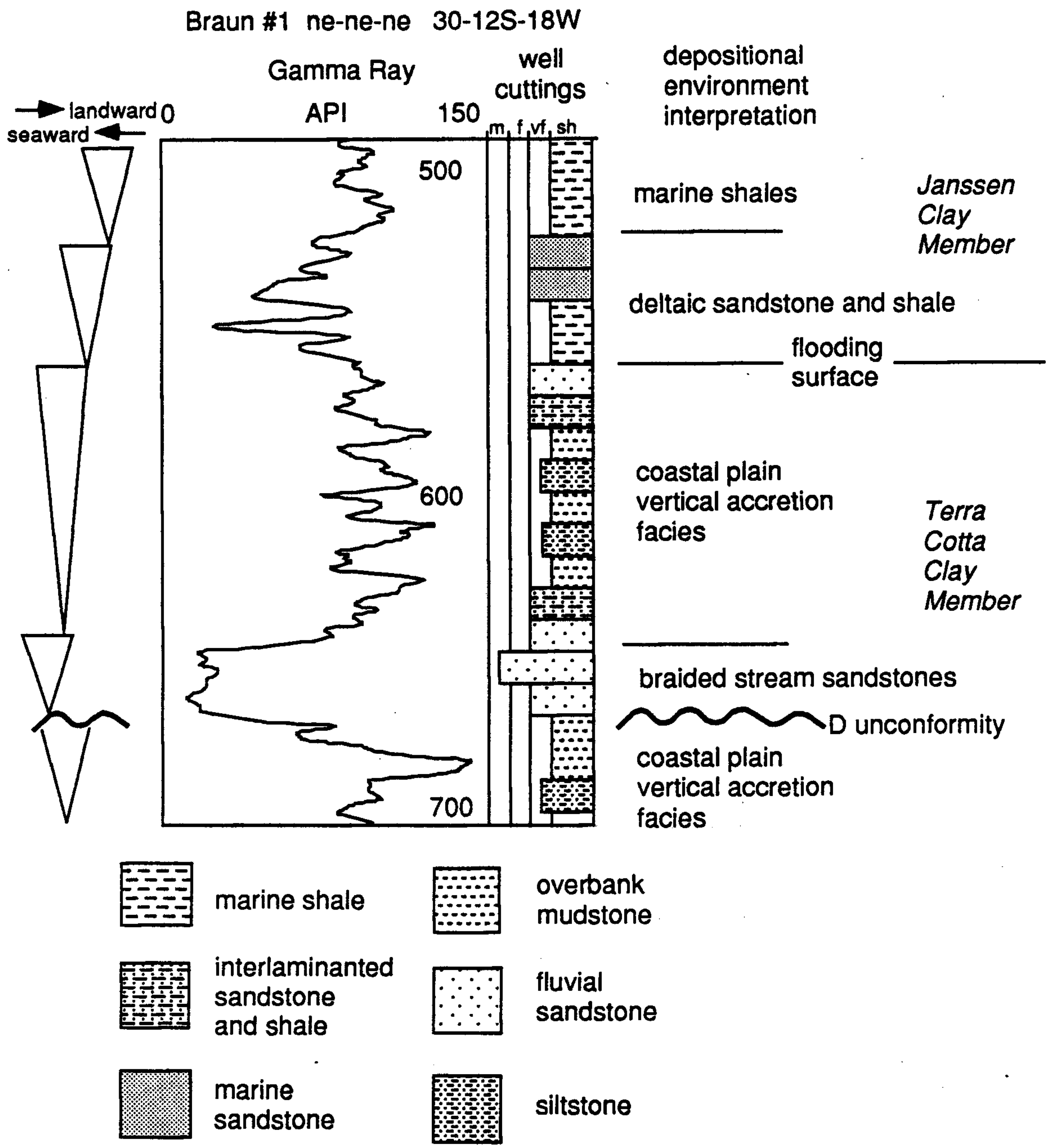


Figure 42: Gamma ray well-log expression of the D unconformity from interpreted facies shifts. Lithologic types are from sample descriptions.

Figure 43: View north from Measured Section #11 (sec 26 T11S R4W) showing laterlly continuous nature and distinct geomorphic expression of facies PTSS (Planar tabular cross-stratified sandstone).

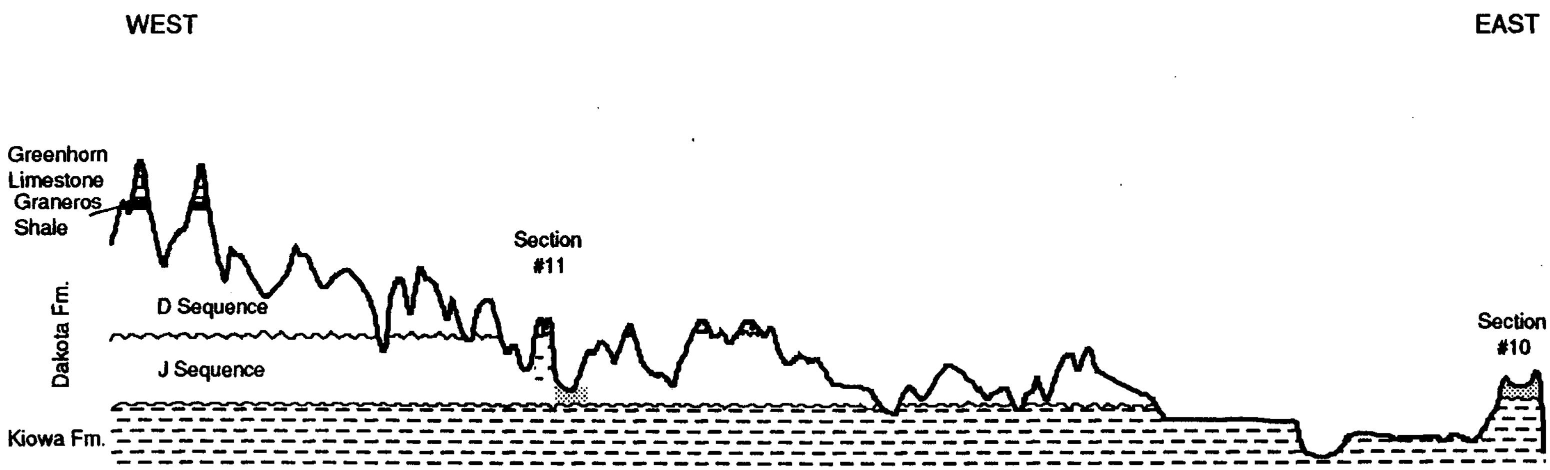


Figure 44: Topographic profile across Dakota Formation outcrop in Ottawa County showing hill-capping expression of the PTSS facies. Measured section locations in Appendix A.

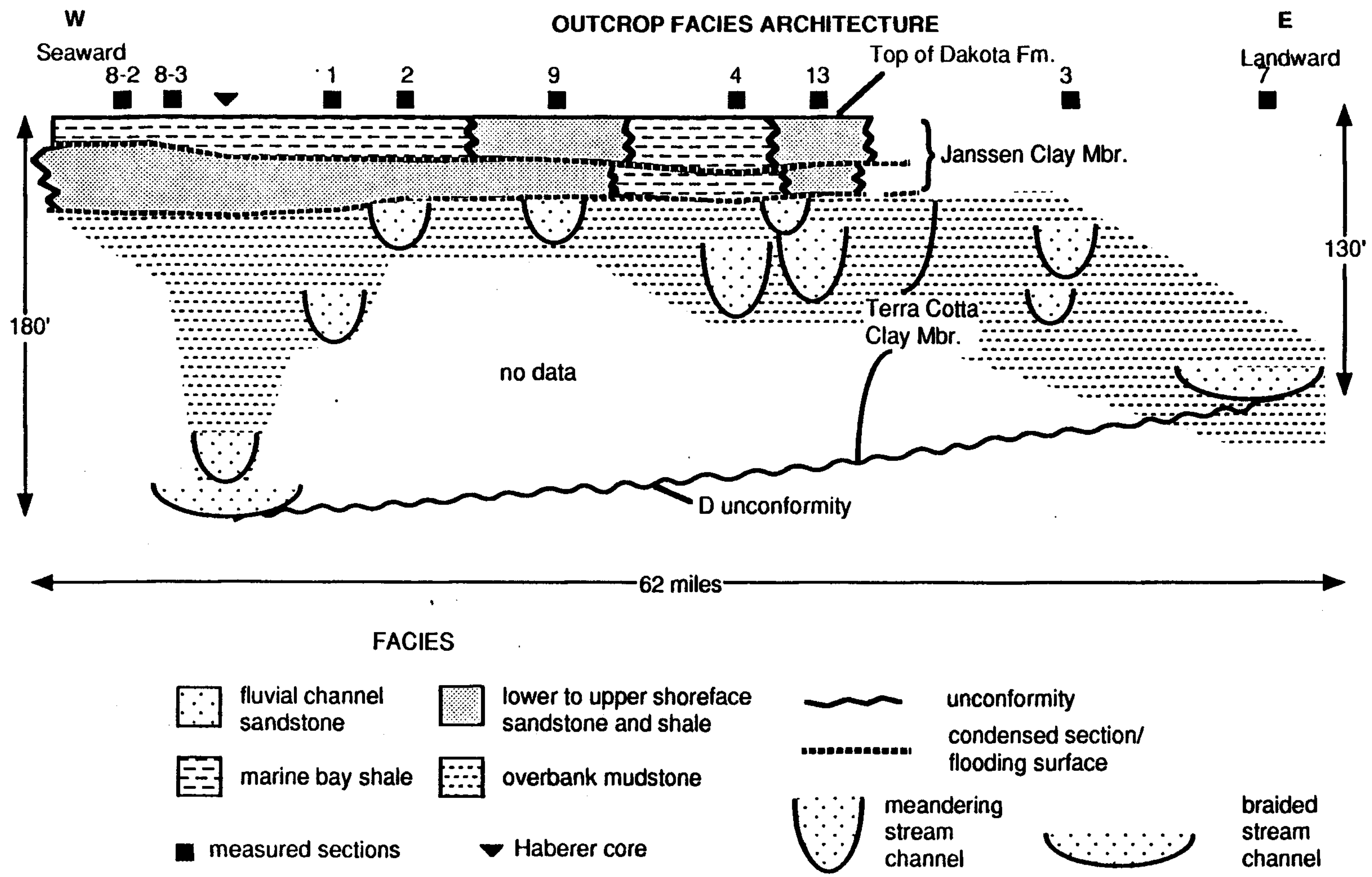


Figure 45: Facies architecture of the upper Dakota Formation condensed from a cross section of outcrop sections. Formation is dominantly nonmarine with two landward-stepping progradational events at the top. Geometry of fluvial channels is schematic. Measured sections are in Appendix A.

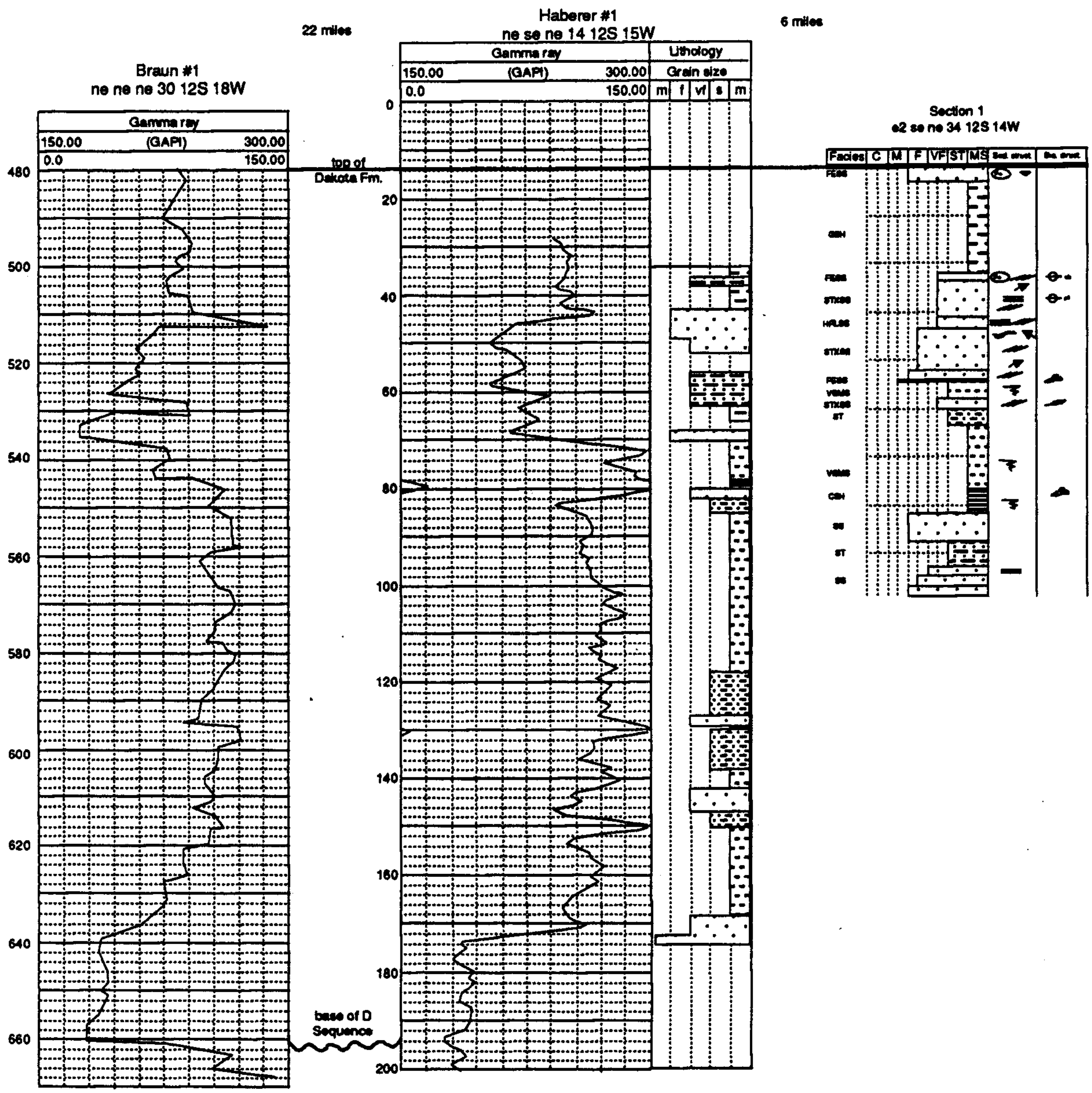


Figure 46: Correlation of outcrop, core and gamma ray well logs. Datum is top of Dakota Formation.

The nonmarine strata consist dominantly of overbank mudstones and siltstones which encase fluvial channel sandstones. These channel sandstones were named the Rocktown channel sandstone by Rubey and Bass (1925) in Russell County, Kansas. They interpreted that there were multiple channel sandstones deposited by streams meandering across a floodplain. My work confirms this style of deposition for the upper half of the Dakota Formation outside of Russell County.

The marine strata are contained in two landward-stepping progradational events. Siemers (1971) recognized these genetic sequences as one unit. He defined it as a subfacies of the Rocktown Channel Sandstone and called it the upper flat-bedded unit (Fig. 4). He interpreted this unit as a marginal marine deltaic complex and interpreted the Rocktown channel sandstone as a distributary river which supplied the deltas. From my observations of sedimentary structures, paleocurrent indicators and geometries of sandstones in this upper unit, which indicate a three dimensional shoreline, I agree with Siemers' interpretation of paleoenvironments.

The contact between the Rocktown channel sandstone (and laterally equivalent floodplain mudstones) and the overlying progradational event is a subhorizontal, planar surface separating overlying marine facies from underlying nonmarine facies. Siemers (1971) described the surface as both erosional and gradational. Where deltaic sandstones rest on variegated mudstones the contact appears erosional. Where deltaic sandstones rest on Rocktown channel sandstone the contact appears gradational. I interpret this contact to be everywhere erosional based on field evidence such as truncation of large cross-bed sets in sandstone, angular truncation of slumped claystone beds, and the presence of a thin coarse-grained sandstone lag between the deltaic sandstone and underlying facies. This erosional surface was produced by a deepening event and reflects a landward displacement of facies tracts across it.

The Dakota Formation is traditionally divided into the lower Terra Cotta Clay and the upper Janssen Clay Members. Based on the arguments presented above, I interpret the contact to represent a flooding surface across which there is a landward displacement of facies (Fig. 45). Siemers (1971) also noted a major lithologic boundary between nonmarine sandstones and claystones and overlying marginal-marine shales and sandstones. This contact is not a sequence boundary but is a flooding surface separating two progradational events. The D Sequence therefore contains the upper part of the Terra Cotta Clay

Member and all of the Janssen Clay Member.

The landward-stepping progradational events at the top of the Dakota Formation were drowned by transgression of the Graneros Sea. The upper bounding unconformity of the D Sequence is placed by Weimer (1984) at the contact between the Carlile Shale and the Niobrara Chalk. This study was concerned with only the Dakota Formation part of this sequence which also includes the Graneros Shale, Greenhorn Limestone, and Carlile Shale.

Discussion

The age of the the Dakota Formation has been uncertain because of a paucity of fossils. Marginal marine deposits in the upper part of the formation directly below the Graneros Shale contain Cenomanian fossils (Hattin, 1965; Franks, 1966). The correlation of unconformities from Colorado where they are dated gives a maximum age for the Dakota Formation of 97 Ma (Weimer, 1984). By the same reasoning, the part of the Dakota Formation in the D Sequence has a maximum age of 95 Ma (Cenomanian). A time-stratigraphic diagram represents these age relationships (Fig. 47). The trend of decreasing age of the D sandstone in an eastward direction is supported by the Graneros Shale being older in southwest Kansas than it is in north-central Kansas (Hattin, 1965). This reinforces the interpretation that strata onlap the unconformity in an eastward direction.

The age of the Kiowa Formation, hence Longford Member and Cheyenne Sandstone, is documented by Scott (1970) as upper Albian. The age of this lower sequence basal unconformity is dated at 100 Ma (Weimer, 1984).

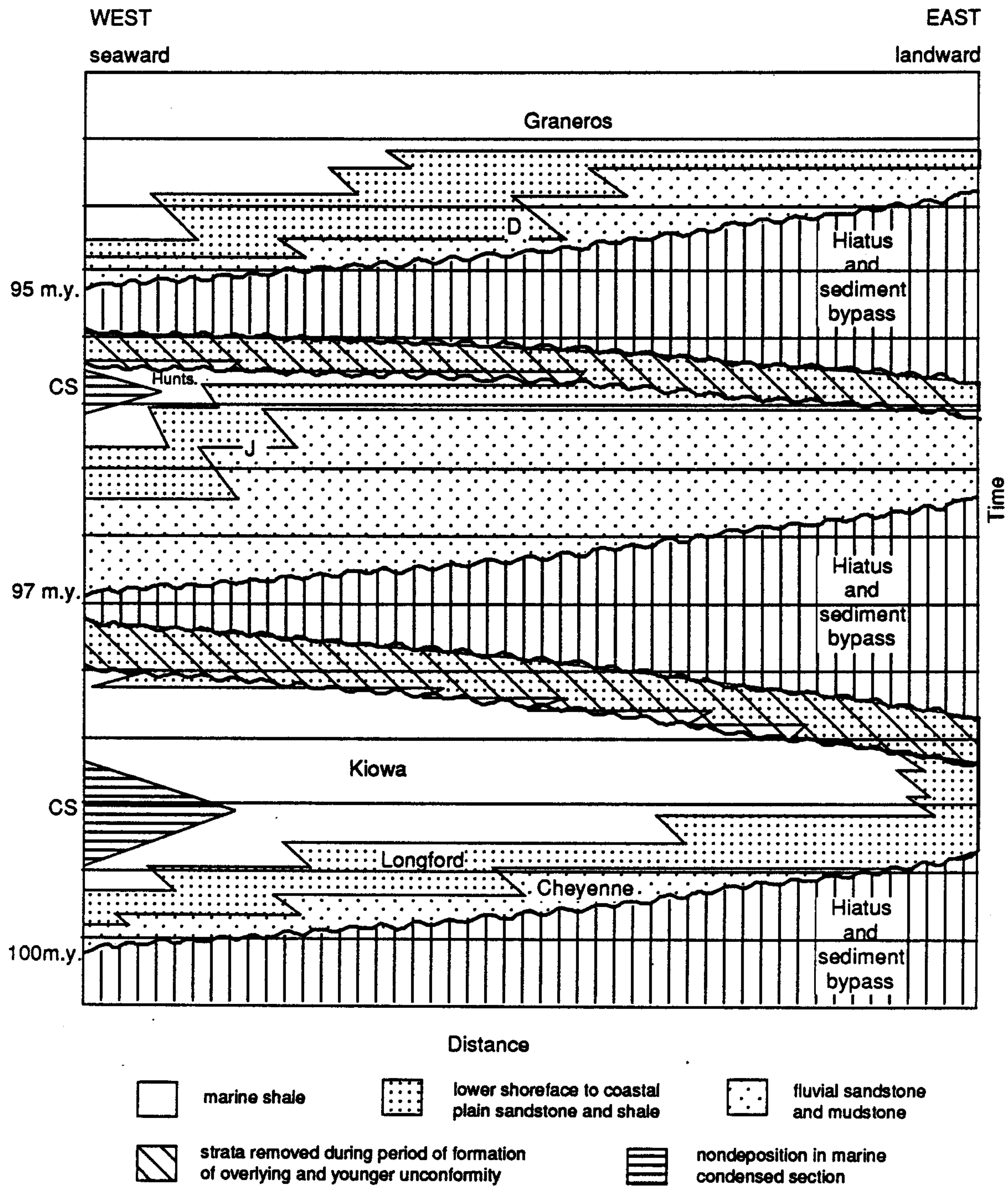


Figure 47: Wheeler (1964) diagram showing time relationships of the sequences and temporal equivalence of nonmarine to marine facies.

Hydrostratigraphic units

The extent of and interconnections between hydrostratigraphic units are dependent on the distribution of facies within the sequences. Although no hydrologic data were used in this study, it is still possible to define the limits of hydrostratigraphic units on the basis of lithofacies distributions. Porosity and permeability measurements, from Merriam et al. (1959), of some of these facies are shown in Figure 48. Interconnections between hydrostratigraphic units were identified from the positions of facies with respect to sequence boundaries. By examining the position of these units with respect to underlying and overlying formations it was possible to define the regional-scale plumbing system both internal and external to the strata of this study.

The factor controlling fluid flow through rock is hydraulic conductivity, which is a function of permeability, porosity, grain size, sorting, cementation, composition, sedimentary structures and stratification (Heath, 1983). These factors segregate an aquifer (rock that transmits and stores water) from an aquitard (rock that restricts water flow). The definition of unconformity-bounded depositional sequences and their internal progradational events allows one to determine the positions of depositional environments through time and space. The depositional energies within each environment control the grain size, sorting and composition of sediment deposited into lithofacies. This in turn controls the hydraulic conductivities of the lithofacies. The movement of environments through time controls the stratigraphic architecture within sequences. Therefore, the spatial arrangement of aquifers and confining beds can be estimated from the sequence stratigraphy and can be used to determine bulk hydrologic properties.

The present-day structural dip on Cretaceous and Permian formations is to the north-northeast. The ground surface dips at a steeper angle to the east. Figure 49 shows the structural configuration of Permian and Cretaceous strata along a southwest to northeast cross section line. Recharge into these formations is in southwestern Kansas where they outcrop and subcrop beneath Cenozoic alluvial deposits and from vertical leakage from adjacent units.

The Dakota Formation and the Cheyenne Sandstone are hydrostratigraphic units that are separated by the Kiowa Formation. All three of these hydrostratigraphic units constitute the Dakota aquifer. In western Kansas the arrangement of these units is straightfor-

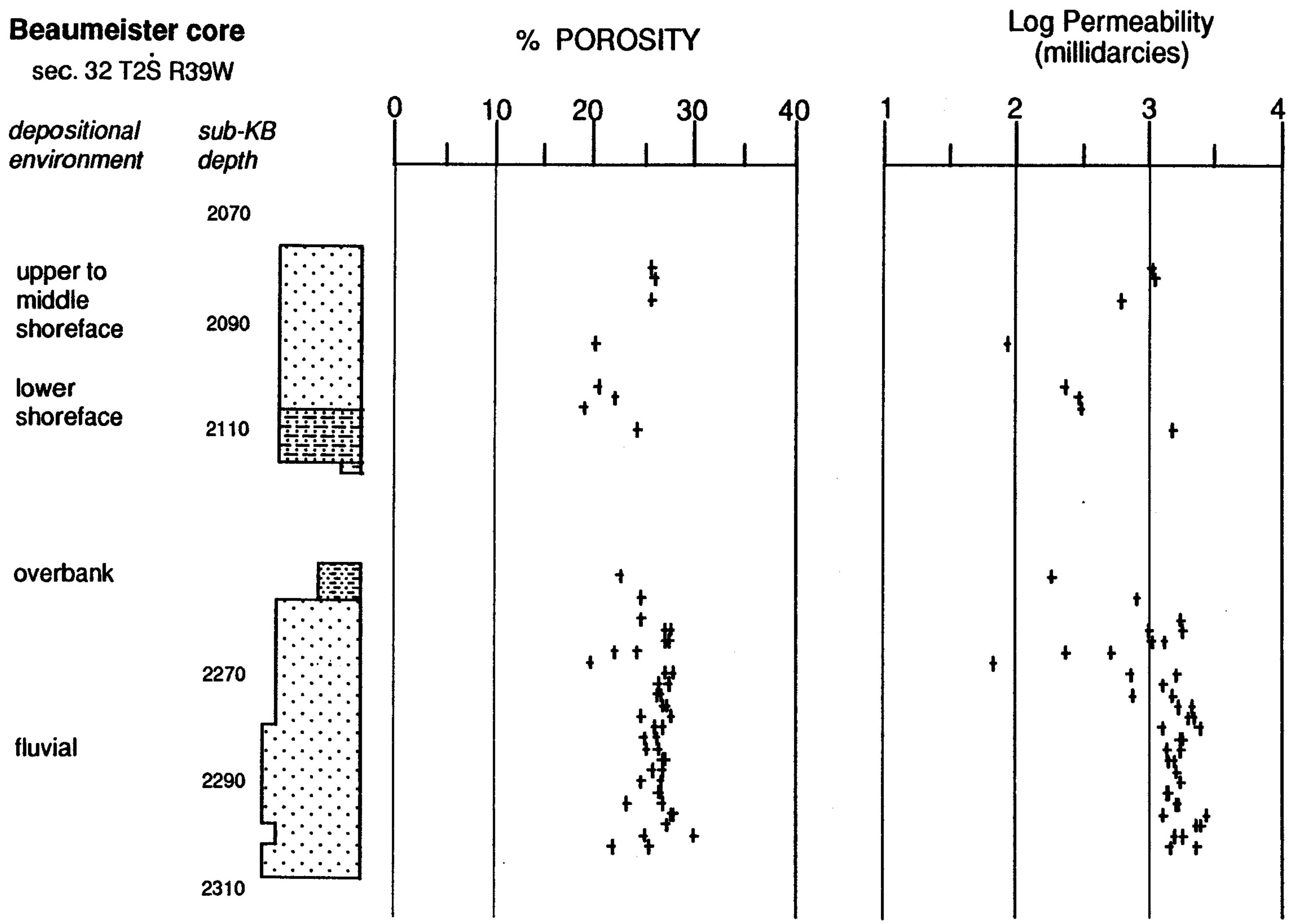


Figure 48: Porosity and permeability data from the Beaumeister core. Values are higher in the fluvial sandstone than in the shoreface sandstone, and generally decrease upwards in the fluvial sandstone and increase upwards in the shoreface sandstone.

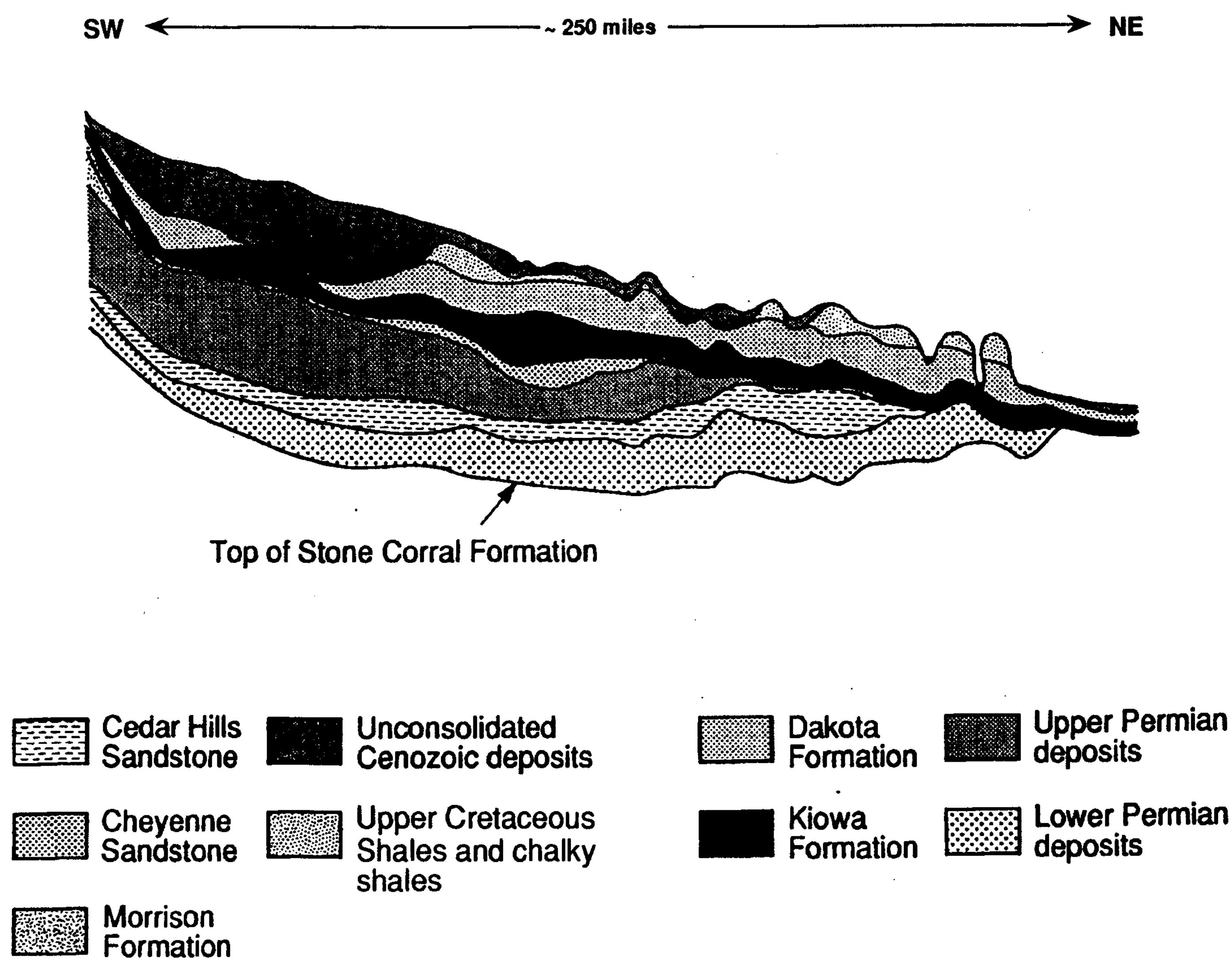


Figure 49: Regional stratigraphic cross section of formations from the top of the Permian Stone Corral to the surface. Datum is sea level. From MacFarlane (1989).

ward (Fig. 50). However, architectural changes in lithologic composition and petrophysical properties of strata are more pronounced in a depositional dip direction (Fig. 51). From west to east, strata are increasingly nonmarine and lithologically complex, and there is an increase in stratigraphic truncation along unconformities. In general, the proportion of more permeable lithofacies in the stratigraphic section increases from west to east.

Within the lower Cheyenne Sequence, the Kiowa Formation shale decreases in thickness due to lateral facies changes eastward into more permeable shoreface and coastal plain facies of the Longford Member and Cheyenne Sandstone (lower Dakota aquifer). Fluvial Cheyenne Sandstone thins depositionally to the east. Based on gamma ray log signatures, outcrops and core, this formation is very sandy and is probably an aquifer. Where present, the thick sequence of shale in the Kiowa Formation is an aquitard separating the Dakota Formation from the underlying Longford Member and Cheyenne Sandstone aquifer units. Across the basal unconformity, the Cheyenne Sandstone is in contact with underlying Jurassic Morrison Formation and Permian Cedar Hills Sandstone. It provides a hydraulic connection between the Longford Member and the Cedar Hills.

Within both the J and D Sequences, which make up the Dakota Formation, nonmarine facies become dominant toward the east. Fluvial sandstones are coarser grained and better sorted than nearshore sandstones in the Dakota Formation and would be better aquifers. Fluvial channel sandstones have varying degrees of lateral and vertical connections. The J and D Sequences are separated to the west by shoreline deposits which consist of interbedded sandstones and shales. Shales are more likely to be laterally continuous in this depositional environment than in the coastal plain deposits and therefore are probably an aquitard between the sequences. Eastward amalgamation of coastal plain sandstones of the sequences would cause them to act as one hydrostratigraphic unit. The D unconformity is usually associated with an overlying sandstone. In the outcrop it is coarse-grained and laterally extensive. It may be an important aquifer within the formation as well as a connecting bed between separate sandstone bodies.

Along the south to north cross section N-N' (Fig. 52), Kiowa Formation shales, and the Longford Member separate the Dakota Formation from Permian formations. The Kiowa consists of shale and would be an aquitard. However, the Longford contains

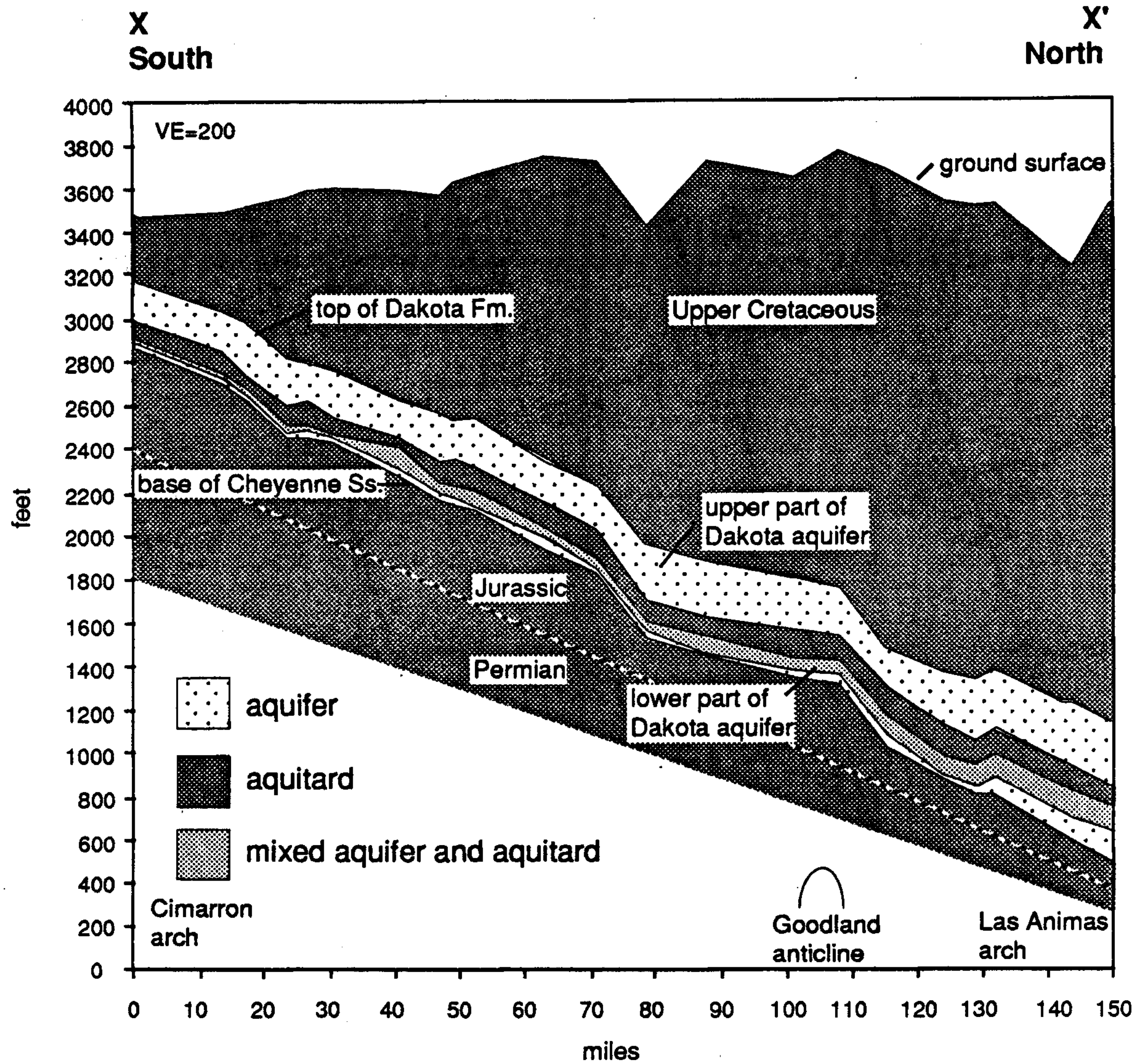


Figure 50: Structural and hydrostratigraphic cross section X-X' showing the Dakota Formation aquifer isolated from the Cheyenne Sandstone aquifer.

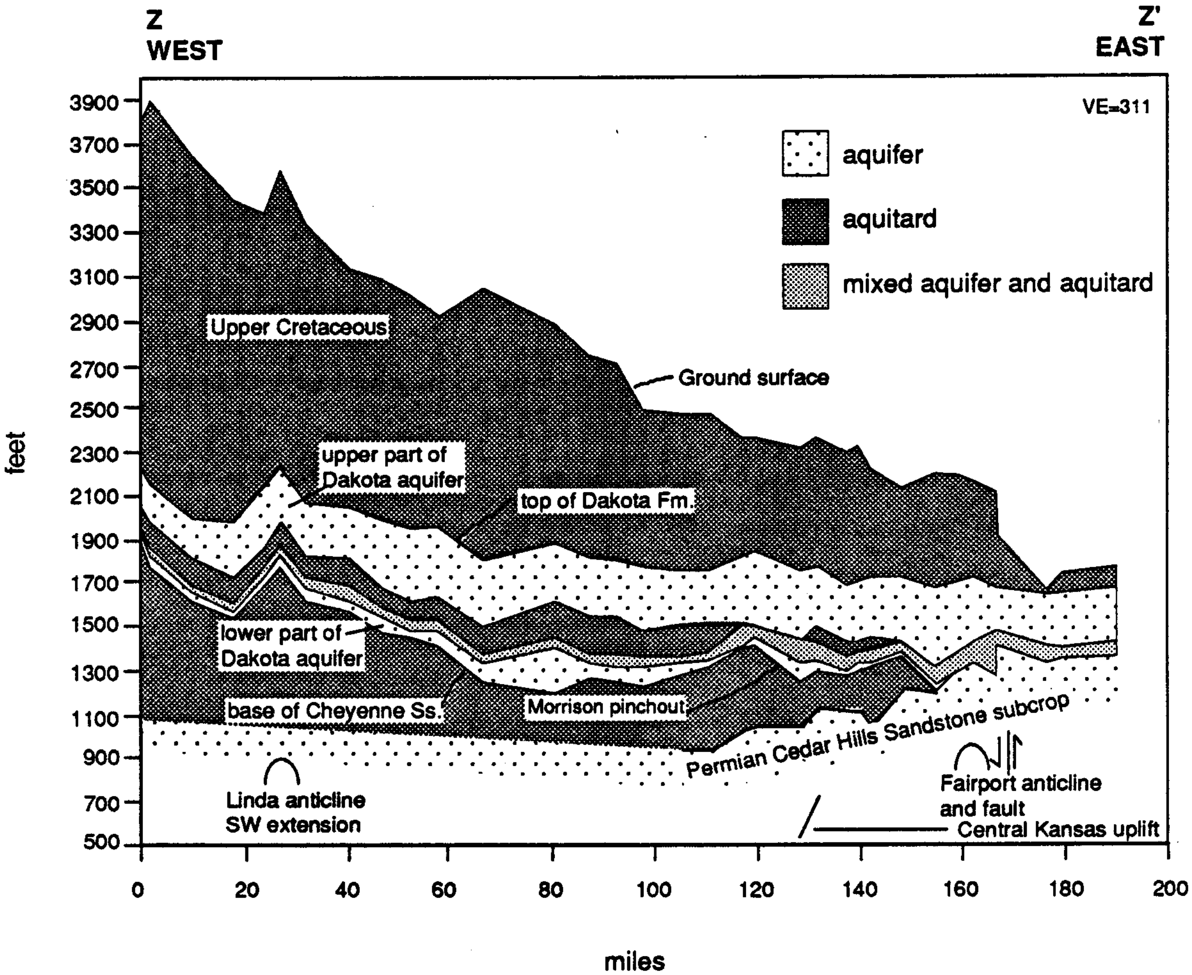


Figure 51: Structural and hydrostratigraphic cross section Z-Z' showing termination of the Cheyenne aquifer at the Cedar Hills subcrop and potential areas of hydraulic connection between the Dakota Formation aquifer and the Cheyenne and Cedar Hills aquifers where the Kiowa Formation shales are not present.

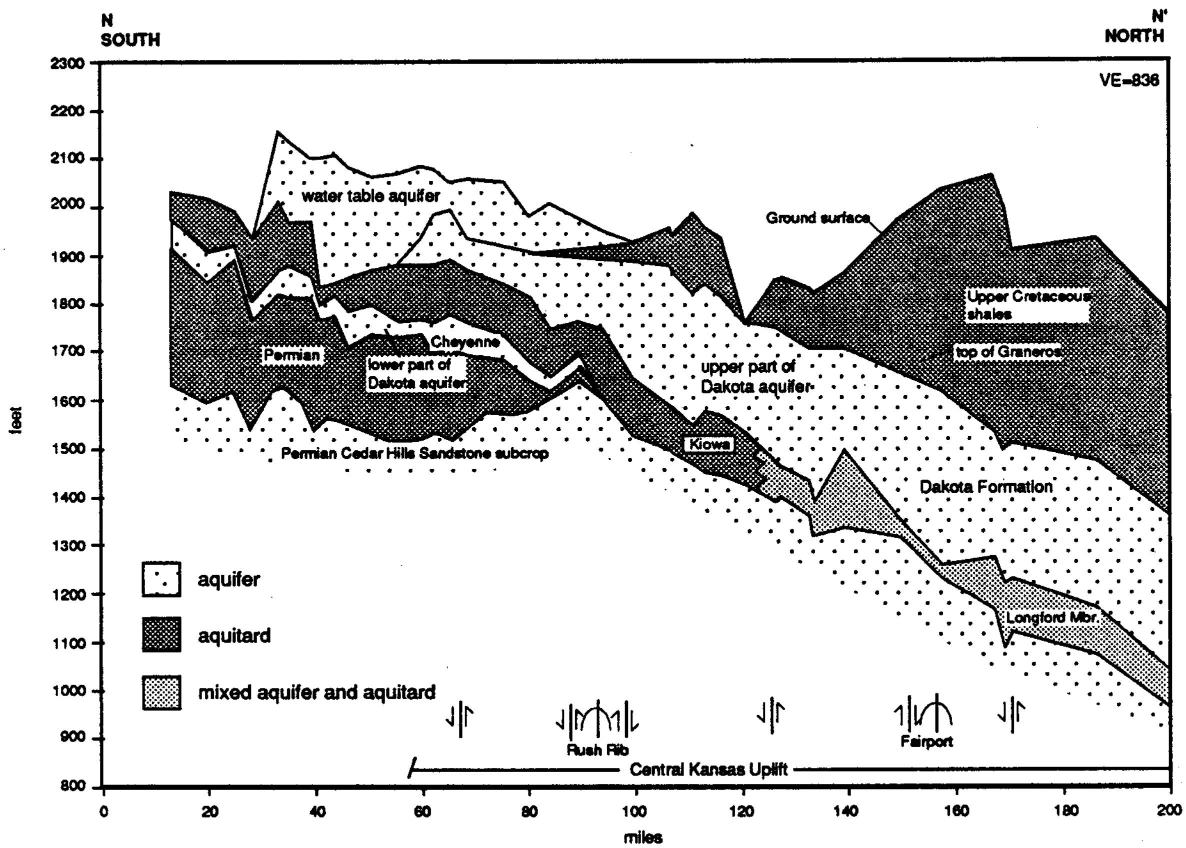


Figure 52: Structural and hydrostratigraphic cross section N-N' showing termination of Cheyenne aquifer at Cedar Hills subcrop, Dakota Formation aquifer recharge area, and potential hydraulic connection of Dakota Formation and Cedar Hills aquifers across the Longford Member.

interbedded sandstones and shales, and probably would behave heterogeneously with respect to vertical fluid flow. Inadequate data preclude the determination of continuous or interconnected sandstone bodies within the member that would act as continuous aquifers. Fractures within the Kiowa Formation may provide a hydraulic connection between the Permian formations and the Dakota Formation.

Application of sequence stratigraphy to identification of stratigraphic units in a local area

A nine township study area containing the Haberer core was selected for mapping stratigraphic units in the subsurface (Fig. 1). The purpose of this detailed study was to evaluate the feasibility of using oil-well logs to identify and map aquifers and aquitards, and to determine potential connections between freshwater and saltwater aquifers. A data base of 127 well logs was used for this purpose (Appendix B). Most well logs are gamma ray-neutron, which generally distinguishes between lithology (sandstones and claystones), and porosity, respectively.

In order to map sequences, formations, sandstone bodies or other lithologic units, it is useful to know the nature of the contacts separating the units and the depositional environments they represent. For example, formation contacts can be erosional unconformities (local or regional), transgressive disconformities, facies offsets, or conformable lithologic changes. It is necessary to know the type of contact before it can be accurately picked on a well log and then mapped. Similarly, it is necessary to know the environment of deposition of sandstone bodies, because it controls their geometry and trend. Sandstone bodies were described in outcrop in terms of their geometries, trends and facies characteristics, and interpreted for their environment of deposition. These outcrop descriptions were used to interpret geometries and patterns of similar facies units identified in the subsurface.

The application of sequence stratigraphic concepts, in which genetically related strata bounded by unconformities are recognized, greatly facilitates the determination of the nature of formation contacts and depositional environments. The regional sequence stratigraphic framework described previously provided the basis for sequence stratigraphic analysis and facies distributions in the local study area (Fig. 53).

Twenty-two contour maps were made, including ten isopach maps, seven structure maps, and five facies maps. Structure maps show structural features that influenced deposition as reflected on the isopach and facies maps. The facies maps show the distribution of facies and inferred depositional environments within stratigraphic sequences. The combination of facies and isopach maps provide the basis for defining the framework of hydrostratigraphic units.

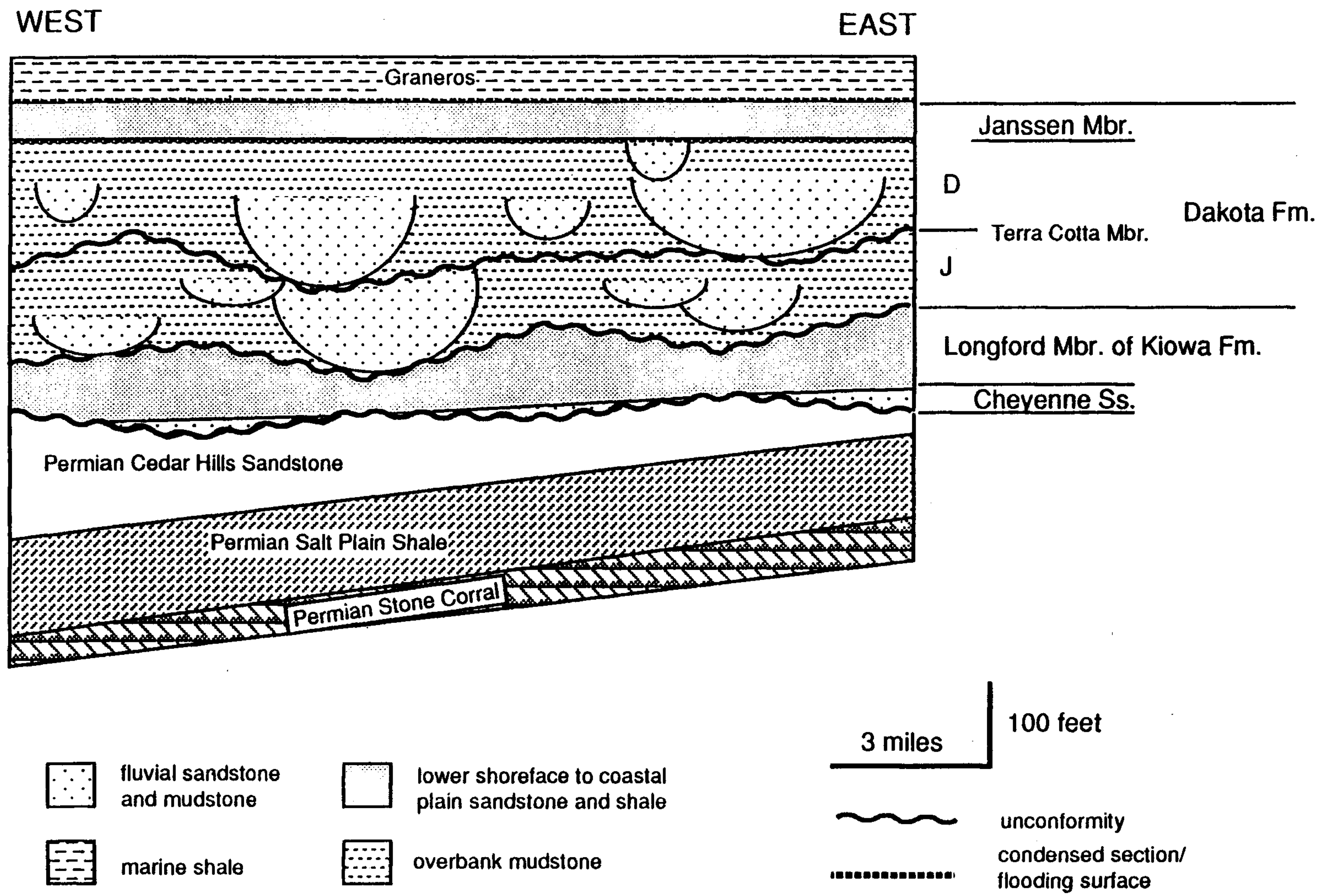


Figure 53: Diagramatic cross section showing application of sequence boundaries and contained facies to the determination of sandstone interconnections within and between sequences.

Graneros Shale top structure

The structure contour map on the top of the Graneros Shale at its contact with the overlying Greenhorn Limestone (Fig. 54) shows present-day structural configuration on the top of a depositionally planar and horizontal datum. In central Kansas outcrop, this datum is approximately 5 ft above the "X" bentonite (Hattin, 1965). This surface was essentially planar with a very slight seaward dip. In well logs this contact is easily recognized and is the best datum. The map shows the Fairport anticline, which plunges to the north-northeast at 5.5 ft/mi and is 6 mi wide. Synclines flank both sides with 60 ft of structural relief from the crest of the anticline to the trough of the synclines. The west flank dips 22.5 ft/mi to the west and the east flank dips 32 ft/mi to the east. Regional dip is to the north-northeast at 6 ft/mi. The primary structural trend is north-northeast - south-southwest. Secondary trends are east-west and northwest-southeast.

No faults are interpreted on this map. Fracturing of the Graneros and underlying upper Dakota Formation is probable across the crest of the anticline. A structure contour map on top of the Dakota Formation was constructed but is not presented because it is almost identical to this map. The difference between the two maps can be estimated from the Graneros Shale isopach map.

Longford Member top structure

The structure contour map on top of the Longford Member of the Kiowa Formation (base of Dakota Formation) shows the configuration of a potential aquitard (Fig. 55). The base of the Dakota contains continuous and interconnected channel sandstones. So this map shows local dip on these aquifers. The Kiowa-Dakota contact is an erosional unconformity. Because the map was contoured by linear interpolation between control points, subtle and detailed topography on the unconformity surface is eliminated. However, the amount of erosional relief on the unconformity is less than structural relief.

The north-northeast anticline trend is apparent and plunges to the north-northeast at approximately 10 ft/mi. There is an eastward dip from the crest to the outcrop of the Dakota Formation.

Fracturing is probably associated with this anticline. The aquitard as well as the basal Dakota sandstone may be fractured here. A structure contour map on the D sequence

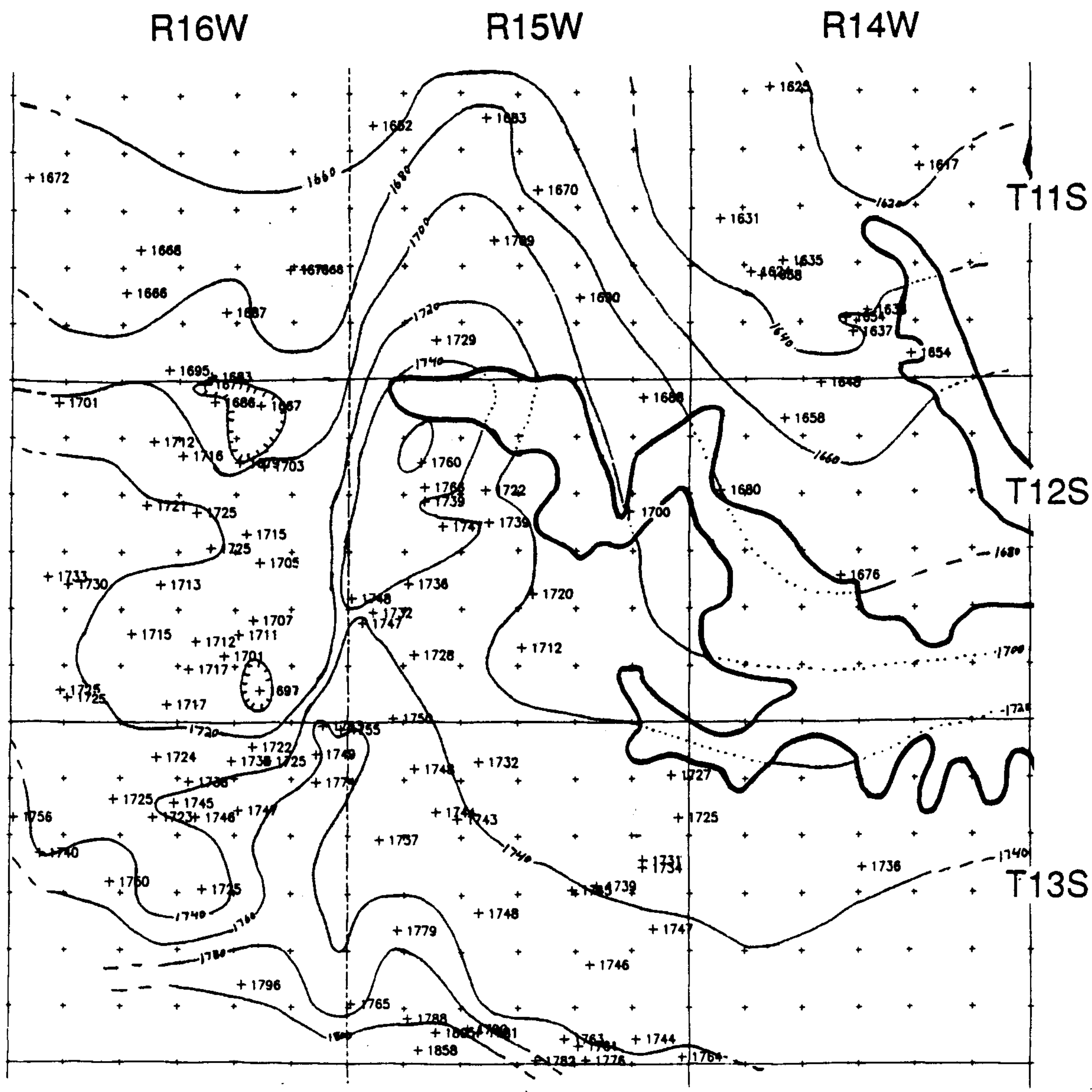


Figure 54: Structure map on top of the Graneros Shale (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

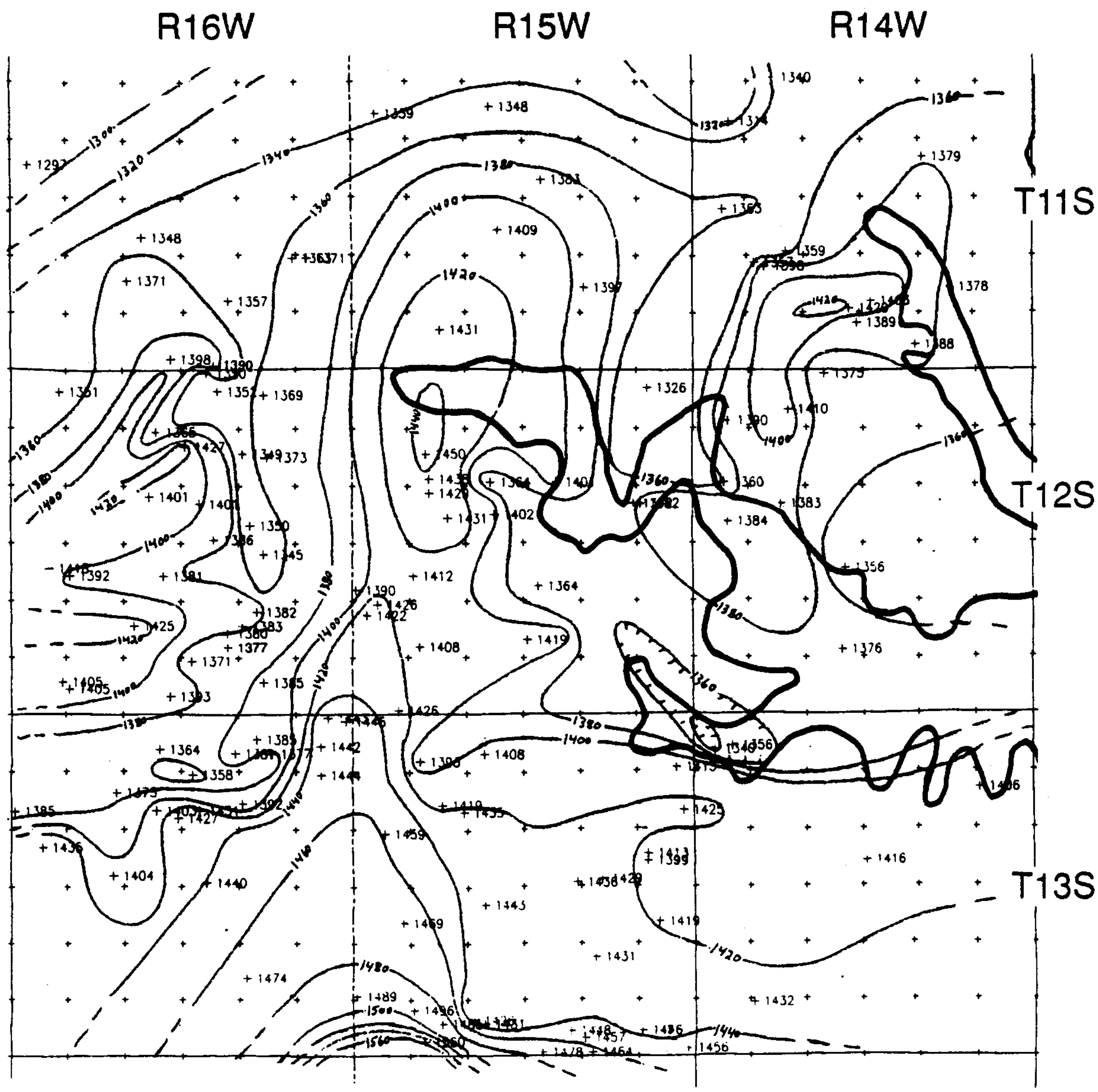


Figure 55: Structure map on top of the Longford Member (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

unconformity in the middle of the Dakota Formation was constructed but is not presented because trends on it are similar to the top of the Graneros structure map.

Permian Cedar Hills Sandstone top structure

The structure contour map of the unconformity surface on top of the Permian Cedar Hills Sandstone (Fig. 56) shows the present configuration of the top of this salt water disposal zone as well as the basal surface of Cretaceous sandstones.

Similar to the top of the Graneros structure map, the Fairport anticline plunges to the north-northeast at 5 ft/mi. The anticlinal structure is more subdued in this map, and does not appear faulted. This surface dips east from the anticline crest to the outcrop.

As with the top of the Kiowa Formation structure map, erosional relief is less than structural relief. Fracturing of the Cedar Hills Sandstone is probable over the crest of the anticline.

Permian Stone Corral Formation top structure

The structure contour map on top of the Permian Stone Corral Formation (Fig. 57) shows the configuration of an originally planar surface beneath Cretaceous strata. This formation is a regional datum that is easy to pick on well logs.

In the same position as the Fairport anticline is a north-northeast trending fault which has 60 ft of dip-slip displacement, upthrown to the east. Orientation of the fault plane is not known for certain. A second-order structural trend identified on this map is north-west-southeast. Regional structural dip is unidentifiable.

The presence of an anticlinal fold on the upthrown block may be due to a fault drag on the upthrown block. The location of the Fairport anticline directly over the fault indicates that it is high angle and possibly vertical. If it were a normal fault the Fairport anticline would probably not be symmetrical and would be more like a monoclinal fold. The reason for a fault at this stratigraphic level rather than a fold may be due to brittle failure of the dolomite as compared to the less competent sandstones and shales above.

Graneros Shale isopach

The Graneros Shale isopach map (Fig. 58) shows the thickness and extent of the

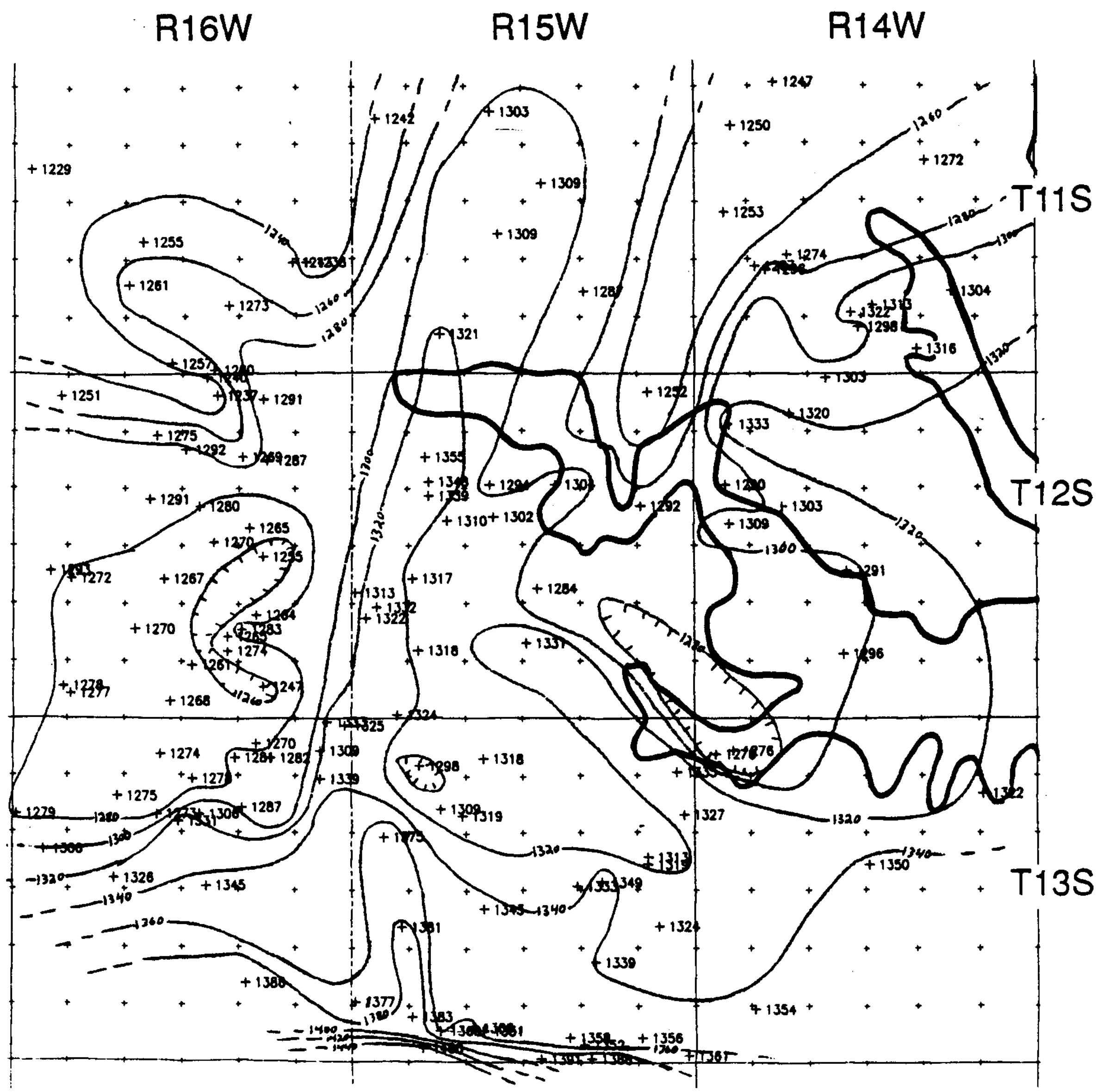


Figure 56: Structure map on top of the Cedar Hills Sandstone (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

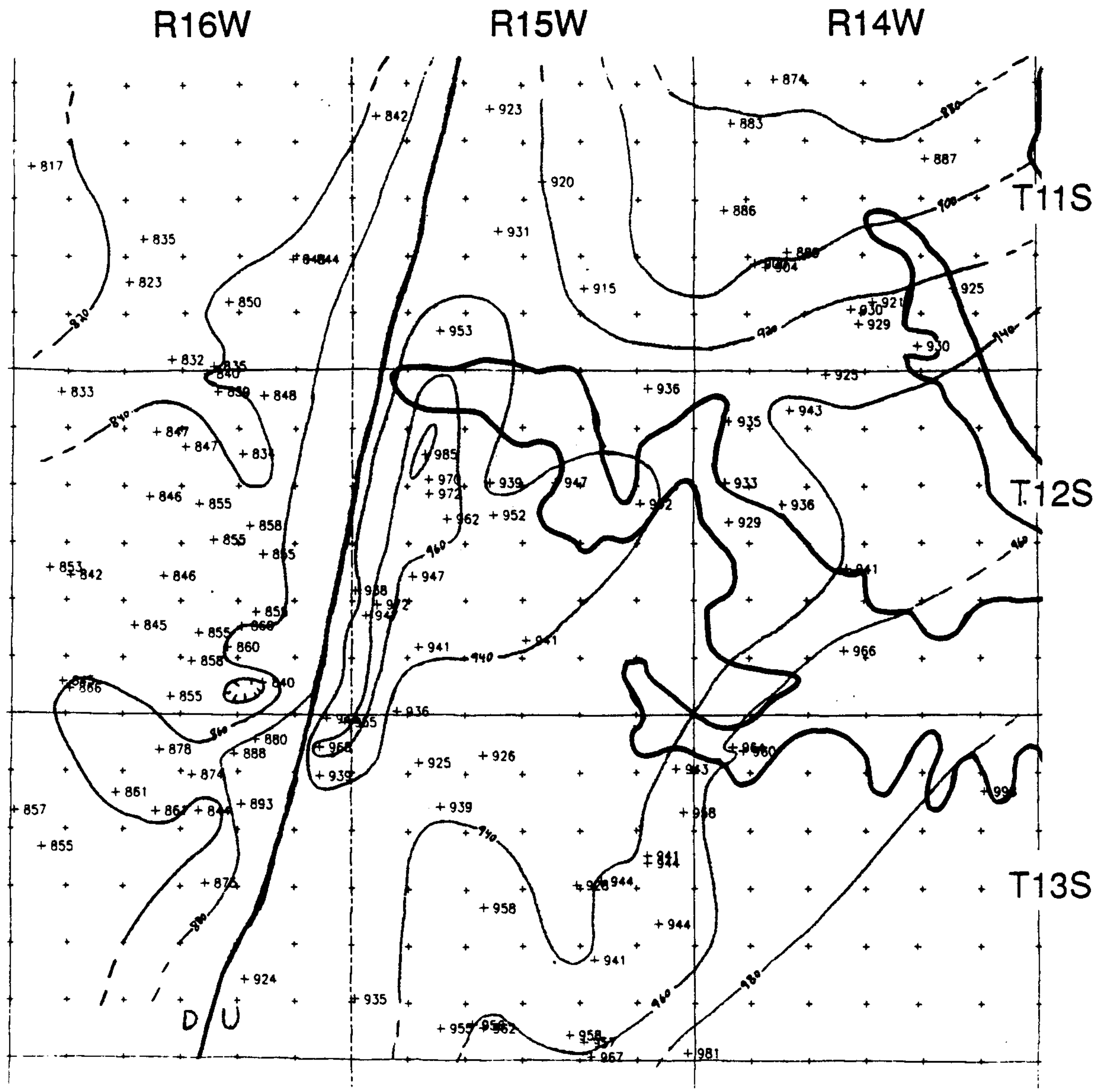


Figure 57: Structure map on top of the Stone Corral Formation (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

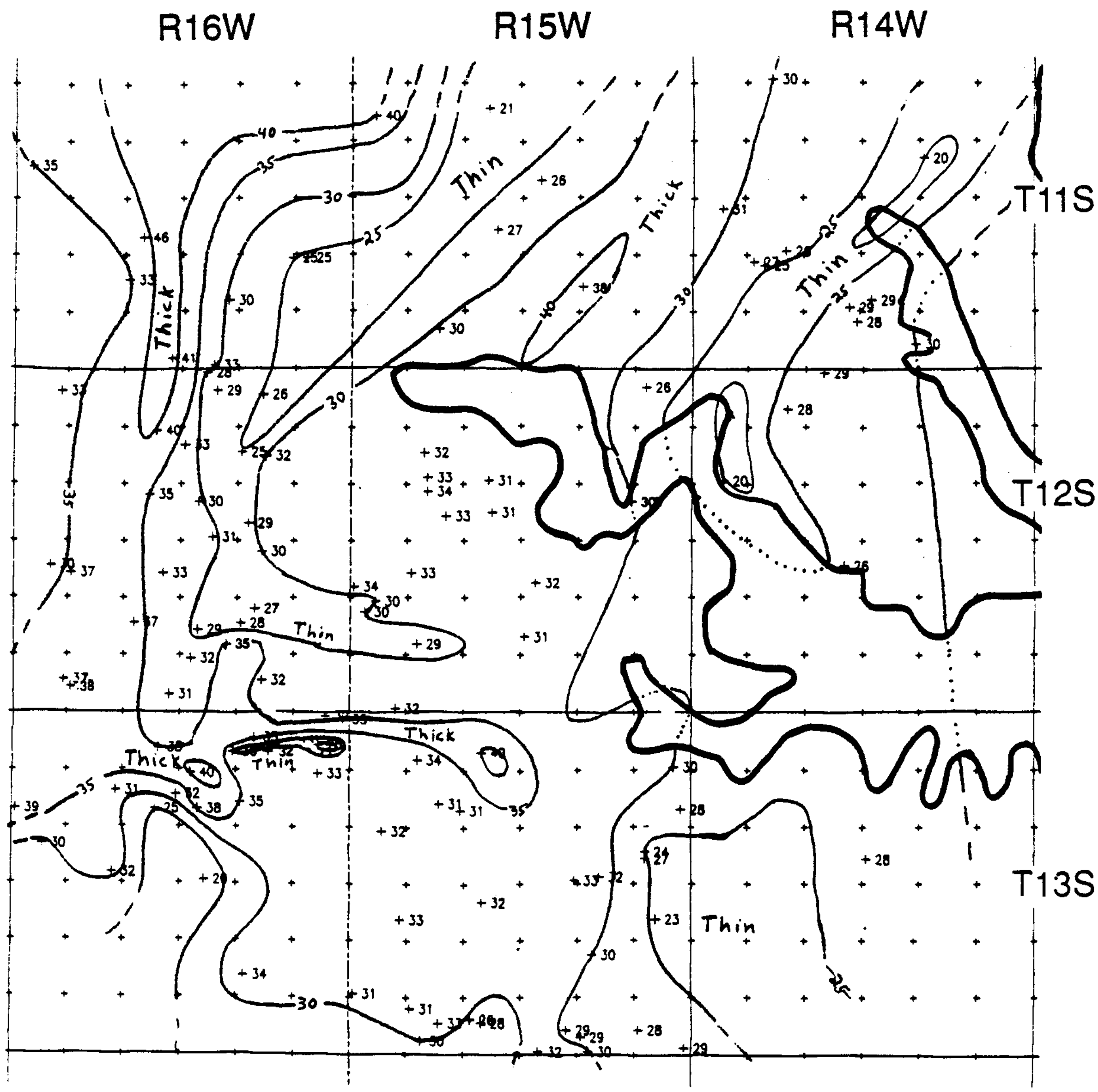


Figure 58: Isopach map of the Graneros Shale (c.i.=10 ft). Heavy line is the outcrop trace of the Dakota Formation.

aquitard over the Dakota Formation. The depositional topography on top of the Dakota Formation can be inferred from this map.

The thickness of the Graneros Shale ranges from 20 ft to 41 ft. It generally thickens to the west, particularly west of the Fairport anticline. There is a northeast-southwest trending thin in the northeast corner of the map, and a northwest-southeast thin in T13S R14W.

The increased thickness to the west indicates that depositional dip was to the west and that the paleoshoreline trended north-south. The thins are interpreted to be depositional thins over delta lobes in the upper Dakota Formation except where the Graneros Shale thins over and east of the Fairport anticline. The anticline is interpreted to have had subtle topographic relief at that time. The structure may have been only a fault at that time with folding occurring after upper Cretaceous deposition.

Dakota Formation isopach

The Dakota Formation isopach map (Fig. 59) shows paleostructural control on deposition, and erosional relief on the basal unconformity. The direction of depositional onlap may be inferred form this map.

The thickness of the Dakota Formation ranges from 205 ft to 340 ft. The thinnest area is in the northeast township and the thickest section is in R16W. There is a prominent east-west trending thick in the middle of T12S.

The Dakota Formation thickens west of the Fairport anticline. The east-west trending thick in T12S cuts perpendicularly across the anticline in R15W. A north-south trending thin in T13S R15/16W occurs along the crest of the anticline. The thin in T11S R15W is across the nose of the anticline. The structural low in T12S is coincident with an isopach thick.

The structure, particularly the Fairport fault, is interpreted to have influenced Dakota deposition with thins occurring over structural highs and thicks in structural lows. The east-west trending thicks in the middle of T12S and in the northern part of T13S are interpreted as valleys along paleodrainage systems cut into the top of the Kiowa Formation. The east-west trending thin in southern T12S is interpreted as a paleodrainage divide. These interpretations indicate that paleodip was to the west. The thickening trend to the west indicates that depositional onlap was from west to east. The secondary east-

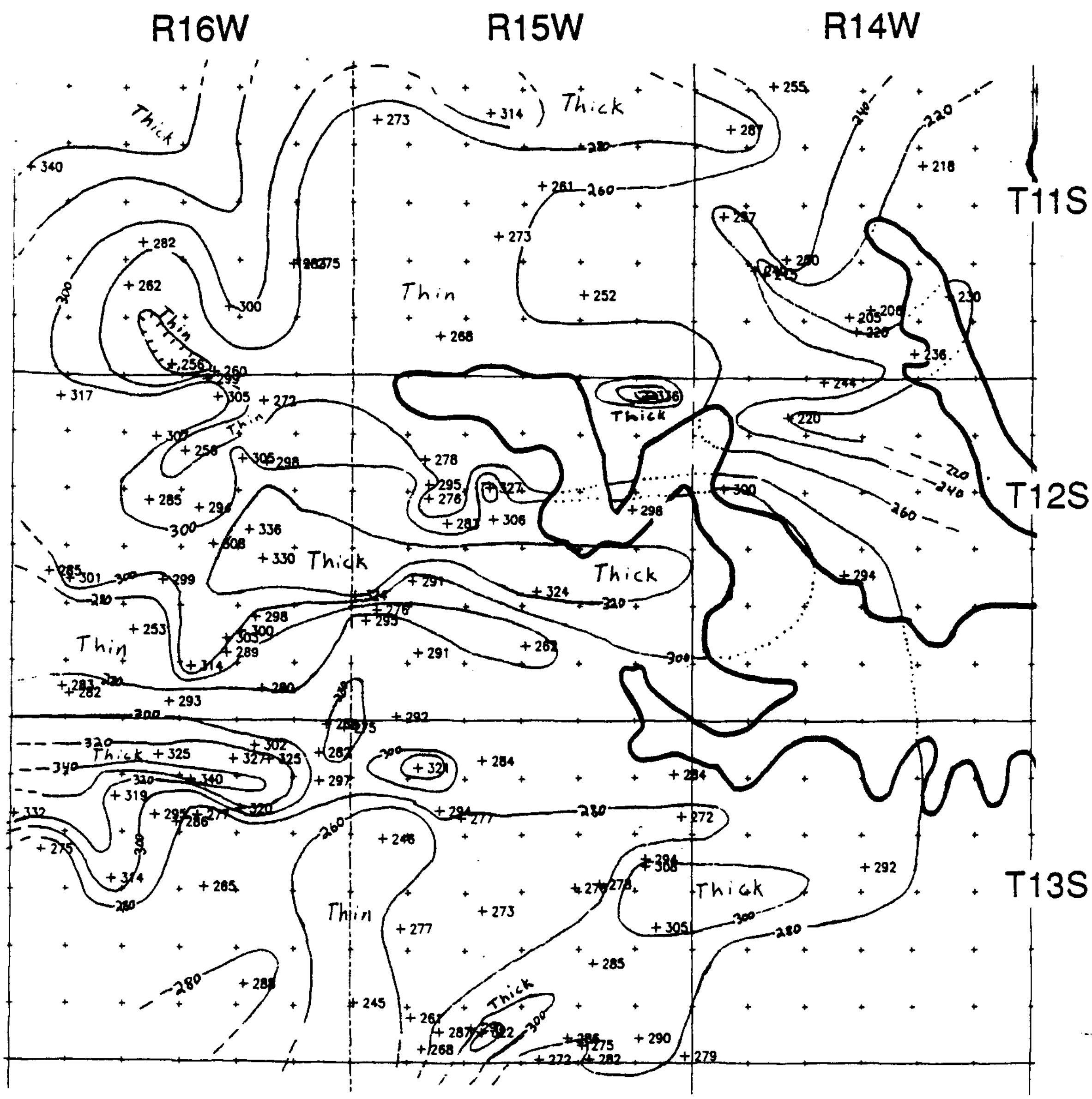


Figure 59: Isopach map of the Dakota Formation (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

west structural trend localized the positions where drainages cut across the primary north-south structural trend.

J Sequence isopach

The J Sequence isopach map (Fig. 60) shows the geometry of the sequence and any structural control on deposition and erosion. There is an inherent uncertainty in interpreting an isopach map of a sequence because erosional relief on its bounding unconformities may obscure depositional trends. An internal datum within the J Sequence is not present to use as a reference for determining relief on the unconformities.

The J Sequence varies in thickness from 70 ft to 202 ft. There is an east-west trending thin in T11S, and a thick in T12S. There are northeast-southwest trending thins and thicks in T13S R15/16W.

The J Sequence has an east-west trending thick in T12S crosses the anticline in the same position as an east-west structural trend. There is a north-south trending thin along the crest of the anticline in T13S R15/16W. The east-west thickness trend in T12S bends to the northeast in the same position as the present-day syncline east of the Fairport anticline. Overall the sequence is thicker west of the anticline.

Compared to the Dakota isopach map, the east-west trending thicks and thins are superposed in T12S and T11S, respectively. Both maps show east-west trending thins in T13S R16W. The north-south trending thins over the anticline in T13S R15/16W are present in both the J Sequence and Dakota Formation isopach maps.

Similar to the Dakota Formation isopach, structural features are interpreted to have influenced deposition of the the J Sequence with thicks in structurally low areas and thins over structurally high areas. Streams in the J Sequence cut east-west across the anticline, and their positions may have controlled by east-west trending secondary structures. Compared to the overlying D Sequence isopach and underlying Cheyenne Sequence isopach, the thickness of the J Sequence appears to be equally controlled by erosion at the base and top.

D Sequence isopach

The D Sequence isopach map (Fig. 61) shows the sequence geometry, structural controls on deposition, direction of onlap, and erosional relief on the basal unconformity.

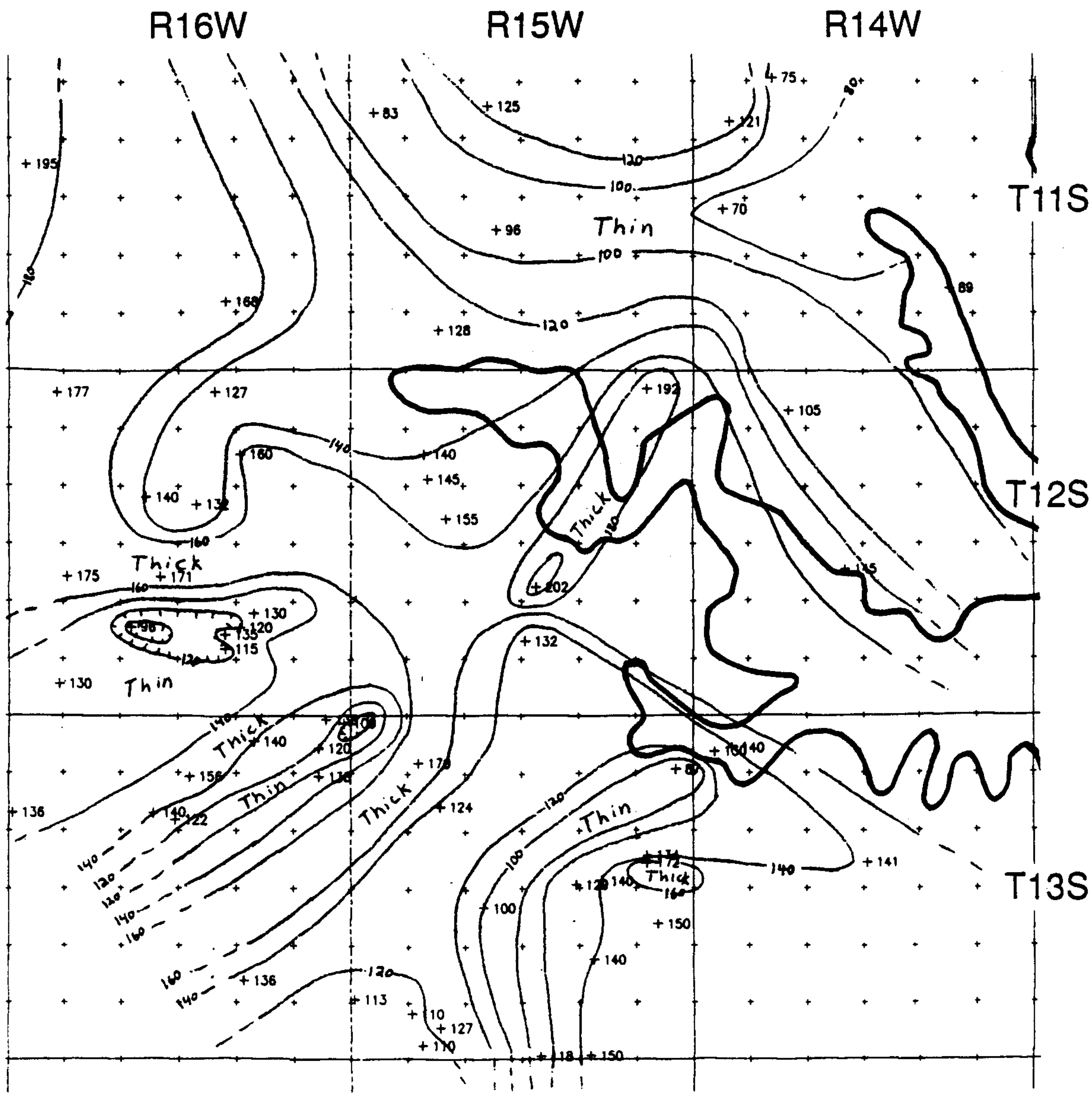


Figure 60: Isopach map of the J Sequence (c.i.=20 ft).
Heavy line is the outcrop trace of the Dakota Formation.

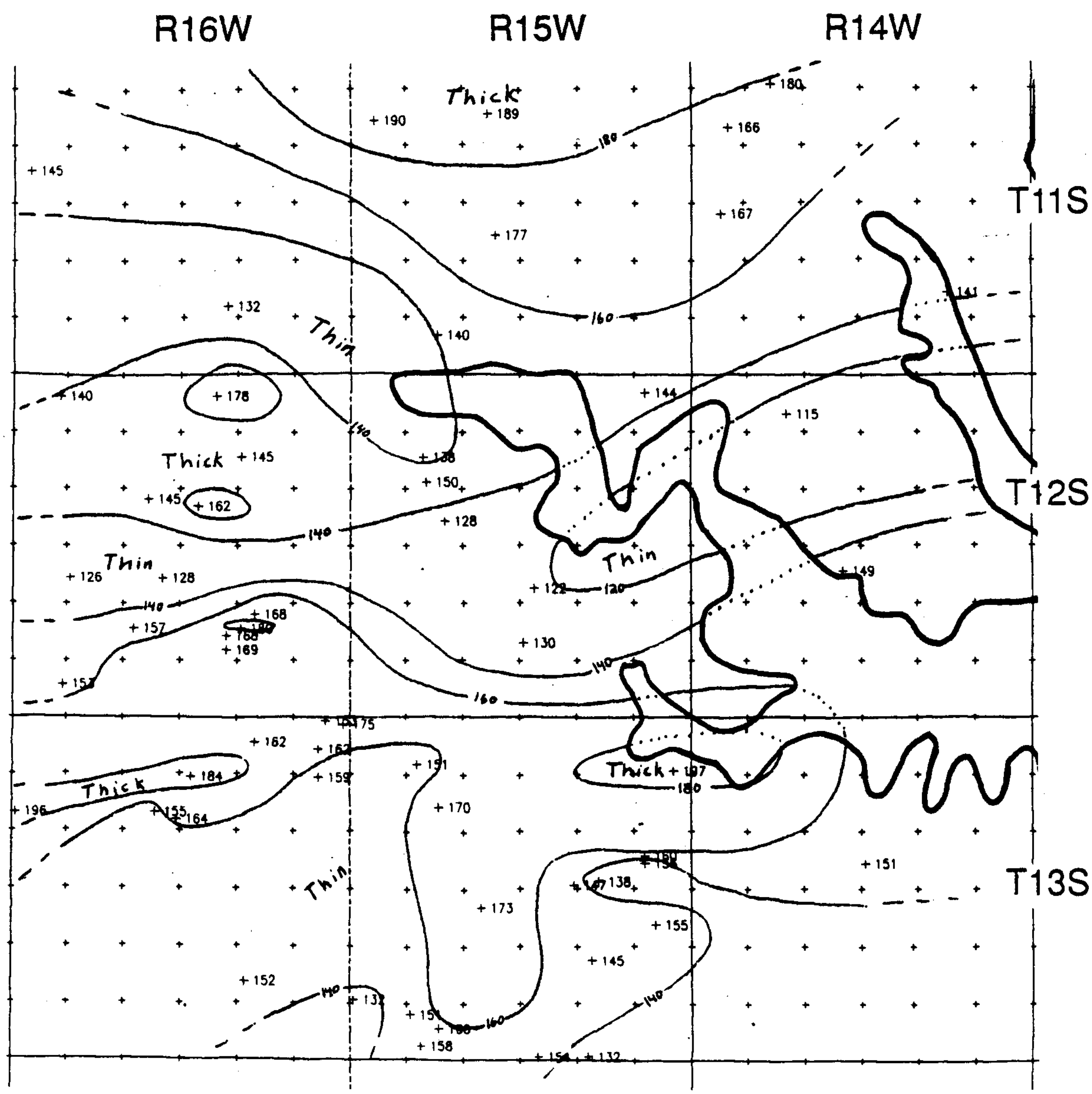


Figure 61: Isopach map of the D Sequence (c.i.=20 ft).
Heavy line is the outcrop trace of the Dakota Formation.

Unlike the J Sequence, interpretations of this map are more confident because the map is the thickness from the transgressive disconformity on top the Dakota Formation to the basal unconformity. Therefore it is not an isopach map of the entire sequence.

The D Sequence ranges in thickness from 115 ft to 196 ft, with the thickest section in the west. There are east-west thicks in northern T13S and middle T12S. Compared to structure, there is a north-south trending thin in T13S R15/16W located over the anticline. The greatest thickness in the sequence occurs west of the anticline in T12S and T13S.

Compared to the J Sequence isopach map, the north-south trending thins in T13S R15/16W are superposed. The northeast-southwest trending thicks in T13S R16W are over thicks in the J Sequence. Both sequences are thin in the south half of T11S.

Compared to the Dakota Formation isopach, both are thin in T13S R15/16W. The east-west trending thicks in T13S R16W are also coincident.

A continued structural control on deposition is interpreted for this sequence as with the J Sequence. The repetition of trends in the J and D Sequences produces the trends present in the Dakota isopach. The strata of the D Sequence onlap the basal unconformity from west to east with paleodip to the west.

Cheyenne/Kiowa sequence isopach

The isopach of the Cheyenne/Kiowa Sequence (Fig. 62) shows its stratal geometry. The problem with using this isopach map as an indication of erosional removal before deposition of the Dakota is that the base of this isopach is an erosional unconformity. Similarly, using this isopach as an indication of erosional relief at the base of the Cretaceous is complicated by erosional removal at the top. No internal datum could be picked confidently within the sequence from which to construct a map that would show these relations.

The thickness of the Cheyenne/Kiowa Sequence ranges from 45 ft to 158 ft, with the thickest section in the west. The thickness is generally constant in R14W and R15W. The thickness pattern within R16W is one of east-west trending thicks and thins with a prominent east-west trending thick across the south half of T11S.

The isopach compared to structure shows a poor correlation except that it is thicker west of the anticline. There is also a thin along the crest of the anticline in T12S.

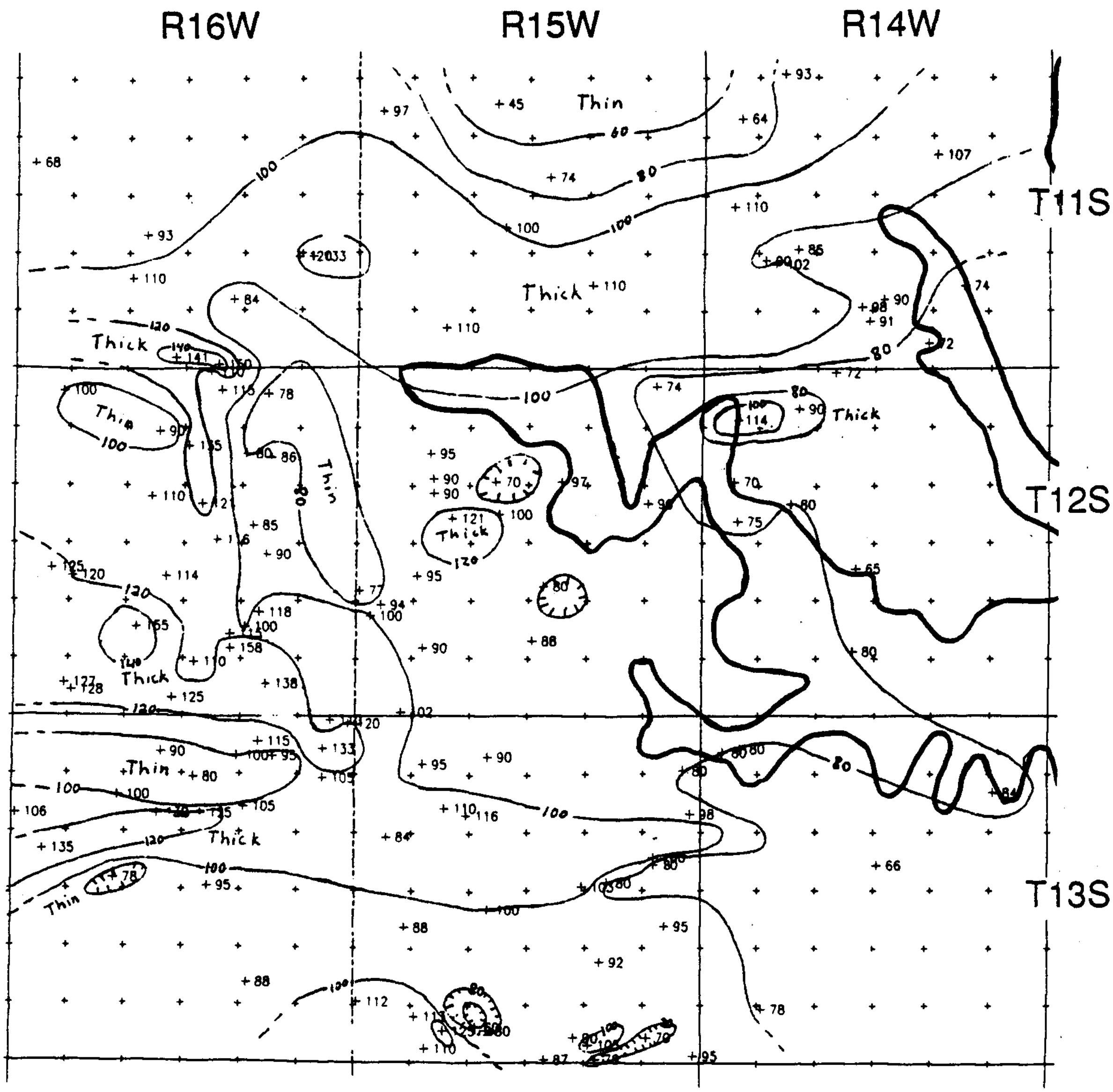


Figure 62: Isopach map of the Cheyenne/Kiowa Sequence (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

Compared to the Dakota Formation isopach, the thick in T11S is below a thin in the Dakota isopach. The east-west trending thin in the north part of T13S R16W is below a thick in the Dakota Formation. Compared to the J Sequence isopach, there is a crude inverse thickness relationship particularly in the south half of T11S and northeast-southwest across T12S R15W.

The strong inverse thickness relationship with the Dakota isopach reinforces the interpreted erosional nature of the Dakota-Kiowa Formation contact. That is, erosion on the unconformity removed lower sequence strata and the valleys were subsequently filled with a greater thickness of Dakota Formation. This relationship indicates that the thickness of the Cheyenne/Kiowa Sequence is mostly controlled by erosion at its top rather than by depositional relief at its base.

Permian Cedar Hills Sandstone isopach

The Cedar Hills Sandstone isopach (Fig. 63) shows the thickness from a lithologic contact (Salt Plain Formation contact) to an erosional, angular unconformity.

The Cedar Hills subcrops everywhere in the study area. It pinches out somewhere east of the study area and is overlain by the Flower Pot Shale west of the study area. The thickness ranges from 23 ft to 170 ft and is overall thicker in the west. There are thicks in T11S R14W and T13S R15W and an east-west trending thin in T12S.

Compared to structure, the thickness trends are parallel to the primary north-northeast - south-southwest structural trend with greatest thickness west of the anticline.

Compared to the Cheyenne/Kiowa Sequence isopach, there is a poor correlation of thicks and thins. The only exception is the thick in northern T12S R16W that is superposed by a thick in the Cheyenne/Kiowa Sequence.

This map is interpreted to show paleodrainage on the Permian surface, paleostructural control on erosion, and paleotopography of the depositional surface at the base of the Cheyenne/Kiowa Sequence. East-west trending thins in the Cedar Hills isopach are paleodrainages that were localized by east-west trending structure. The strike of the angular unconformity appears to be coincident with the north-northeast - south-southwest structural trend.

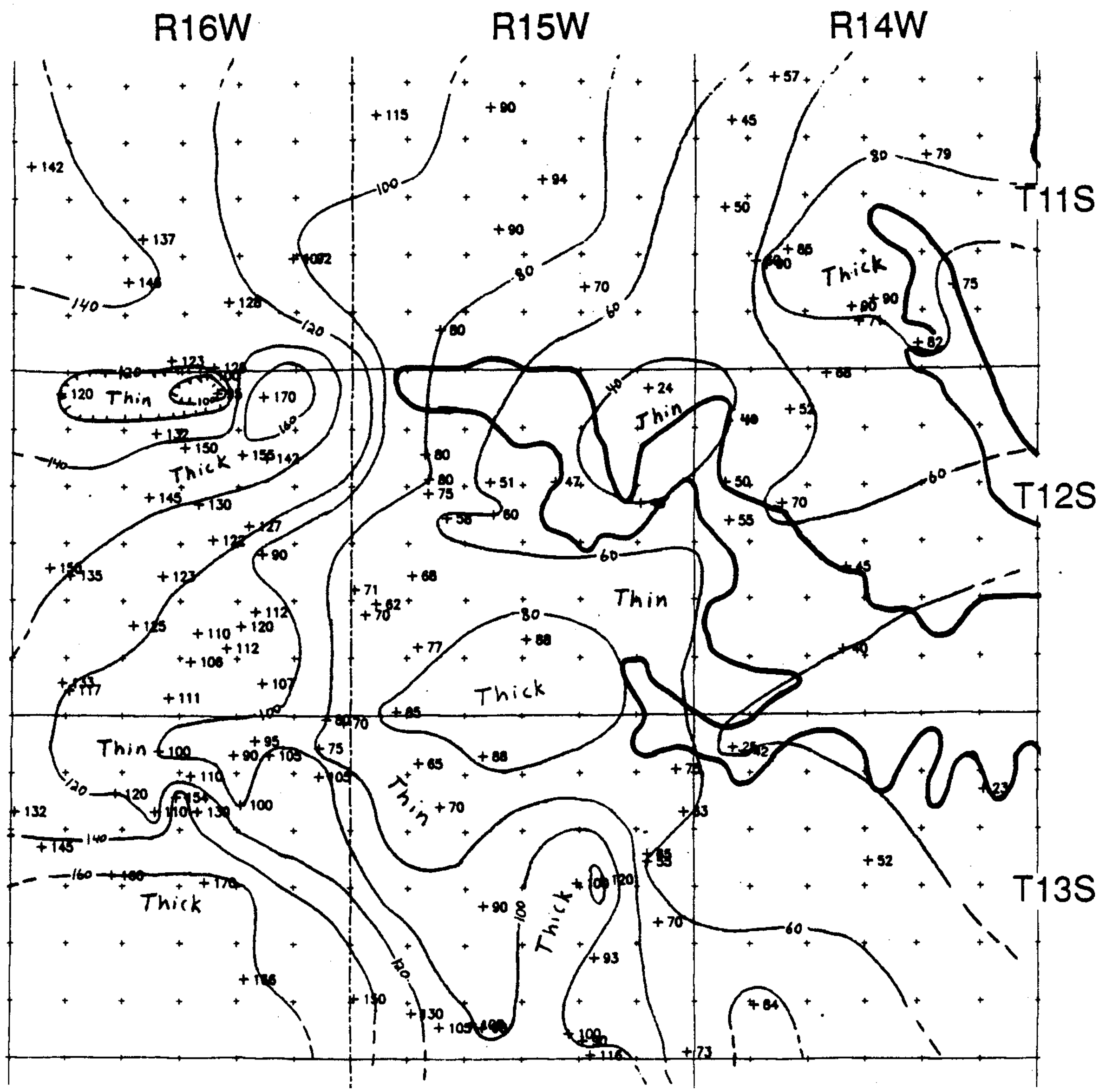


Figure 63: Isopach map of the Cedar Hills Sandstone (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

Top of Graneros Shale to top of Permian Cedar Hills Sandstone isopach

The isopach map of Cretaceous strata up to the Greenhorn Limestone (Fig. 64) shows the overall thickness trends and structural controls on deposition during Late Albian and Early Cenomanian time.

The thickness of this interval ranges from 325 ft to 477 ft. The average thickness is 350 ft in R14W, 420 ft in R15W, and 440 ft in R16W. The northeast-southwest thickness trend in T12S R15W connects to a thick in T12S R16W.

Compared to structure, thins are aligned along the crest of the anticline and the thickest section is in the structural low in T12S R16W. Compared to the Dakota isopach, thicks and thins are superposed.

This map shows that the Fairport anticline controlled deposition of Cretaceous strata. There was an overall decrease in deposition east of the fault due to its structurally and topographically high position.

Two additional maps were made but not included because they are redundant. The isopach map from the top of the Graneros to the top of the Stone Corral shows the similar trends as in the Graneros to Cedar Hills isopach. The isopach map from the top of the Stone Corral to the top of Cedar Hills Sandstone shows a thickening to the west that is also shown in the Cedar Hills isopach. Trends on both of these maps are sensitive to thickness changes in the Cedar Hills Sandstone. East to west trends on these maps are mostly the result of east to west trends in the Cedar Hills isopach.

J Sequence basal sandstone isopach

The lithofacies map of the J Sequence basal sandstone (Fig. 65) shows the geometry and distribution of this aquifer

The thickness ranges from 0 to 135 ft with an average of 100 ft. Three east-west trending thicks are about 2 mi wide and occur in each township.

Compared to structure, the east-west thicks are draped over the anticline and dip east towards the outcrop. The sandstone body in T12S widens west of the anticline into a structural low, and is also parallel to a secondary east-west structural trend.

Compared to the J Sequence isopach, the sandstone body in T12S is within a thick, and the thin in the J Sequence in south T11S has no sandstone within it.

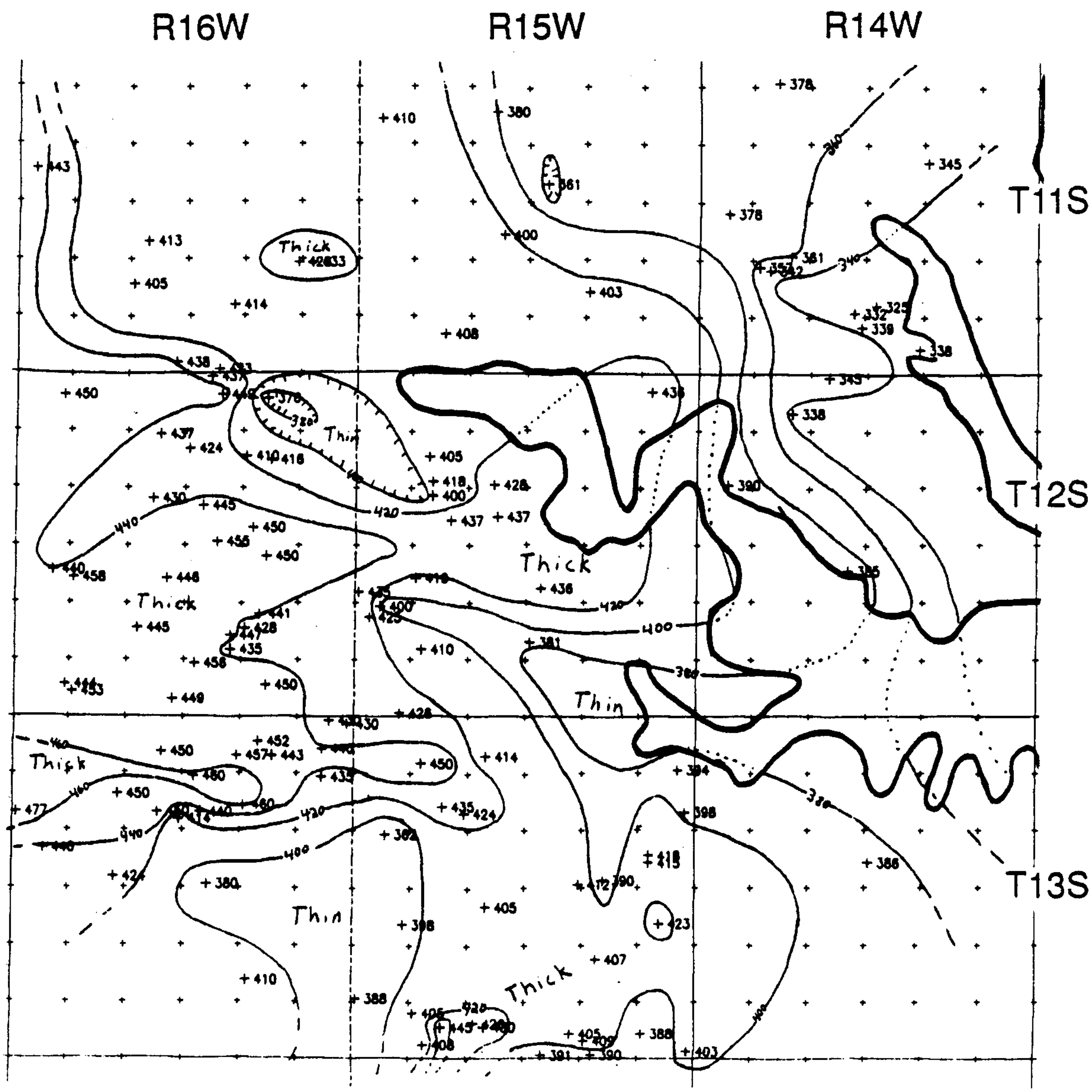


Figure 64: Isopach map from the top of the Permian Cedar Hills Sandstone to the top of the Graneros Shale (c.i.=20 ft). Heavy line is the outcrop trace of the Dakota Formation.

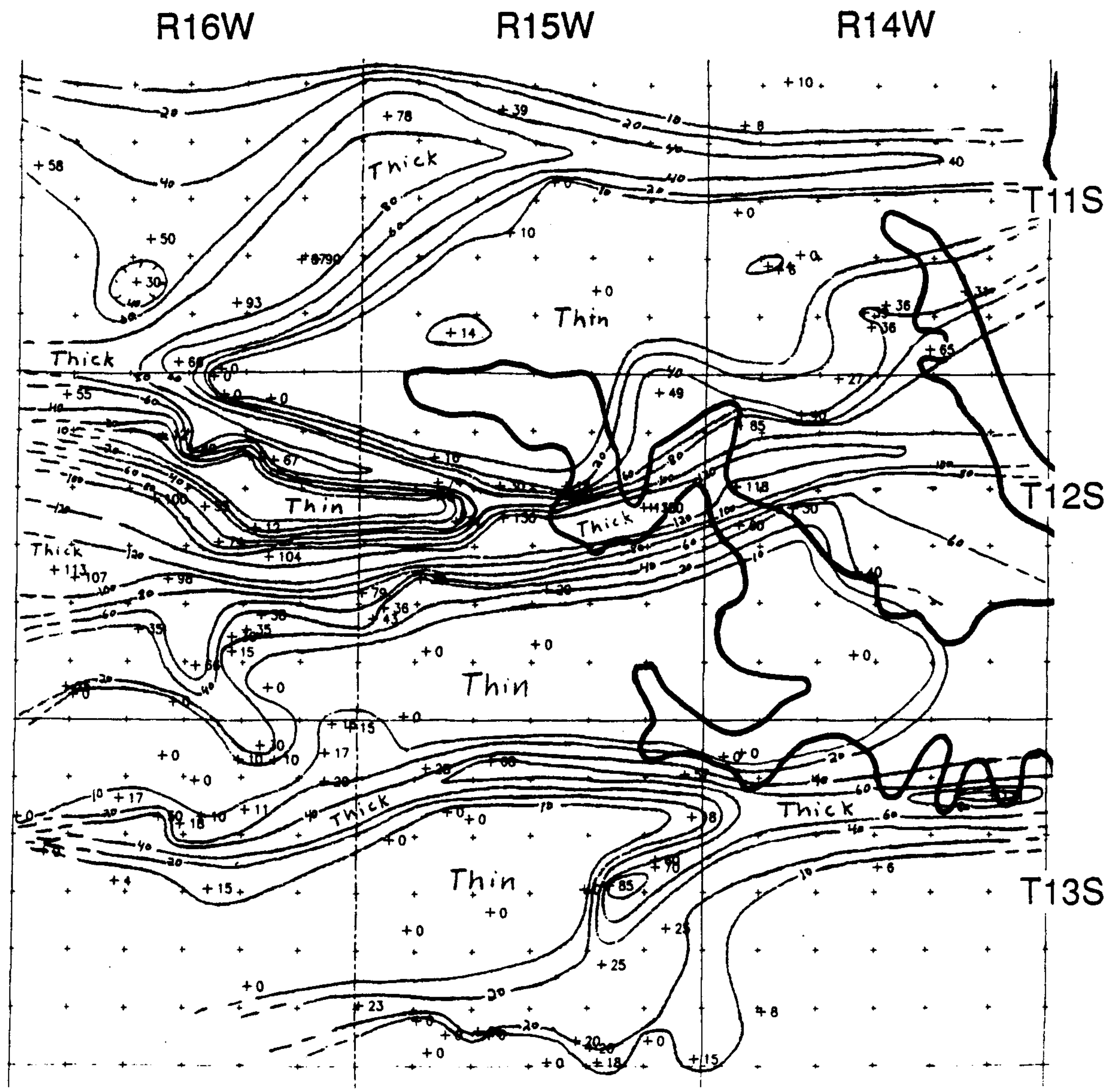


Figure 65: Isopach map of the J Sequence basal sandstone (c.i.=20 ft).
Additional contour line at 10 ft to show sandstone limit.
Heavy line is the outcrop trace of the Dakota Formation.

Compared to the Dakota isopach, the east-west trending sandstone thicks in T12S and northern T11S are in east-west trending isopach thicks. There is no basal sandstone in the Dakota thick in the north half of T13S R16W, but there is one in a thick in T13S R14/15W.

Compared to the Cheyenne/Kiowa Sequence isopach, the thin to no sandstone in T11S is over a thick. The sandstone thick in T12S R15W is over a thin.

This sandstone isopach map shows east to west paleodrainages with a paleoslope dipping to the west. Based on outcrop observations and the size of the sandstone bodies, they are interpreted as a vertical amalgamation of numerous smaller channel sandstones. This vertical localization is interpreted as a structural control on stream location. The importance of these observations and interpretations is that structure maps can be used in concert with Dakota Formation and J and D Sequence isopach maps to locate areas of thick sandstone bodies.

J Sequence second sandstone isopach

The isopach map of the J Sequence second sandstone (Fig. 66) shows the distribution and geometry of this aquifer. The position of this sandstone was picked with respect to the base and top of the Dakota Formation. Even though efforts were made to pick this sandstone at about the same depth below the top of the Dakota, they may not all be genetically related. The interpretation of this map is complicated by the amalgamation of the second sandstone with the basal sandstone. Differentiation of the two on well logs is impossible when they are amalgamated. In these cases, amalgamated sandstone bodies were mapped as basal sandstones.

The thickness of the second sandstone ranges from 0 to 73 ft with a 50 ft average. Sandstone bodies trend east-west and are about 1 mi wide with individual channels about 30 ft thick.

Compared to structure, all the sandstones cross the Fairport anticline at right angles. There is no strong control by structure except that the sandstones may occur over secondary east-west structural trends.

Compared to the J Sequence basal sandstone isopach, these sandstones are generally in the same localities but slightly offset laterally. Compared to the J Sequence isopach, the sandstone thicks are generally coincident.

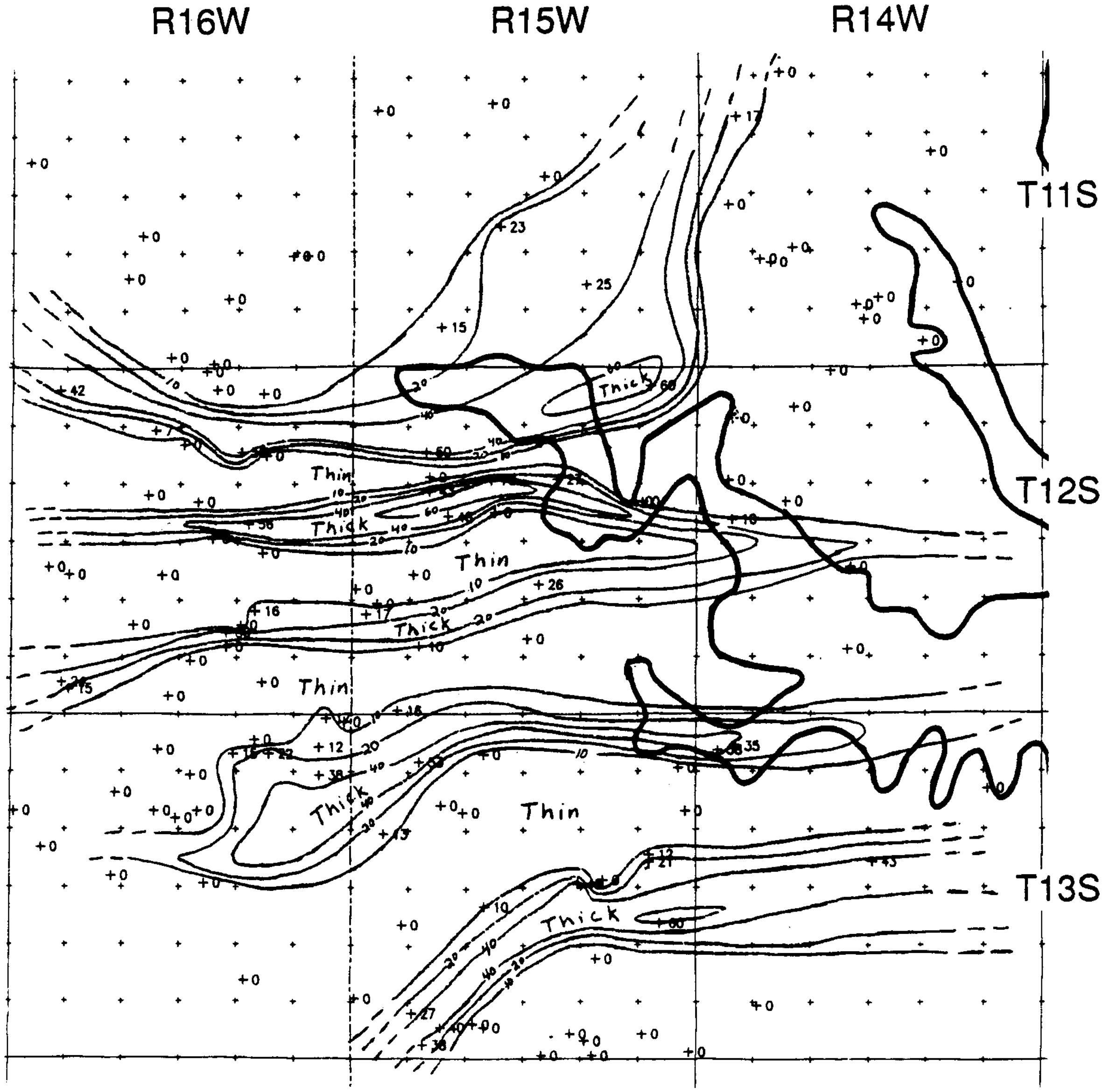


Figure 66: Isopach map of the J Sequence second sandstone (c.i.=20 ft).
Additional contour line at 10 ft to show sandstone limit.
Heavy line is the outcrop trace of the Dakota Formation.

The thicker sections of sandstone are interpreted as vertically amalgamated sandstones of individual channels. Because these sandstones are not as laterally confined as the basal sandstones, they are inferred to be the deposits of more sinuous and meandering rivers. Combined with a less apparent structural control on deposition, this may indicate that external factors such as rising base level controlled deposition more than structure.

D Sequence basal sandstone isopach

The D Sequence basal sandstone isopach (Fig. 67) shows the geometry and distribution of a mid-Dakota Formation aquifer. Given the nonmarine depositional environment of most of the Dakota Formation, the position of the sequence boundary picked on well logs is often uncertain, and the confidence of the depicted contour is low.

The sandstone bodies range in thickness from 0 to 117 ft. They trend east-west and are approximately 1 mi wide. Individual channels are about 30 ft thick and less than 1/4 mi wide. There is a thick in the northern part of T13S which connects to the Rocktown channel sandstone in outcrop as mapped by Siemers (1971).

Compared to structure, the sandstones are discontinuous across the anticline except for the one in northern T13S. This sandstone dips east away from the anticline towards the outcrop.

Compared to the J Sequence isopach, a sandstone thick is over a thin in T11S. Two sandstone thicks are over northeast-southwest thins in T13S R16W and T12S R16W. Compared to the D Sequence isopach, the thickest sandstones are spatially coincident with isopach thicks and thin sandstones are spatially coincident with isopach thins, particularly in T12S R14W and T12S R15W.

The sandstones are thin and laterally extensive over structural highs and are thick and vertically amalgamated in structural lows. This vertical amalgamation of individual channel sandstones is supported by the fact that the Rocktown channel sandstone is less than 75 ft thick in outcrop, yet over 100 ft of continuous sandstone is present in the subsurface. The secondary east-west structural trend localized the position of sandstone thicks, particularly in northern T13S. The inverse thickness relationship of this sandstone isopach and the J Sequence isopach emphasizes that thicks and thins in the J Sequence isopach may not have the same meaning as in the D Sequence isopach. That is, some of the thins in the J Sequence are due to erosion at the base of D Sequence thicks and are not

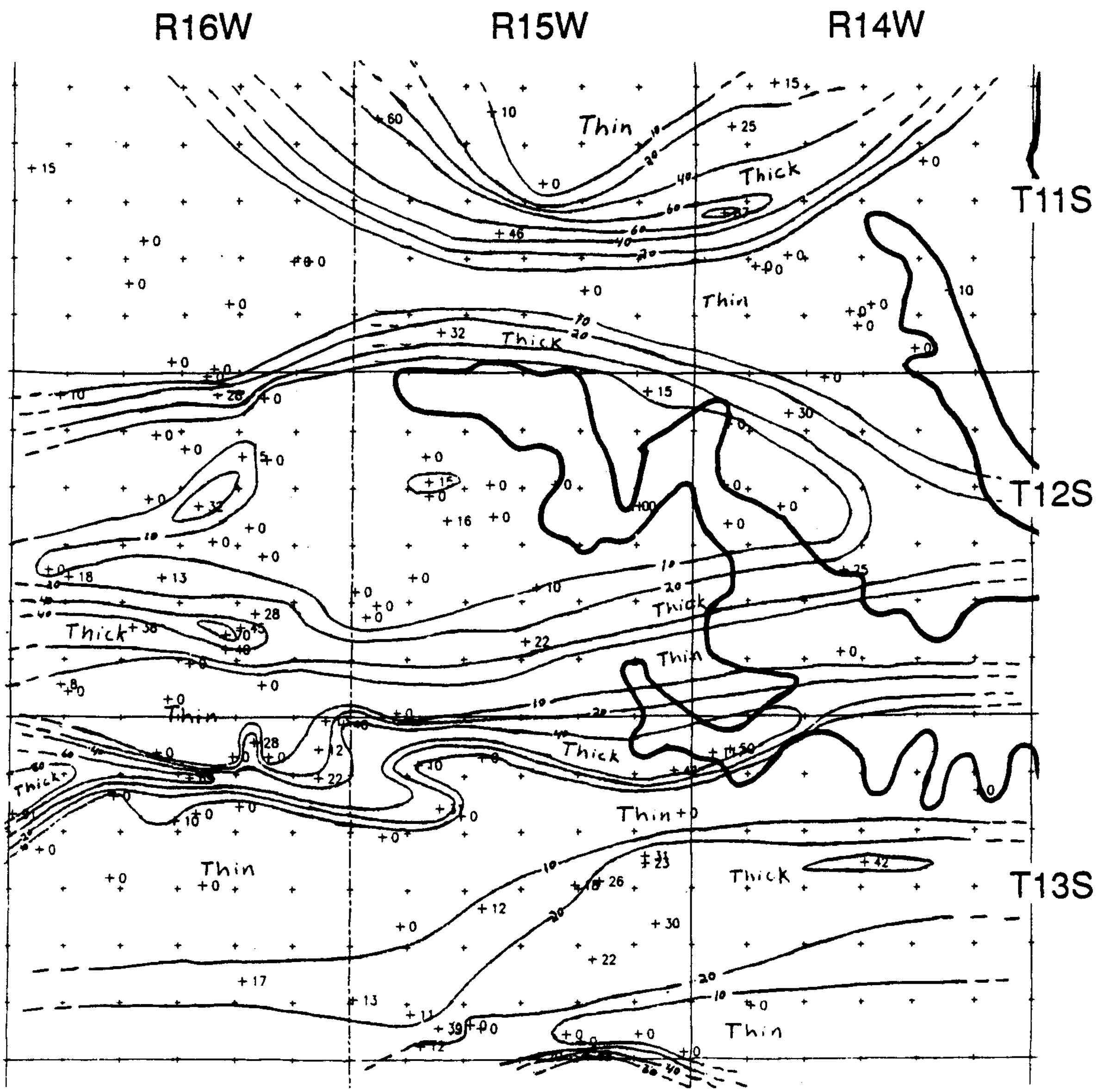


Figure 67: Isopach map of the D Sequence basal sandstone (c.i.=20 ft). Additional contour line at 10 ft to show sandstone limit. Heavy line is the outcrop trace of the Dakota Formation.

the result of depositional thinning over structural highs.

Cheyenne Sandstone isopach

The Cheyenne Sandstone isopach map (Fig. 68) shows the geometry and distribution of a formerly used oil-field brine disposal zone.

The sandstone at the base of the lower stratigraphic sequence rests directly on the Permian Cedar Hills Sandstone and ranges in thickness from 0 to 44 ft with a 25 ft average. The sandstones are ribbon-like, trend in an east-west direction, and are about 1.5 mi wide.

Compared to structure, all of the sandstones are draped across the anticline and are thickest west of the anticline.

Compared to the Cheyenne/Kiowa Sequence, the east-west trending sandstone thicks in southern T11S and northern T13S R16W are spatially coincident with isopach thicks. The thin in T12S R15W has very little sandstone in it.

Compared to the Cedar Hills Sandstone isopach, an inverse thickness relationship is evident. Thick sandstone in the Cheyenne Sequence is over the east-west trending thin in T12S R15W. The thick in the Cedar Hills in northern T12S R16W is overlain by a thin sandstone. Conversely, a thin in northern T13S R16W is overlain by a thick sandstone.

This sandstone isopach map shows paleodrainage on top of the Permian that had a topographic slope to the west. Not all of the sandstone thicks are located in Cheyenne/ Kiowa Sequence thicks due to the erosional nature of the contact with the overlying J Sequence which modified the sequence thickness.

Upper genetic sequence isopach

The upper genetic sequence isopach map (Fig. 69) shows trends that assist in the interpretation of depositional environments. This isopach interval is assumed to be bound by marine flooding surfaces, and that all strata within it were deposited in temporally equivalent environments.

The prominent trends are lobate thicks in T13S R15W, T11S R14W, and T12S R16W and thins in T11S R15W and T12S R15W.

Compared to structure, the thick in T13S R15W is parallel to and east of the anticline and the thick in T12S R16W is in a structural low. The thins in T11S R15W and T12S

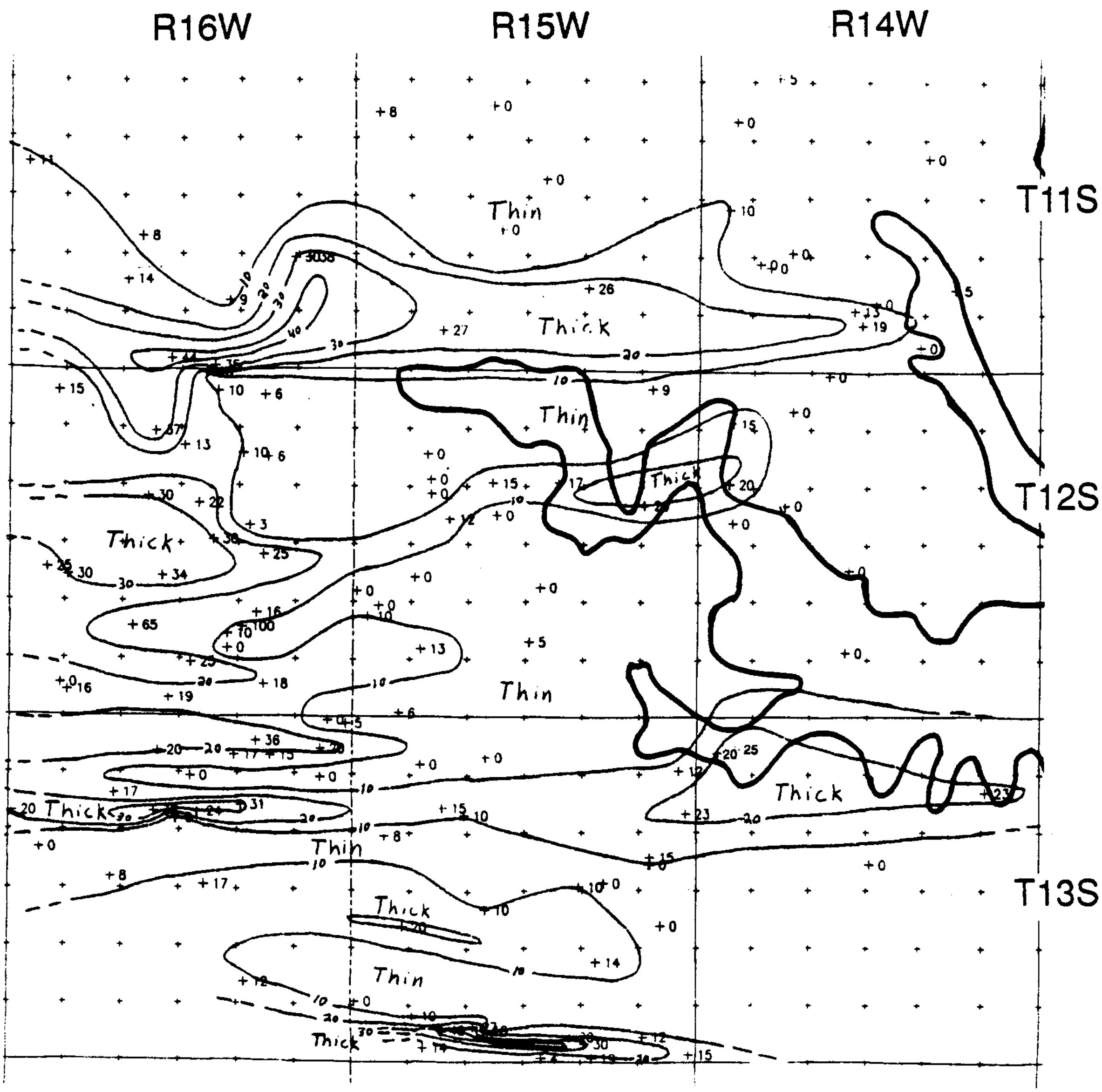


Figure 68: Isopach map of the Cheyenne Sandstone (c.i.=10 ft).
Additional contour line at 10 ft to show sandstone limit.
Heavy line is the outcrop trace of the Dakota Formation.

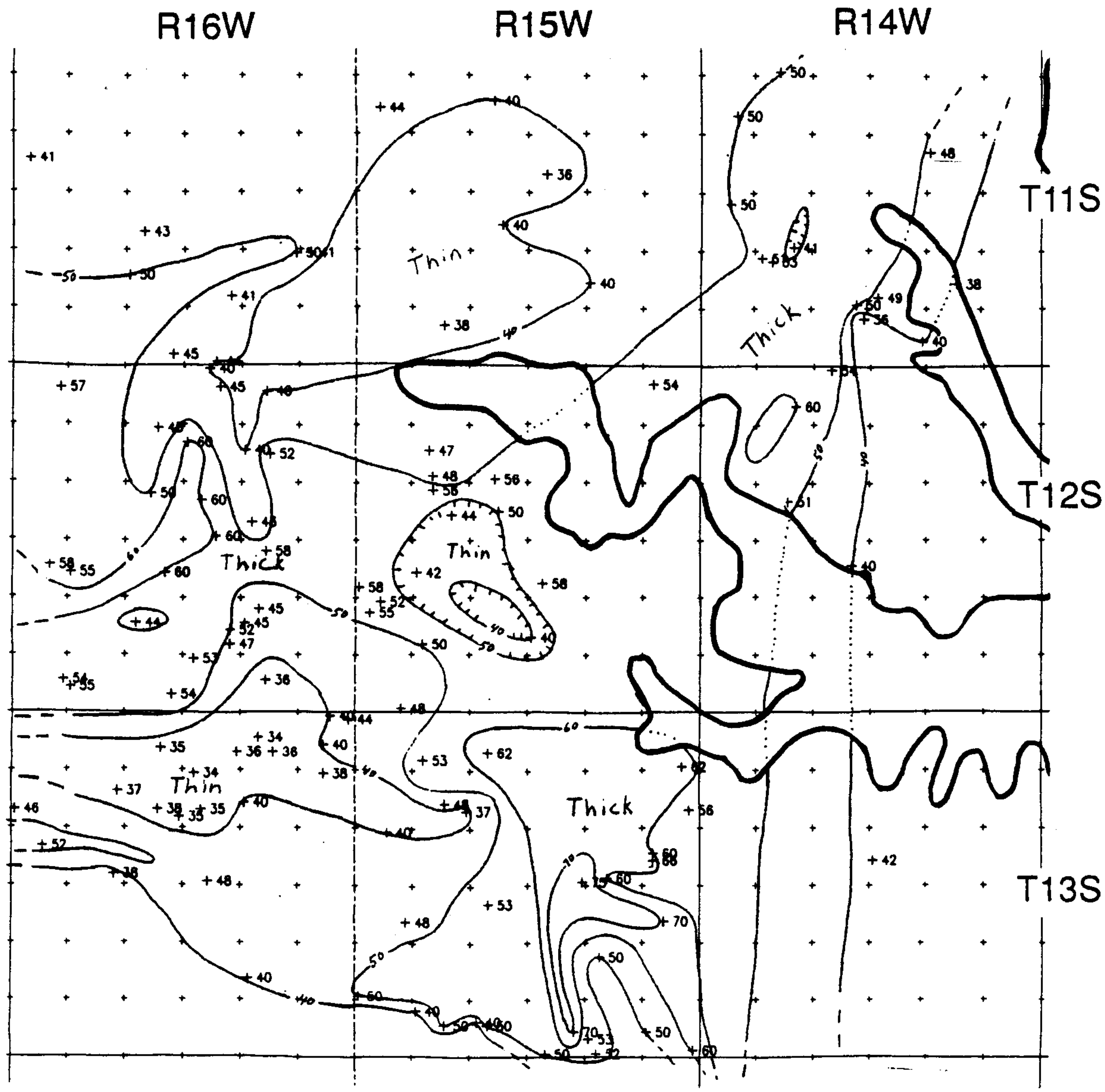


Figure 69: Isopach map of the upper genetic sequence (c.i.=10 ft). Heavy line is the outcrop trace of the Dakota Formation.

R15W are along the crest of the anticline.

There is an inverse thickness relationship between this map and the Graneros isopach map. That is, thicks in the upper genetic sequence are thins in the Graneros. This represents depositional topography on top of delta lobes. The delta interpretation is supported by field evidence of a three-dimensional shoreline and by Siemers (1971).

Upper genetic sequence sandstone percentage map

The sandstone percentage map (Fig. 70) in the upper genetic sequence indicates the depositional environments of different lithologic units. Compared to the isopach map, thins are shaly and thicks are sandy. This shows that the thicks were areas of greatest sand deposition supporting a delta interpretation. These deltas were localized in structural lows in the same manner as rivers in the Dakota Formation.

With the depositional environment and sandstone body geometry determined, future isopach and sandstone percent maps need not be made. A simple isopach map of the sandstone itself in this upper genetic sequence would be more practical for hydrologic purposes. However, without these initial determinations of depositional environment, sandstone trends could not be contoured as confidently.

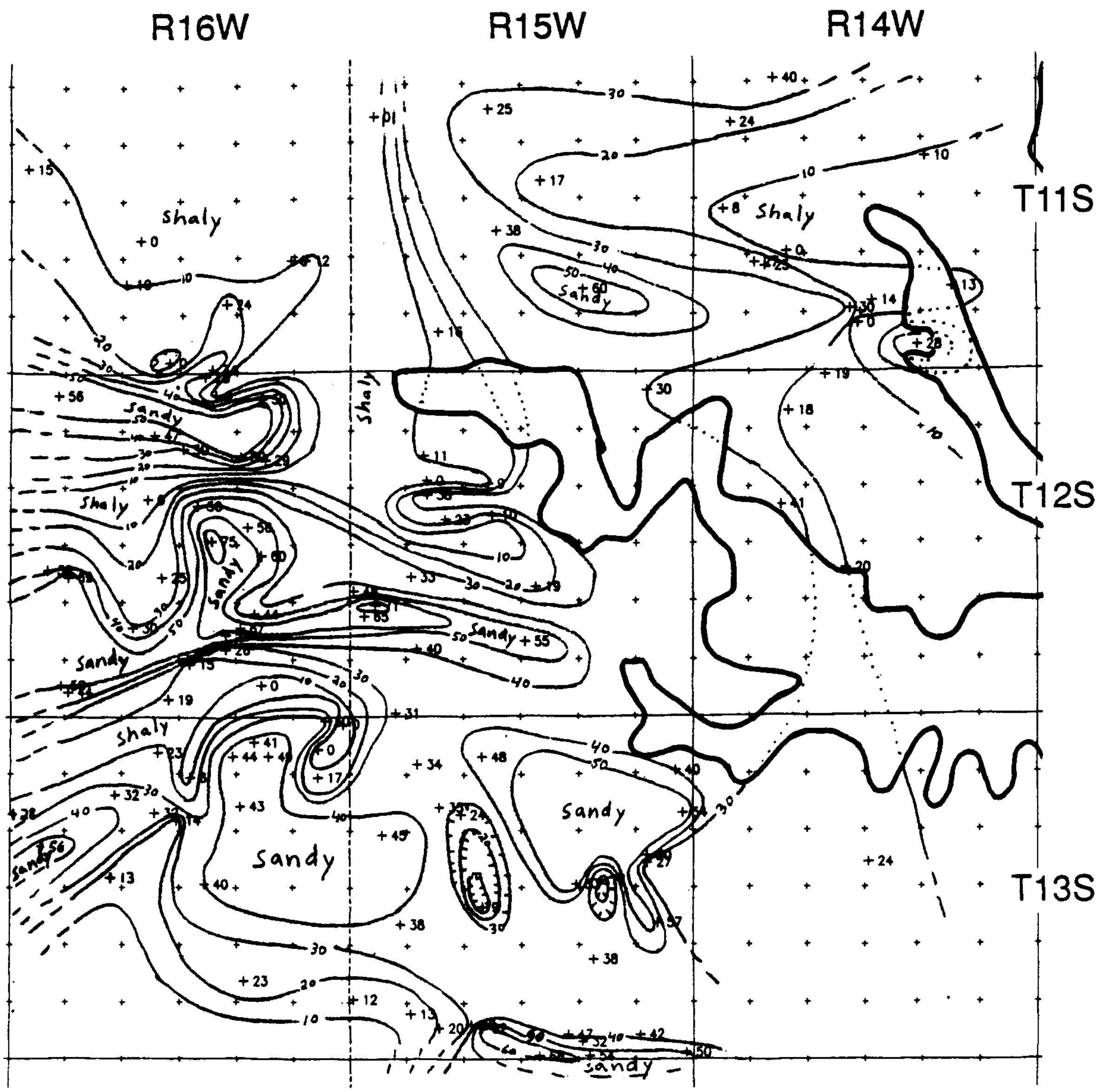


Figure 70: Sandstone percentage map of the upper genetic sequence (c.i.=10 %). Heavy line is the outcrop trace of the Dakota Formation.

Sandstone Interconnections

The establishment of sandstone body interconnections is critical to the evaluation of ground-water flow pathways and consequently water quality data. If there are no known connections between aquifers, but water chemistry data suggest that particular stratigraphic units may be in fluid communication, then alternative hypotheses must be made to explain trends in water chemistry between aquifers. The sandstone facies maps were examined to determine areas where the sandstones might be in direct connection. A few of these connections are discussed and illustrated for the Dakota Formation.

The interbedded nature of the sandstones and shales in the Longford Member make this a difficult unit to interpret in terms of fluid flow through it. Some sections are generally very sandy and other sections are generally very shaly. This member was not studied sufficiently to interpret any sandstone body trends which may exist in it. The assumption then is that if salt water can get from the underlying Cheyenne Sandstone and Permian Cedar Hills Sandstone, through the Longford Member, and into the Dakota Formation, then it could follow several flowpaths through the Dakota. Fractures or intergranular pathways in the Longford, especially over the Fairport anticline, may provide a pathway for salt water to go from the Cedar Hills into the Dakota Formation. The Longford is certainly not an aquitard like the marine shales that comprise much of the Kiowa Formation to the west of the study area.

The large sandstone bodies mapped in the Dakota Formation consist of multiple individual channel sandstones which are all connected. Outside of these mappable sandstone bodies, individual channel sandstones are hydraulically isolated and unmappable because of sparse data density. The J Sequence second sandstone is in fluid communication with the J Sequence basal sandstone (Fig. 71). Given the thickest basal sandstone is 130 ft thick and the thinnest J Sequence is 89 ft thick, it is possible to have D Sequence basal sandstone directly on J Sequence basal and second sandstones.

This evaluation of sandstone interconnectedness within the Dakota Formation establishes that some of the sandstones are connected. No sandstone body in the Dakota Formation is absolutely isolated from other sandstones in the Dakota. Common practice in brine disposal decisions is to assume that if vertical continuity of sandstones between the upper and lower parts of the Dakota Formation does not exist, then upper and lower

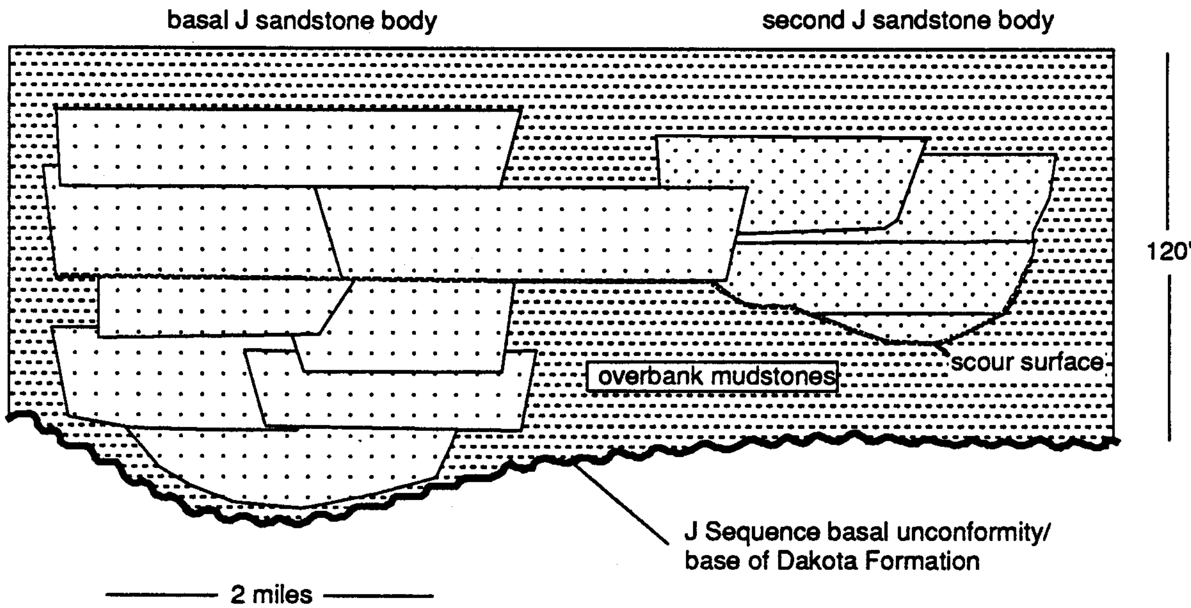


Figure 71: Schematic diagram of the position of J Sequence sandstone bodies and perceived internal composition of amalgamated channel sandstones.

Dakota sandstones are not hydraulically connected. The examples illustrated below show that this assumption is invalid.

Stratigraphic cross sections were constructed from the isopach maps in two areas where subadjacent sandstone bodies intersect. One such area is T13S R15W and is illustrated in Figure 72. The isopach trends show potential direct connections of sandstones and thus a potential flow path from the basal J sandstone to the deltaic sandstones at the top of the Dakota Formation. A cross section in T11S R15W shows a potential connection between J Sequence basal sandstone and D Sequence basal sandstone (Fig. 73). An important point to note is that a single vertical section from the well on the right of the figure would incorrectly suggest that the middle sandstone is isolated from underlying sandstones.

Salt Marsh

Adjacent to the Haberer well in T12S R15W is a salt marsh. Sulfur isotope analysis indicated that the salt water is derived from naturally occurring salt water in the Cedar Hills Sandstone M. Townsend, 1989, (personal communication). One D Sequence sandstone trends under this area and then west over the Fairport anticline. This sandstone may be interconnected with other sandstones illustrated in Figures 72 and 73. With 70 ft of structural relief from the anticline to the salt marsh, it is possible to establish an artesian head at the salt marsh. Salt water charge into the Dakota Formation is likely from fractures localized around the anticline. The Cedar Hills Sandstone is overpressured so flow within it would be updip, and the Dakota Formation is underpressured so flow within it would be downdip. Thus the anticline is a natural place for movement of salt water into the Dakota Formation.

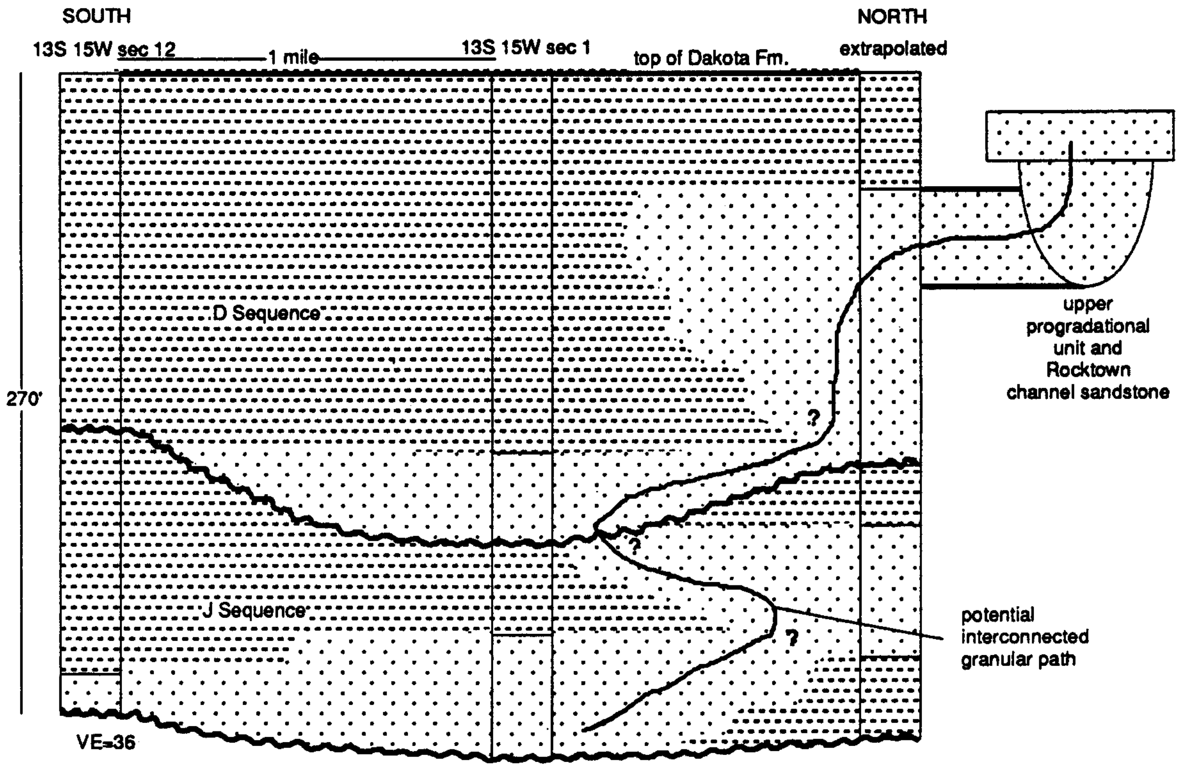


Figure 72: Possible connection of J and D Sequence sandstone bodies in the subsurface with the Rocktown channel sandstone in the outcrop.

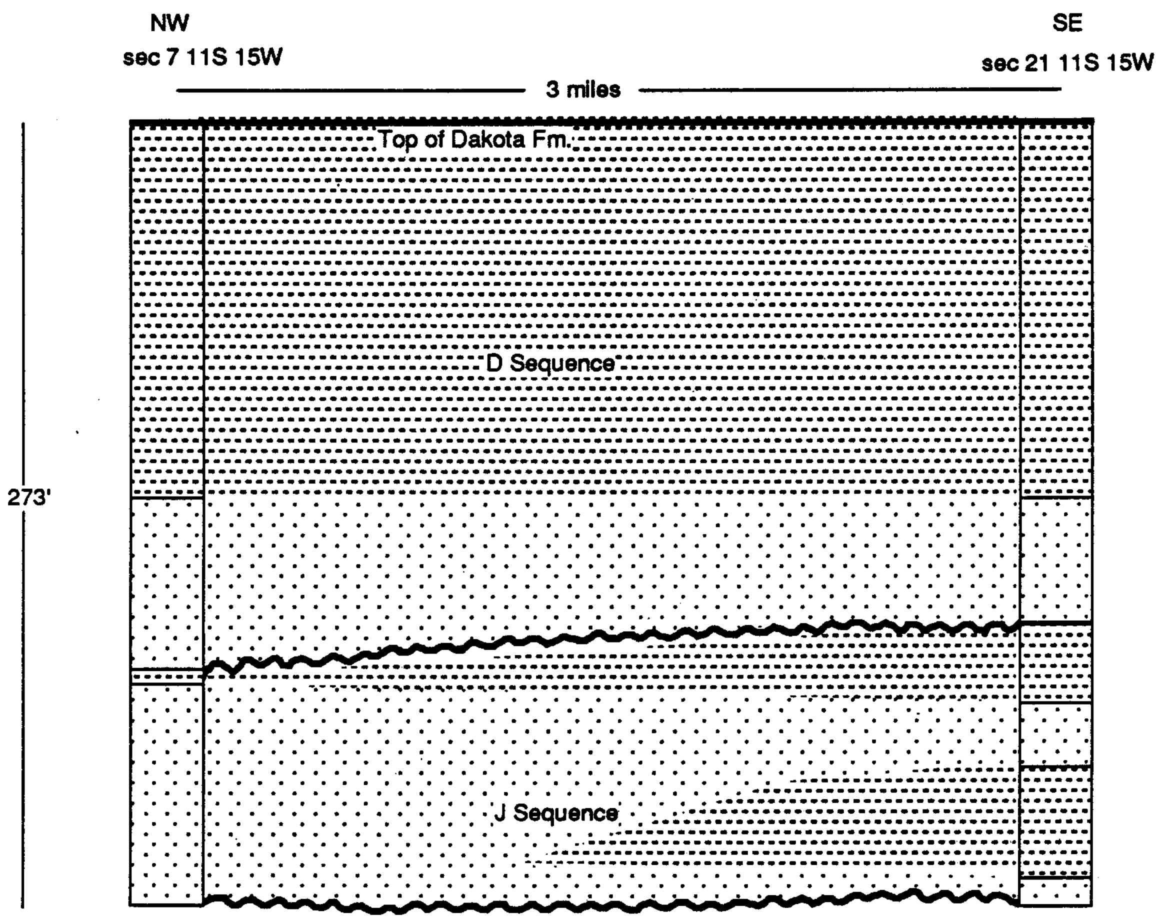


Figure 73: Near connection of J and D sequence sandstone bodies, which probably converge to the northwest, based on isopach trends.

Conclusions

Cretaceous strata of this study in Kansas were divided into three unconformity-bounded sequences. The lower Cheyenne/Kiowa Sequence contains the Cheyenne Sandstone and Kiowa Formation. The middle, J Sequence consists of the lower Dakota Formation. The upper Dakota Formation is contained within the base of a third, D Sequence, which is bound by an unconformity stratigraphically above the section of study.

Three of the Cretaceous sequences defined by Weimer (1984) in Colorado are present in Kansas. The sequence containing the Plainview Formation and Skull Creek Shale is the Cheyenne/Kiowa Sequence in Kansas. The sequence containing the J sandstone and Huntsman Shale is the J Sequence in Kansas. The sequence containing the D sandstone is the D Sequence in Kansas. The sequence containing the Lytle Formation is not present in Kansas.

The internal stratal architecture of the sequences consists dominantly of landward-stepping progradational events which onlap the basal unconformities. Facies within the sequences change from dominantly marine to dominantly nonmarine laterally from west to east. Vertically stacked progradational events representing highstand deposits are interpreted in the Longford Member of the Kiowa Formation. In the lower and middle sequences, seaward-stepping progradational events deposited prior to lowstands of sea level were removed by subaerial erosion.

The Cheyenne Sandstone is unconformable upon Jurassic and Permian strata and is a lateral facies equivalent of the Longford Member. The Kiowa Formation is transgressively disconformable upon the Longford Member. The Dakota Formation is unconformable upon the Kiowa Formation. The Terra Cotta Clay Member and Janssen Clay Member contact is a landward facies offset. The Graneros Shale is transgressively disconformable upon the Dakota Formation.

The Cheyenne Sandstone, Longford Member and Kiowa Formation are temporally equivalent and facies a succession of landward-stepping progradational events. The Dakota Formation in Kansas is temporally equivalent to the J sandstone, Mowry Shale, Huntsman Shale, and D sandstone in Colorado. The age of the Dakota Formation is determined from the correlation of unconformities from Colorado. The lower part of the formation is in the J Sequence and is late Albian (J sandstone equivalent). The upper part of the formation is in the D Sequence and is early Cenomanian (D sandstone equivalent).

Structural features affected deposition and erosion of the stratigraphic sequences on both regional and local scales. Regional structural and topographic positive features were the Las Animas arch, Cimarron arch, and Central Kansas uplift. The sequences thin over these areas. Erosion at the base of the Dakota Formation was greatest west of and adjacent to the Central Kansas uplift. The Fairport anticline/fault was a positive structural and topographic feature in the local study area during deposition of Cheyenne, Kiowa and Dakota Formations. In the local study area, sandstone body trends are parallel to west-east oriented structures and sequences thicken west of the Fairport anticline.

A paleodrainage divide that separated the southern and northern Cretaceous seas prior to their connection is interpreted to have been located in the subsurface north of the Cheyenne Sandstone and Kiowa Formation type sections in southwest Kansas. The divide probably trended along the north edge of the Hugoton embayment and connected the Cimarron arch with the Central Kansas uplift.

Three hydrostratigraphic units are defined in strata beneath the Graneros Shale. The aquifer units include the Dakota Formation and the Cheyenne Sandstone/Longford Member. They are separated by the Kiowa Formation shale aquitard unit in the subsurface west of the Central Kansas uplift. On and east of the uplift the units are amalgamated.

Sandstone bodies in the local study area are linear, lens-shaped, and have concave-up bases. They are up to 120 ft thick and 1 mi wide. They are composed of multiple amalgamated fluvial channel sandstones. East-west trending structural features localized stream positions. Sandstone bodies are in direct contact laterally and vertically throughout the Dakota Formation in two places in the local study area.

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APPENDIX A:

OUTCROP MEASURED SECTIONS

Outcrop Measured Sections

Number	Location						Elevations of sections	Dak./Gran. elev. in feet	Dak/Kiowa elev. in feet	Feet measured
	Twnshp South	Range West	Section	Quadrangle	Area	County				
1&2	12	14	34 e/2 se ne	Russell	Saline River	Russell	1552/1587 base	1640/1643		74.5/56
							1640 top			
3	14	7	8 ne se se	Westfall SE	1-70 & H-156	Ellsworth	1550 base	> 1660		62.5
4	13	10 &11	13 & 18 ne-nw	Wilson NW	Wilson Lake	Russ/Lincoln	1550	1638		88
5	16	7	1 se sw	Carniero	Franks #8	Ellsworth	1550 base	~1700		111
							1611 top		Kiowa 1520	
6	17	8	4 ne se	Geneseo	Well L1	Ellsworth	1640 base	~1775		114
							1754 top		Kiowa 1550?	
7	13	5	33 ne se se	Brookville S	I-70	Saline	1450	1600?	1350-1400	37.5
8	12	15	14 se ne	Paradise	salt marsh	Russell	1640	1664		41.5
9	13	12	7 s/2 nw nw	Dorrance NW	Wilson Lake	Russell	1600 base	1660		90
							1690 top			
10	12	2	18/19 c-s/2 / n/2	Bennington	Solomon River	Ottawa	1206 base	?	1250	90
11	11	4	26ne nw nw	Minneapolis S	Rock City	Ottawa	1270 base	?	1255	100
12	16	6	8-sw sw se	Carneiro	Kanopolis	Ellsworth	1465 base	?	1470	105
							1570 top			
13	13	10	19 ne nw se	Wilson NW	Wilson Lake	Lincoln	1555 base	> 1630		65
							1620 top			
									total feet	1059

OUTCROP LEGEND

LITHOLOGY

- shale
- sandstone
- interlaminated shale and sandstone
- siltstone
- lignite
- overbank mudstone

SEDIMENTARY STRUCTURES

- horizontal stratification
- ripple laminations
- wavy laminations
- cross stratification
- slickensides
- load feature
- pyrite nodule
- iron cement
- micro slump fault
- rip-up clasts
- sideritic spherulites

BIOLOGIC STRUCTURES

- bioturbation
- pl Planolites
- sk Skolithos
- roots
- wood chips
- wood stick
- leaves
- c carbon flakes
- diplocraterion

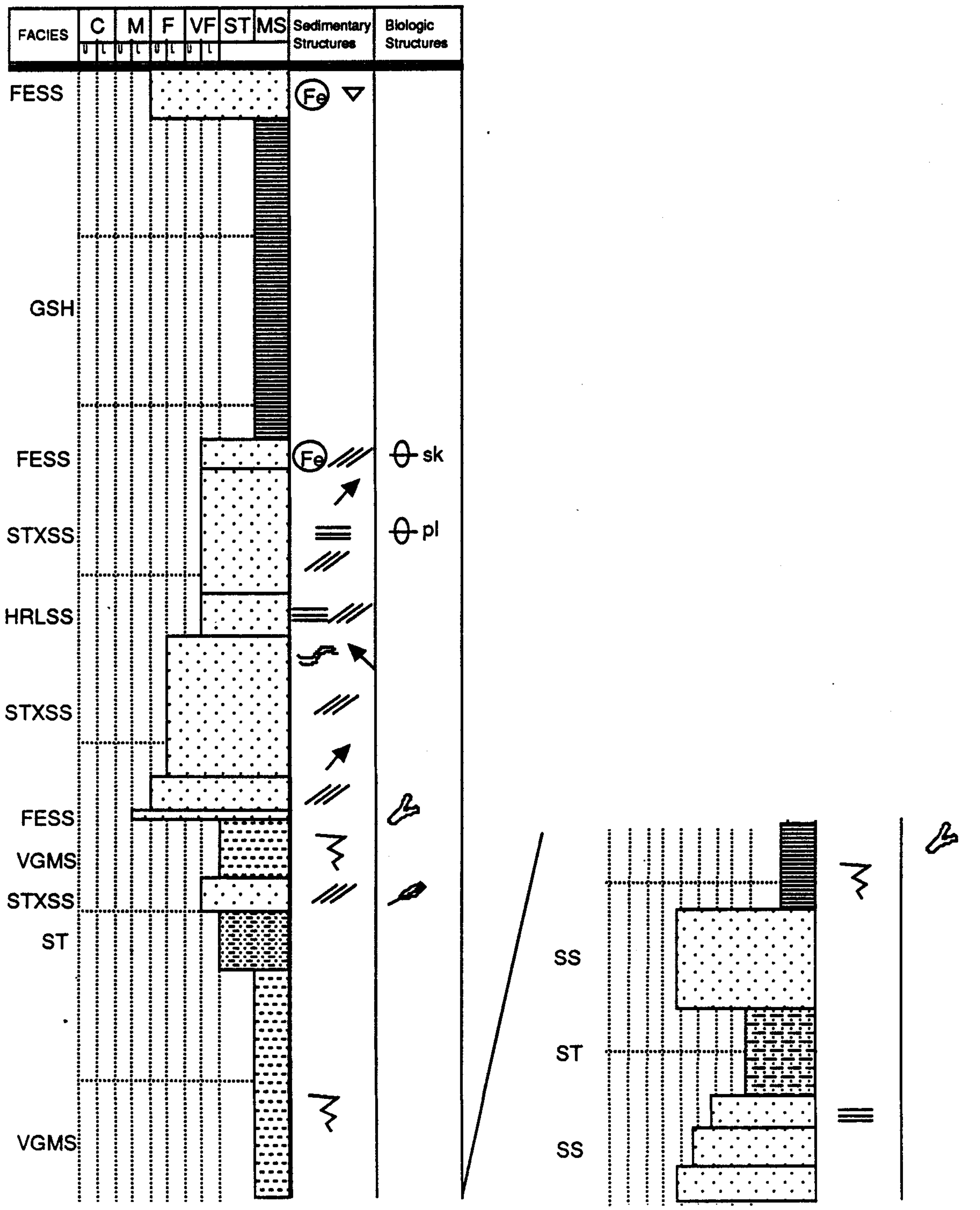
LITHOFACIES

CSH	Carbonaceous shale
HRLSS	Horizontal to ripple laminated sandstone
FESS	Iron cemented sandtone
LTXSS	Large-scale trough cross-stratified sandstone
SS	Massive sandstone
PTSS	Planar-tabular cross-stratified sandstone
SH	Shale
SS/SH	Interlaminated sandstone and shale
SS/ST	Interlaminated sandstone and siltstone
ST	siltstone
STSS	Silty sandstone
STXSS	Small-scale trough cross-stratified sandstone
VGMS	Variegated mudstone

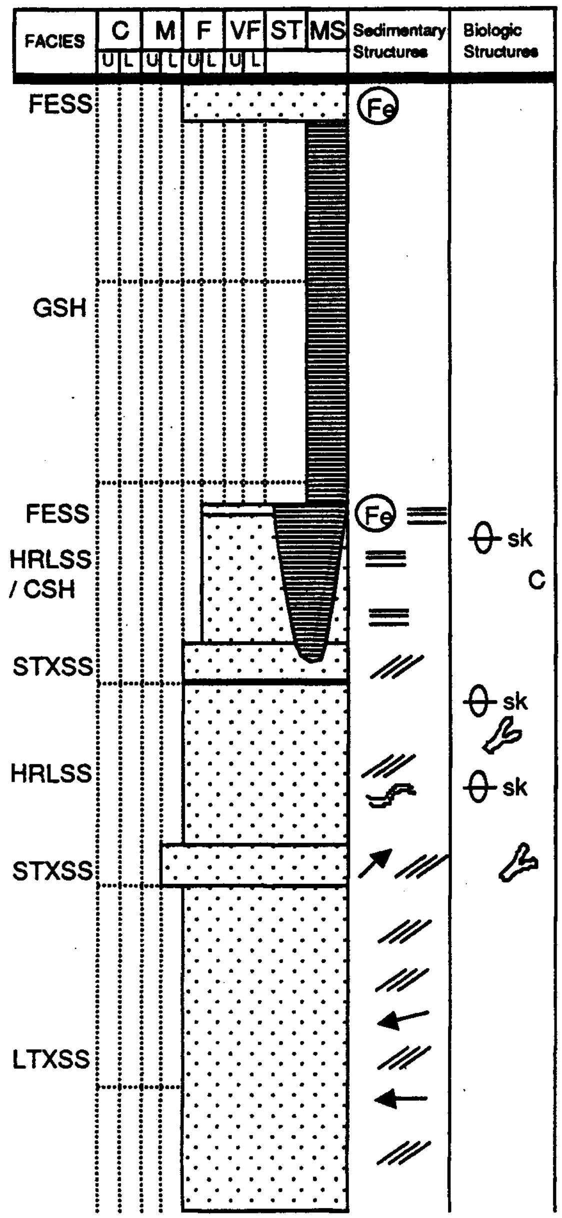
paleocurrent direction (north to top of page)

VERTICAL SCALE: 1"=10'

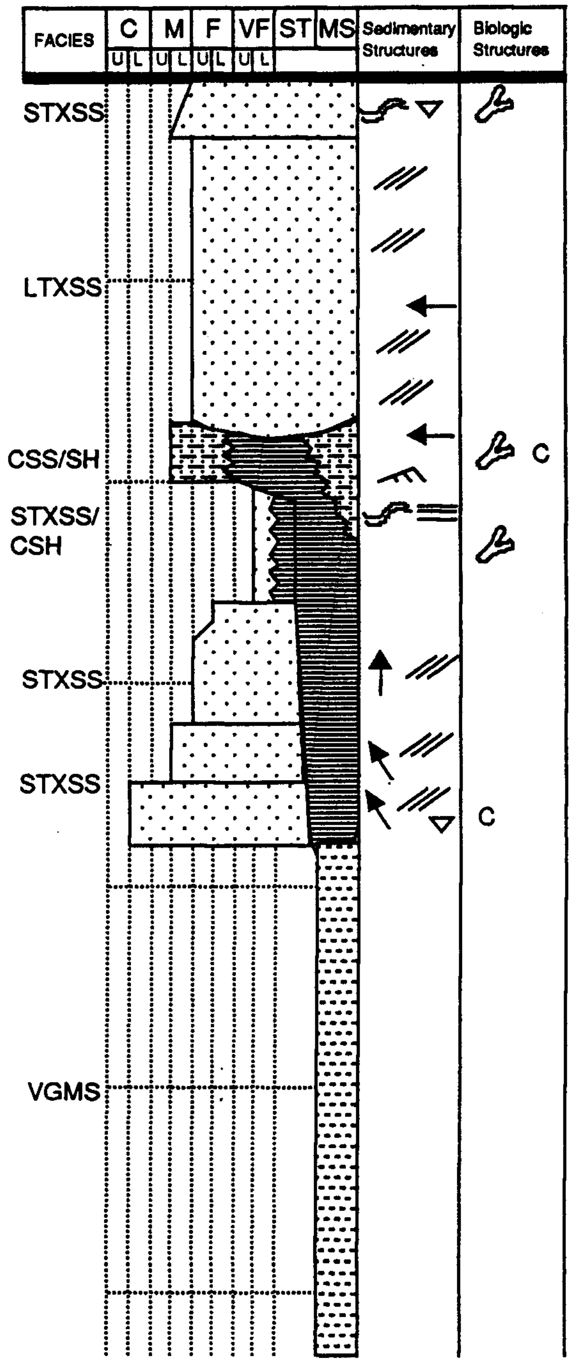
Section 1
T12S R14W sec 34 e/2 se ne
Dakota / Graneros @ 1640'

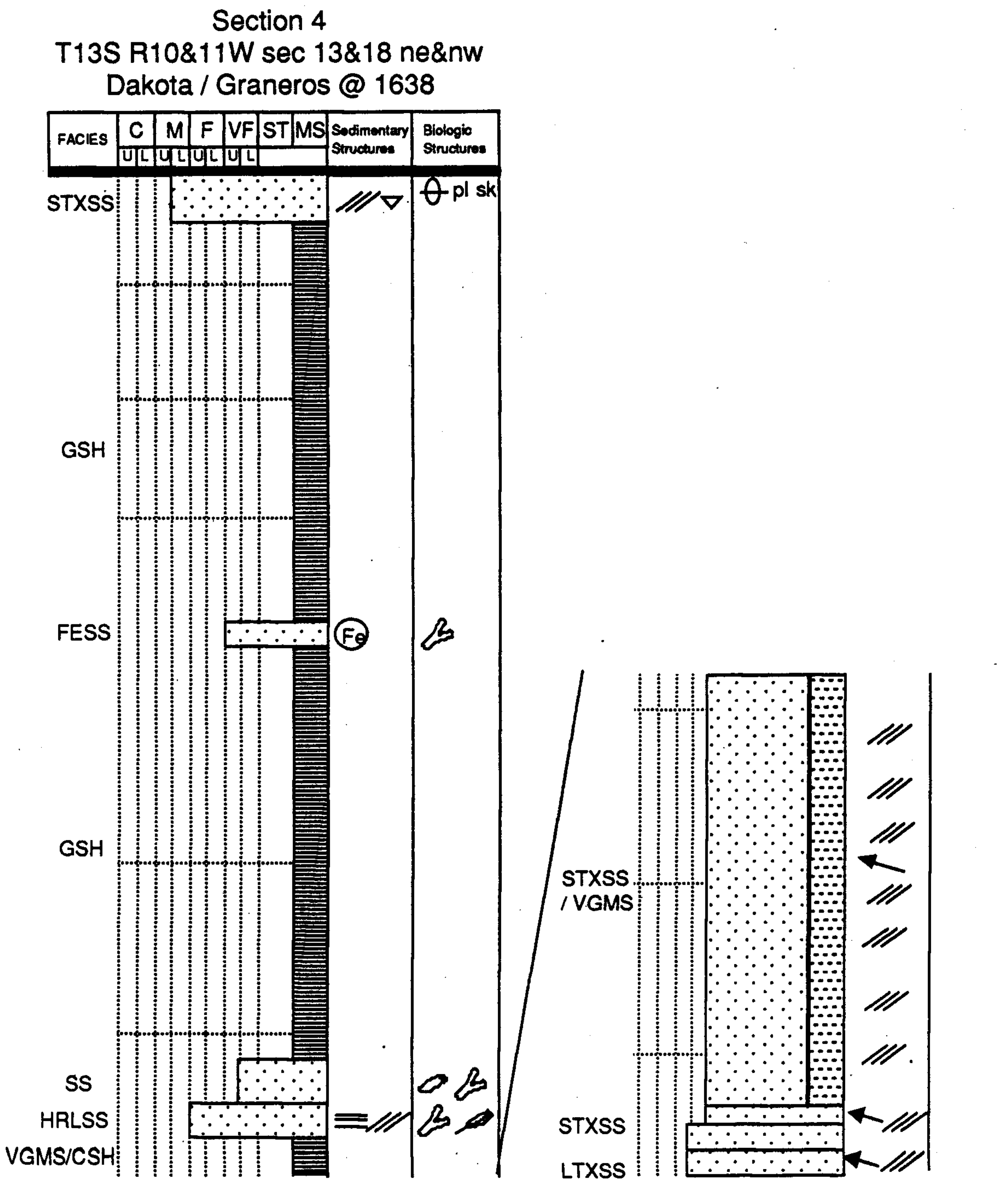


Section 2
T12S R14W sec 34 e/2 se ne
Dakota / Graneros @ 1643

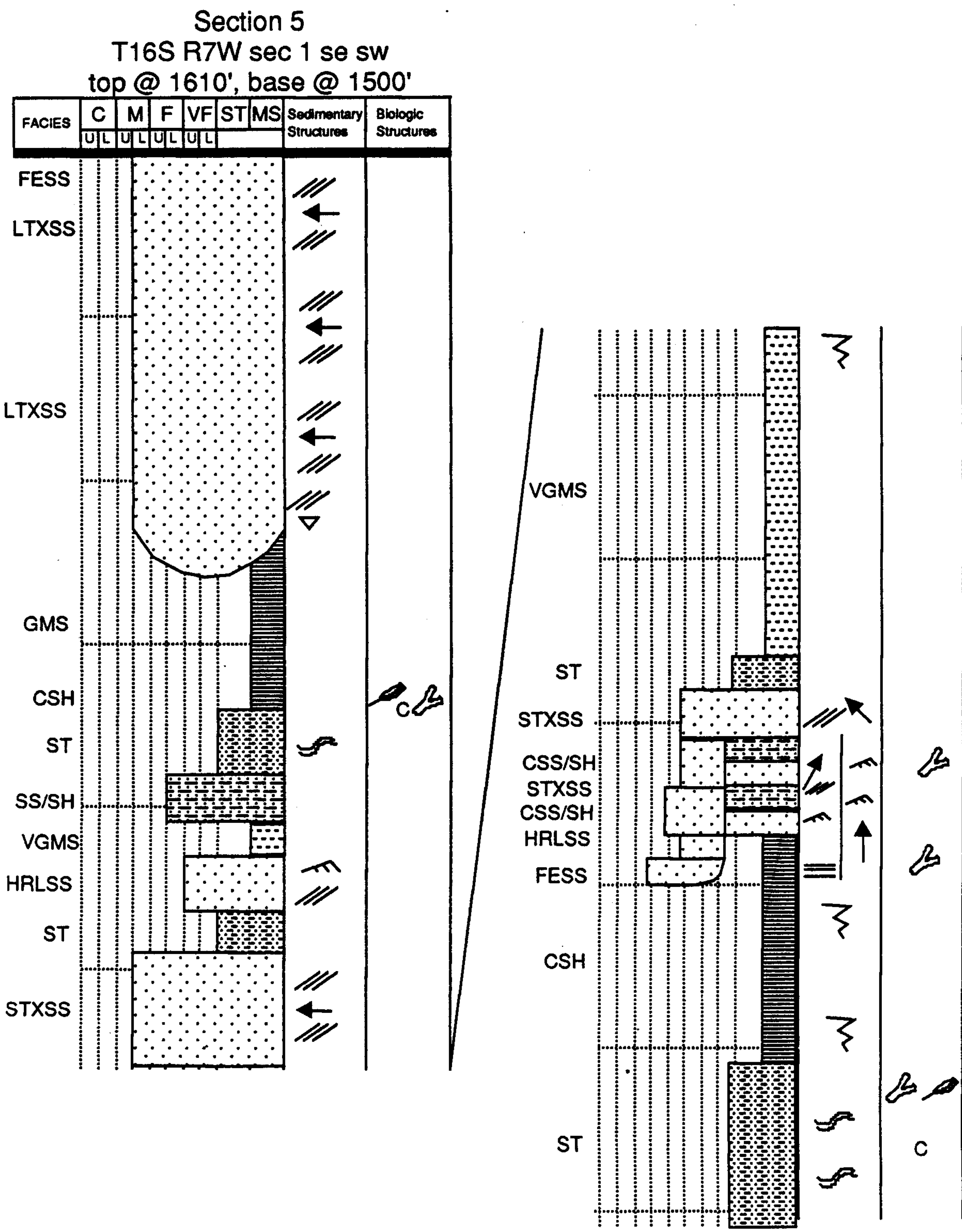


Section 3
T14S R7W sec 8 ne se se
Dakota / Graneros @ 1660'

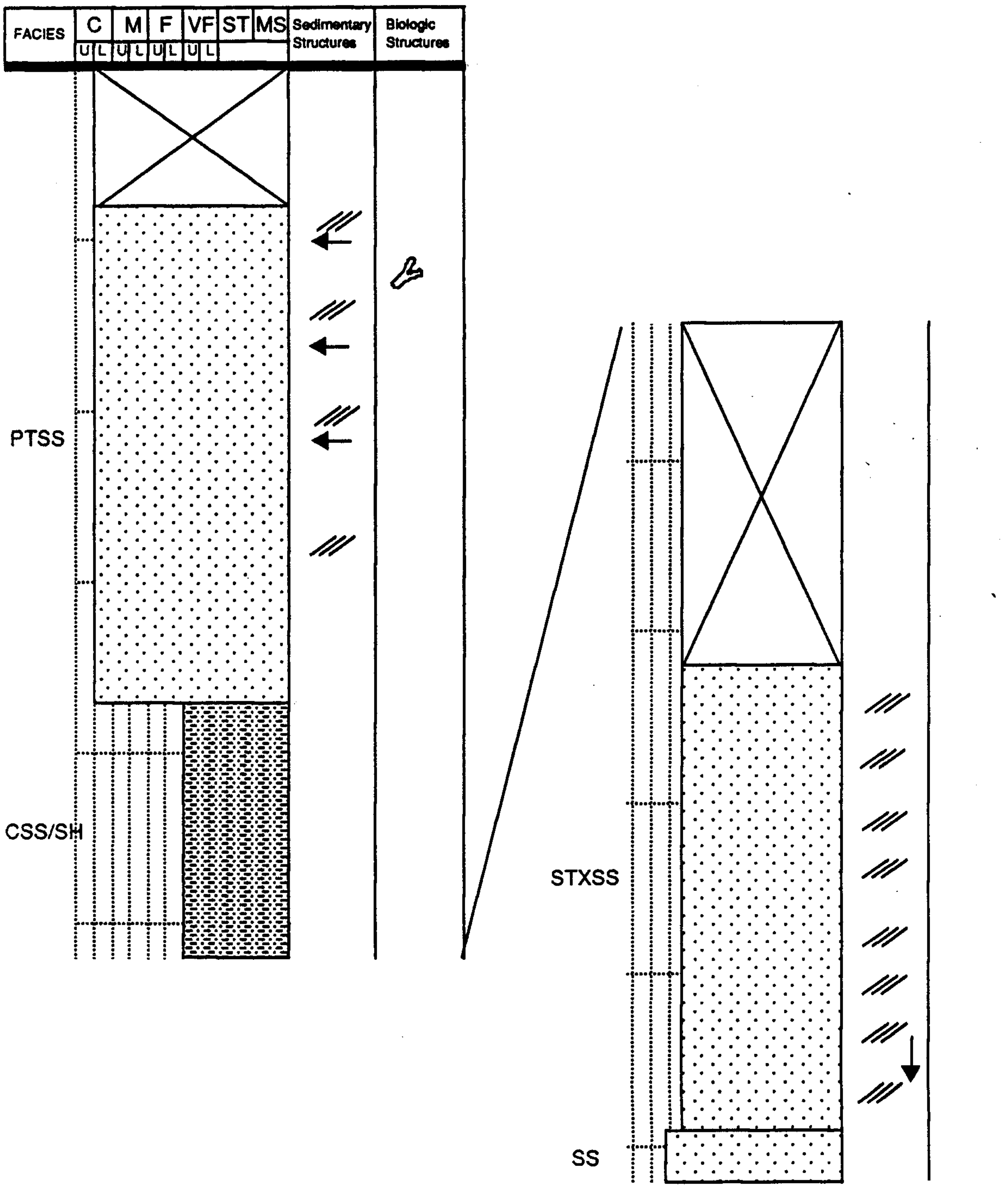




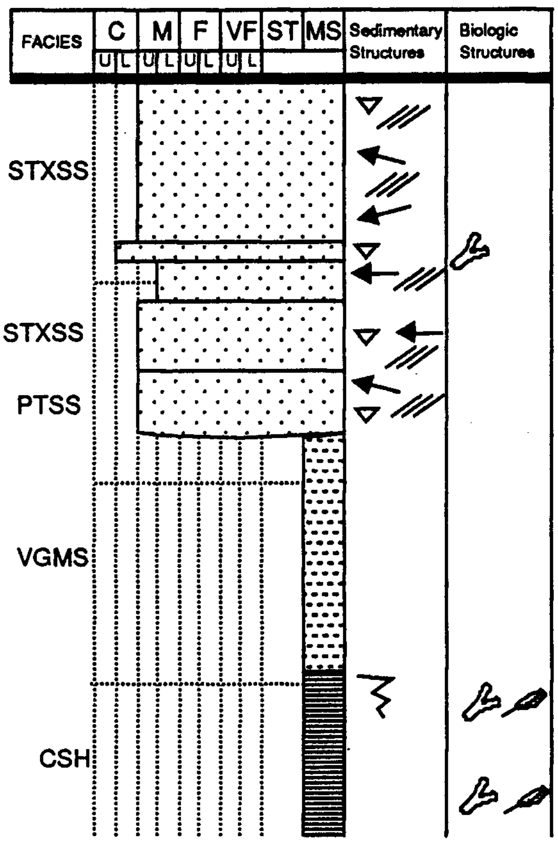
Section 4
T13S R10&11W sec 13&18 ne&nw
Dakota / Graneros @ 1638
FACIES
C
M
F
VF
ST
MS
U L U L U L U L
Sedimentary Structures
Biologic Structures
pl sk
STXSS
GSH
FESS
Fe
GSH
SS
HRLSS
VGMS/CSH
STXSS / VGMS
STXSS
LTXSS


Section 5
T16S R7W sec 1 se sw
top @ 1610', base @ 1500'
FACIES
C
M
F
VF
ST
MS
U L U L U L U L
Sedimentary Structures
Biologic Structures
FESS
LTXSS
LTXSS
GMS
CSH
ST
SS/SH
VGMS
HRLSS
ST
STXSS
C
VGMS
ST
STXSS
CSS/SH
STXSS
CSS/SH
HRLSS
FESS
CSH
ST
C

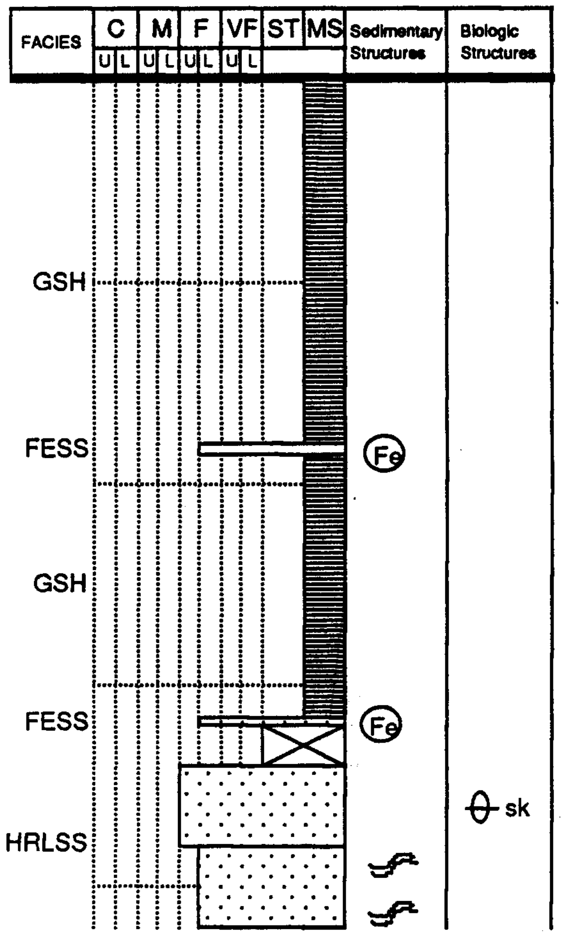
Section 6
T17S R8W sec4 ne se
base @ 1640'



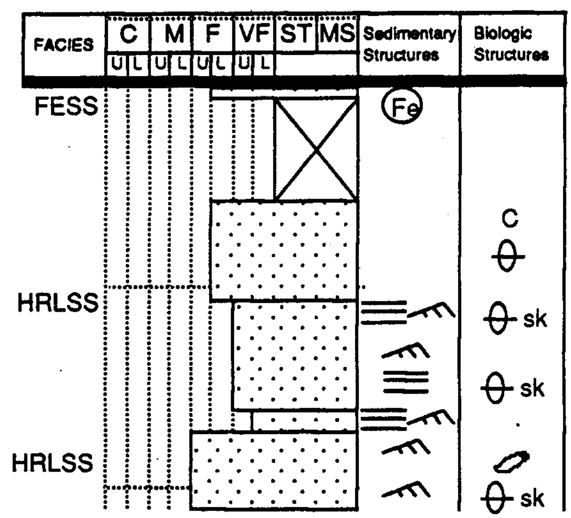
Section 7
T13S R5W sec 33 ne se se
base elevation 1450'



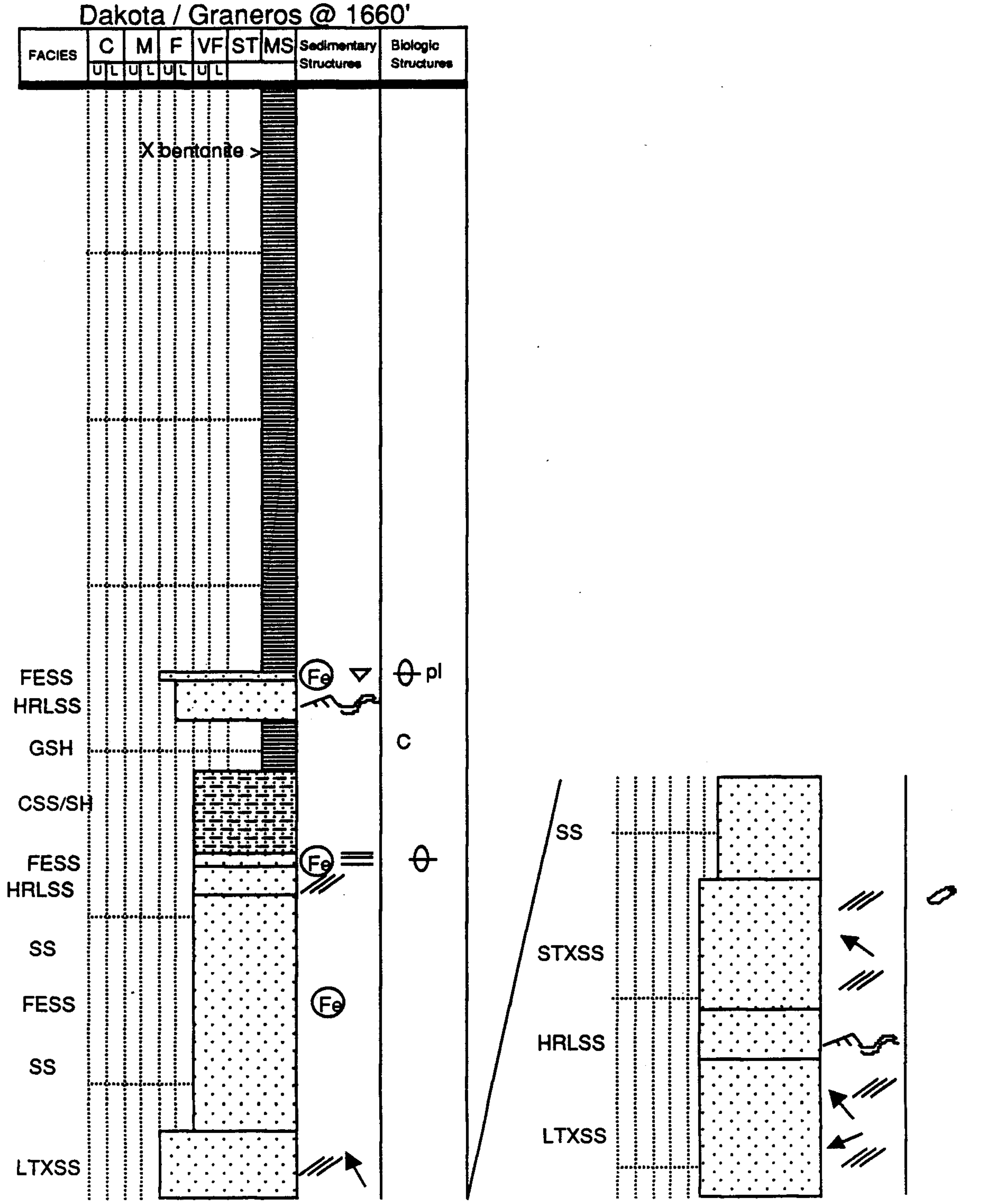
Section 8-2 Salt Marsh
T12S R15W sec 14 ne se ne
Dakota / Graneros @ 1664'



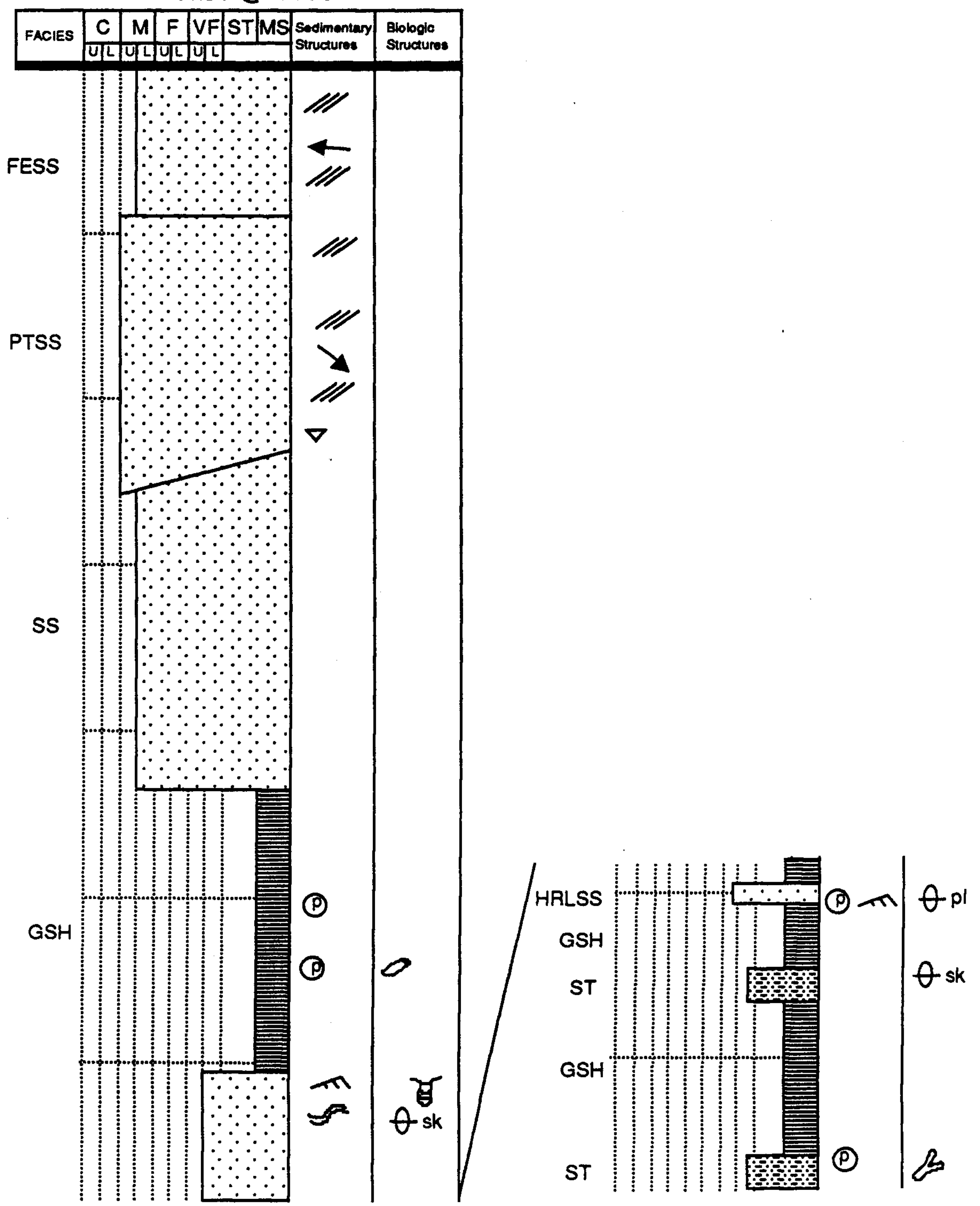
Section 8-3 Salt Marsh
T12S R15W sec 14 ne se ne
Dakota / Graneros @ 1664'



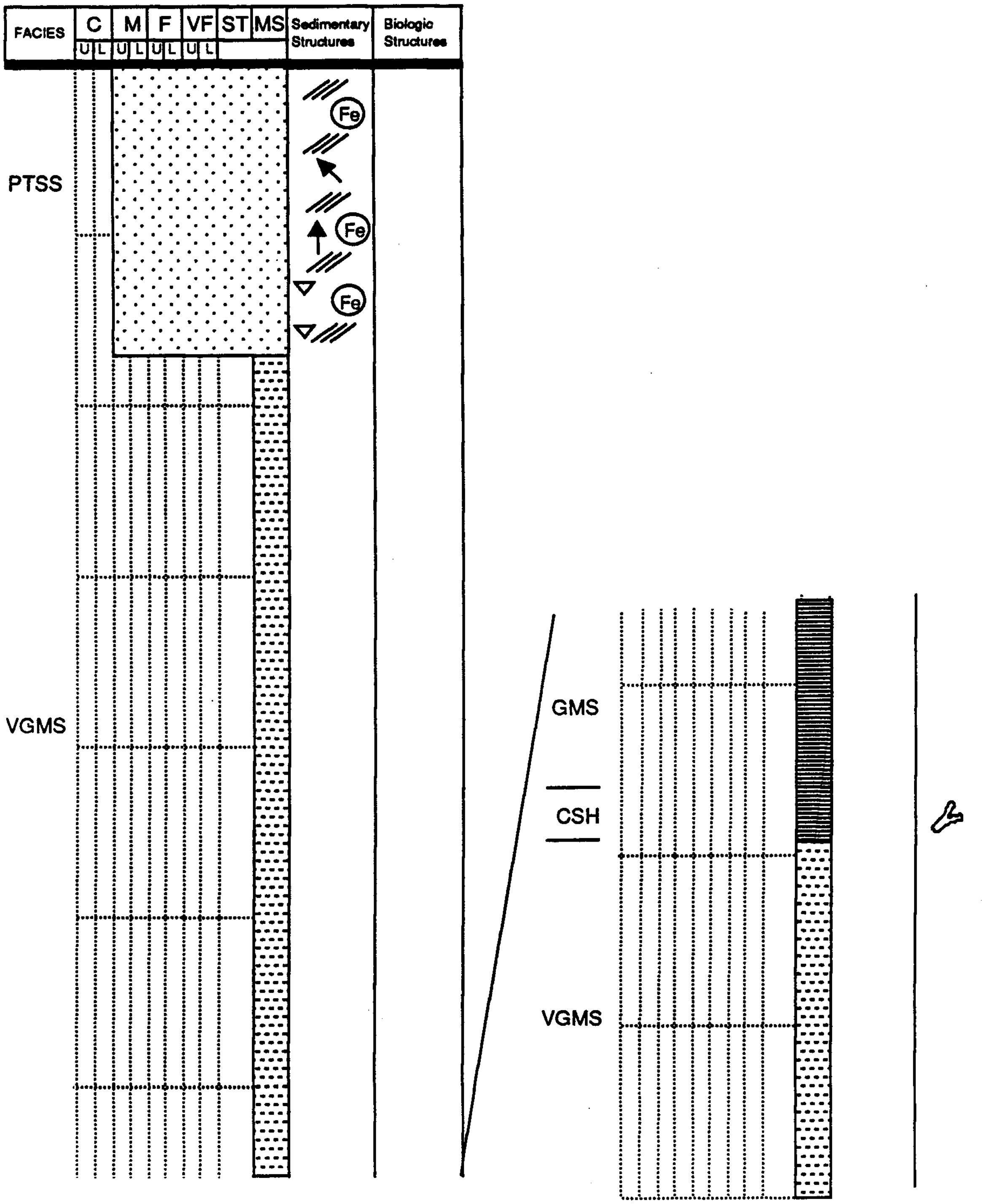
Section 9
T13S R12W sec 7 s/2 nw nw
Dakota / Graneros @ 1660'



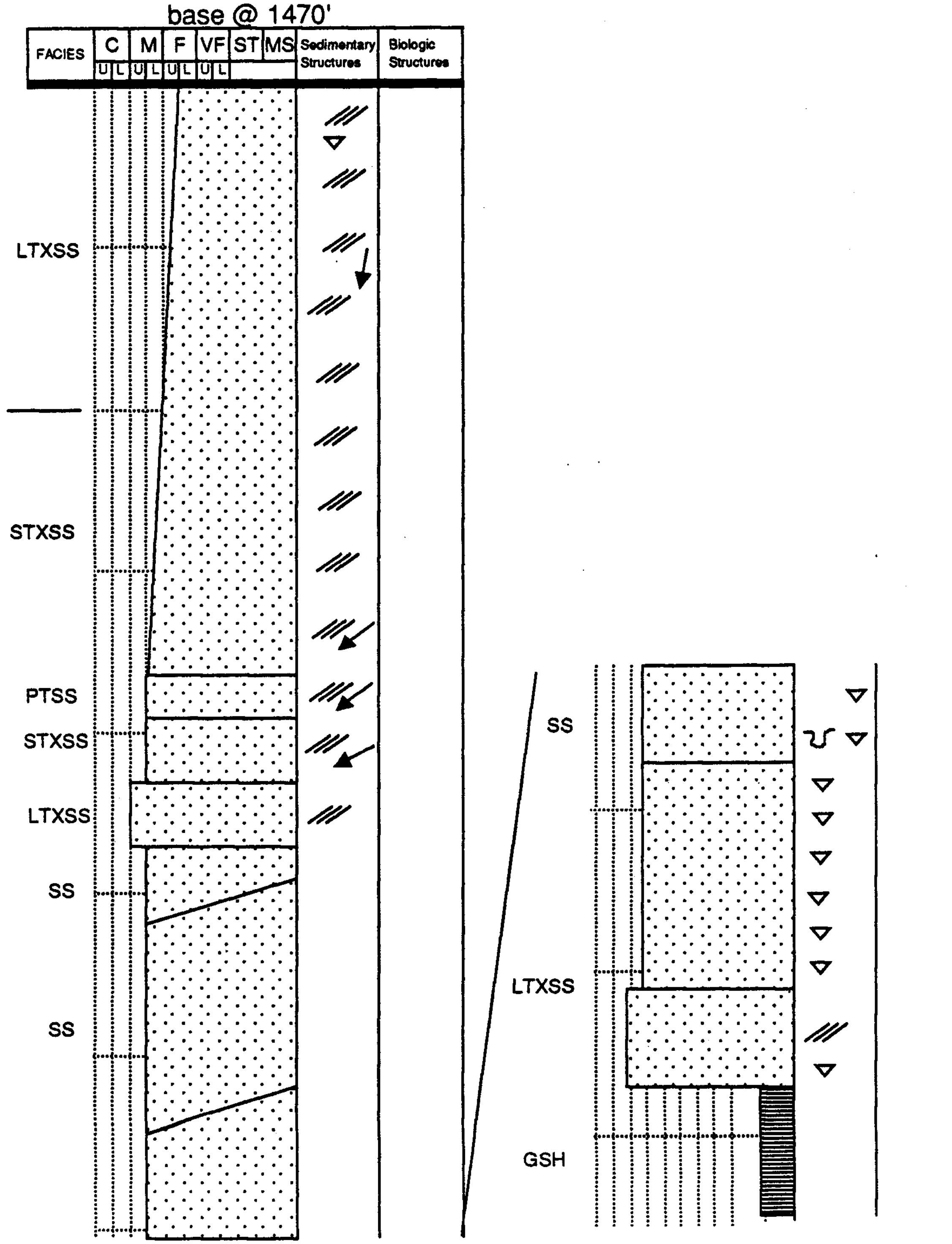
Section 10
T 12S R2W sec 18/19 c s1/2 / n/2
base @ 1206'

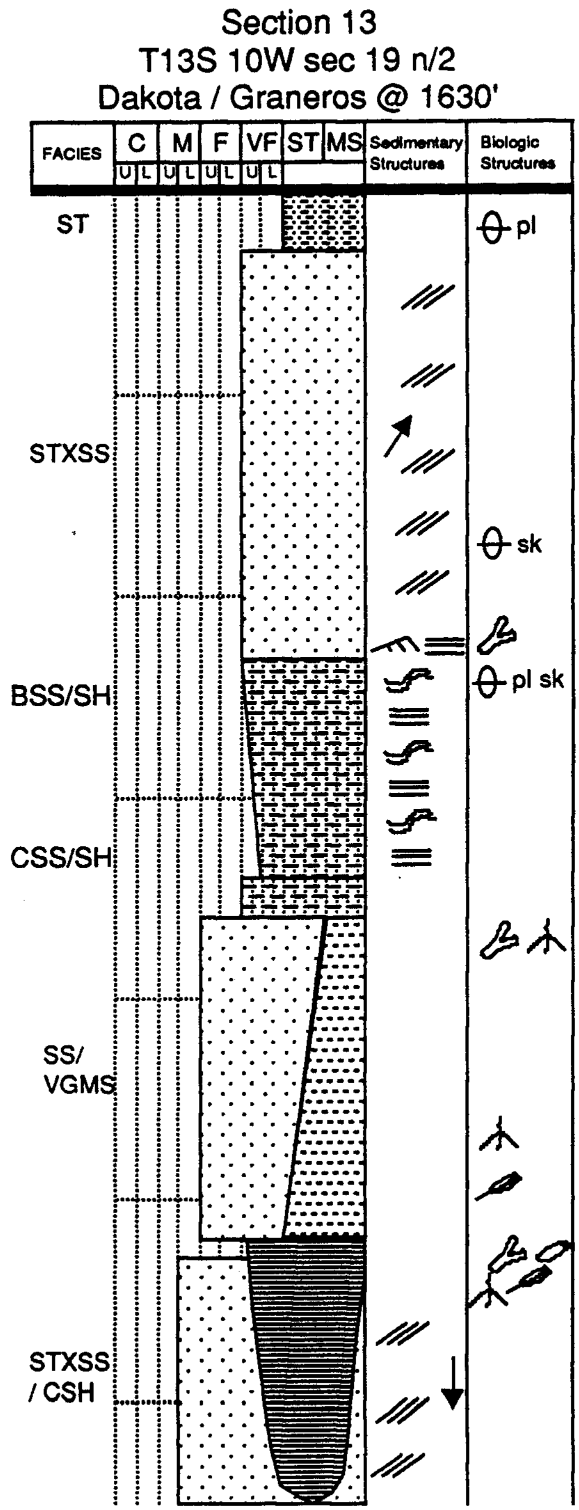


SECTION 11
T11S R4W sec 26 ne nw nw
base @ 1270'



Section 12
T16S R6W sec 8 sw sw se
base @ 1470'




Section 13
T13S 10W sec 19 n/2
Dakota / Graneros @ 1630'
FACIES
C
M
F
VF
ST
MS
U L U L U L U L
Sedimentary Structures
Biologic Structures
ST
STXSS
BSS/SH
CSS/SH
SS/ VGMS
STXSS / CSH
pl
sk
pl sk

APPENDIX B:

WELL LOG INFORMATION

Cross Section X-X'														
Well name	Section	Twnshp	Range	KB elev.	next well	top elevations								
		South	West	ft	in miles	Graneros	Dakota	Hunt.	J ss	J2	Kiowa	Long.	Chey.	Jur.
Wagner #1	5 c sw sw	2	40	3523		1245	1128	1053	1038	963	843	753	633	506
Pugh #1	30 c se ne	2	39	3231	6.5	1341	1231	1148	1138	1041	931	821	691	591
Beaumeister #1	31 c se nw	2	39	3266	1.5	1354	1232		1130	1077	951	846		
Anderson #1	28 c sw nw	4	39	3514	10.5	1494	1384	1329	1289	1206	1099	974	888	807
Neitzel #1	3 c nw ne	5	39	3516	2.5	1446	1336	1286	1261	1146	1056	946	846	806
Rudder #1	29 c sw sw	5	39	3529	5	1484	1371	1324	1294	1194	1119	979	899	869
Hevner #1	12 c nw se	8	40	3678	9	1626	1483			1353	1298	1163	1078	1024
Philbrick #1	16 c sw nw	9	40	3765	7	1899	1757		1670	1605	1537	1425	1355	1315
Goodland #1	7 sw se sw	10	39	3643	7	1943	1813		1743	1653	1573	1431	1378	1343
Stover #1	7 c ne ne	12	40	3723	13.5	2018	1880		1843	1718	1626	1530	1454	1440
Finley #1	13 c ne se	13	40	3417	9	2097	1962		1890	1790	1707	1602	1557	1527
Warledge #1	21 c sw nw	14	40	3724	7.5	2369	2224		2166	2069	2024	1901	1871	1829
Clark-Mobil #1	27 c ne ne	15	41	3748	8	2488	2348		2268	2188	2148	2033	1988	1938
Clift #1	17 c se	17	40	3646	11	2676	2541		2441	2383	2326	2216	2166	2116
Teichmann #1	33 c sw sw	17	40	3626	3	2676	2541		2483	2401	2362	2226	2194	2146
Byerly #1	2 c sw sw	18	40	3568	2.3	2691	2568		2478	2413	2343	2241	2198	2163
Fecht #1	3 c ne sw	19	40	3586	6	2756	2626		2566	2461	2411	2316		2281
Householder #1	29 c se	20	40	3600	10	2885	2760			2600	2543	2465	2455	2440
B. Grilliot #1	18 c se nw	21	40	3591	4	2930	2802		2731	2661	2621	2511	2486	2456
Dikeman #1	22 c ne sw	21	40	3550	3	2925	2820		2730	2645	2600	2508	2480	2457
P.C. Frazee #1	28 c se nw	22	40	3514	6.5	3094	2974		2889	2824	2734	2679	2644	2624
Maxfield #1	1 c n/2 s/2	23	41	3489	3.5	3163	3034		2967	2909	2845	2749	2724	2700
Raney #1	10 c se nw	25	41	3475	13	3305	3165		3105	3061	2983	2899	2875	2861

Cross Section Z-Z'												
Well name	Section	Twnshp	Range	KB elev.	next well	top elevations						
		South	West	ft	in miles	Graneros	Dakota	D unc.	Kiowa	Long.	Chey.	Perm/Jur
	2 sw sw se	12	13	1761	10	1676	1651	1421				1351
Weilert #1	6 c sw se	12	14	1715	3			1455		1383		1335
Foster #1	10 sw sw se	12	15	1639	9.5			1486		1397		1319
	16 se ne nw	12	16	1901	0.5	1721	1681	1481		1401		1321
Hall #1	1 nw ne ne	12	17	2104	4	1694	1655	1462		1379		1264
Schmeidler #1	16 sw se se	12	17	2142	3.5	1742	1703	1520		1414		1317
	12 se ne se	12	18	2176	3.5	1726	1694	1471		1361		1276
K. State #1	9 se sw nw	12	18	2181	6.5	1691	1651	1441		1294	1221	1191
Spreen No. 1	8 ne ne ne	12	19	2117	6	1737	1707	1555		1417	1367	1347
Nicholson #1	21 sw sw sw	12	20	2205	2	1745	1705	1593	1435	1385	1305	1295
Mal #1	18 sw nw sw	12	20	2303	2.5	1735	1695	1573	1413	1363	1313	1283
Elsie Hurt No. 2	15 se ne se	12	21	2289	6	1724	1680	1599	1413	1349	1289	1271
	26 nw sw sw	12	22	2353	3	1803	1753	1653	1483	1423	1328	1288
	5 se se	13	22	2300	9	1780	1735	1580		1420	1320	1235
Folkers "A" #1	31 sw sw sw	13	23	2353	2	1863	1821	1683		1493	1428	1408
Schneider#1	35 c sw nw	13	24	2354	6.5	1854	1812	1664		1494	1404	1384
	23 c sw nw	13	25	2457	6.5	1795	1747	1627	1497	1372	1337	1307
Herl "E" No. 1	34 c sw ne	13	26	2455	6.5	1795	1745	1655	1485	1350	1315	1265
Coberly No. 1	15 c se se	13	27	2470	5.5	1810	1765	1650	1470	1343	1306	1207
Roberts No. 1	23 c ne sw	13	28	2695	5	1840	1790	1628	1530	1355	1295	1225
Earl Johnson #1	25 c ne se	13	29	2728	6.5	1858	1798	1653	1538	1348	1318	1243
Moore "L" No. 1	25 c ne nw	13	30	2866	14	1926	1866	1724	1596	1434	1376	1161
Cunningham #1	27 c nw nw	13	32	3033	9.5	1853	1783	1675	1493	1358	1318	1228
Wieland No. 1	19 c se sw	13	33	2918	5	2023	1943	1858	1618	1523	1465	1368
Molby #1-A	17 c se sw	13	34	3002	5	2012	1930	1834	1597	1513	1472	1432
Nye No. 1	4 ne ne ne	13	35	3074	7	2064	1974	1842	1654	1564	1523	1444
Hanson No. 1	28 se se se	13	36	3118	8	2128	2033	1945	1788	1673	1608	1558
Surratt "D"No.1	6 nw nw nw	14	37	3318	5.5	2168	2048	1983	1803	1705	1648	1608
Pearce No.1	18 c ne ne	14	38	3559	3	2334	2209	2146	1959	1859	1809	1759
Jennings #1	2 c ne ne	14	39	3368	6	2258	2130	2078	1848	1764	1708	1673
Finley #1	13 c ne se	13	40	3417	8	2097	1962	1887	1707	1587	1557	1527
Pearce #1	2 c ne se	14	41	3634	10	2129	1984	1909	1789	1674	1644	1604
N.D. Sexson "A"	29 se se nw	13	42	3878	1.5	2291	2138	2064	1968	1838	1815	1765
Alvord No. 1	24 nw se ne	13	43	3821		2361	2206	2121	2021	1931	1911	1861

Cross Section N-N'													
Well name	Section	Twnshp	Range	KB elev.	next well	top elevations							
		South	West	ft	in miles	Graneros	Dakota	D unc.	Kiowa	Long.	Chey.	Perm.	Cedar Hills
Robbins Unit #1	6 c nw	31	16	2033	7				2033		1973	1913	1663
Rice No. 1-1	2 c se se	30	17	2022	5				2022		1911	1842	1622
Rezeau No. 1	27 ne ne ne	29	16	1989	3				1989		1919	1889	1649
Pyle No. 1	10 c ne nw	29	16	1935	5				1915		1805	1765	1555
Smitherman No. 1	16 sw nw	28	16	2160	2				2011		1870	1820	1650
Binord "A" #1	4 c ne nw	28	16	2136	4				1966		1876	1813	1666
Warren No. 1	16 c nw nw	27	16	2102	2				1972		1857	1814	1622
Jewett No. 1	4 c nw ne	27	16	2104	2.5				1834		1794	1764	1554
Schultz No. 2	21 se se sw	26	16	2111	2.5				1841		1816	1771	1581
R. A. Parker No. 1	9 ne sw nw	26	16	2083	4.5				1853		1783	1708	1573
Kearns No. 2	23 sw sw se	25	16	2061	5				1871		1796	1736	1551
Enlow #3	25 c nw se	24	16	2071	4.5				1881		1761	1728	1521
Rudd Estate #1	16 ne sw nw	24	16	2086	2				1933		1766	1736	1521
Doll #1	5 c ne	24	16	2083	3.5		1983		1878		1758	1693	1533
Horton #1	16 ne sw sw	23	16	2054	3		1994		1891		1774	1704	1544
Windmill No. 1	32 sw sw sw	22	16	2060	7		1938		1870		1760	1690	1530
Minor #1	25 nw ne se	21	17	2050	5		2050		1840		1730	1682	1600
Glaze No. 1	15 se se ne	21	16	1983	3.5		1903		1813		1673	1637	1593
G. Bradley No. 1-35	35 nw ne nw	20	16	2008	4				1745		1647	1617	1598
M. Smith #1	7 nw sw nw	20	15	2034	6				1764		1694	1674	1634
Russell #1	14 nw ne nw	19	15	1954	5.5				1744			1599	
Jilg No. 1	14 se se sw	18	15	1923	7	1923	1885	1793	1643			1523	
Max Mater #5	11 nw nw sw	17	15	1956	0.5	1906	1876	1750	1586			1496	
E. Mater #1	11 ne nw sw	17	15	1939	4	1899	1869	1739	1584			1489	
Hewy #1	23 se ne se	16	15	1985	2	1855	1818	1665	1545			1465	
No. B-1 Karst	11 nw se se	16	15	1958	3.5	1868	1838	1683	1578			1448	
Wegele #1	32 sw nw se	15	15	1933	4.5	1843	1813	1727	1568			1443	
Poleyn #1	10 se se se	15	15	1752	5.5		1752	1616	1530			1422	
Polcyn D-7	14 se ne nw	14	15	1850	1	1770	1750	1550	1470			1390	
Mills #3	12 ne ne sw	14	15	1852	5			1557	1462			1398	
No. 1 Brunghardt	14 c se sw	13	15	1829	1	1739	1709	1569	1429			1357	
Bicker No. 1	13 ne nw sw	13	15	1819	5.5	1729	1709	1569	1399			1319	
Rogg #1	31 sw se se	12	15	1864	10.5	1742	1704	1619	1494			1334	
Cook No. 3	9 se se nw	11	15	1973	7.5	1683	1653	1539		1351		1313	
O'leary "A" No. 1	34 e/2 ne se	10	16	2034	10	1654	1616	1484		1256		1232	
Sarver No. 2	12 sw sw sw	9	16	2065	2	1575	1535	1444		1275		1165	
McFadden "D" No. 1	3 c se sw	9	16	2002	1.5	1529	1497	1374		1222		1087	
Adams "B" No. 1	33 c ne ne	8	16	1911	7	1551	1511	1391		1231		1121	
Jones "B" No. 2	28 nw se ne	7	16		8.5								
N.G. Riffel #2	31 se ne se	6	17	1934	14	1509	1474	1314		1169		1074	
Selbe #2	19 c sw sw	4	17	1780		1385	1358	1150		1045		960	

Map well log data																
Well name	Section	Twnshp	Range	KB	Top elevations											
		South	West	elev. ft.	Graneros	Dakota	Long.	Pch	Psp	Psc	1 Kd ss	2 Kd ss	2 Kd ss	D unc	D basal ss	Chey.
												top	base		top	
Anschutz D #1	5 se se sw	11	14	1795	1625	1595	1340	1247	1190	874	1350			1415	1430	1252
Thompson #1	7 se nw se	11	14	1695		1601	1314	1250	1205	883	1322	1385	1368	1435	1460	
Archer #1	14 nw sw nw	11	14	1757	1617	1597	1379	1272	1193	887	1419					
Chrisler-Roda #1	19 sw nw ne	11	14	1793	1631	1600	1363	1253	1203	886	1363			1433	1520	1263
Fowler #1	20 se sw se	11	14	1789	1635	1609	1359	1274	1189	889	1359					
Terry #1	26 nw nw se	11	14	1649		1608	1378	1304	1229	925	1409			1467	1477	1309
Weeks #1	27 ne sw sw	11	14	1743	1638	1609	1403	1313	1223	921	1439					
Bar S Ranch B #1	28 sw se se	11	14	1822	1654	1625	1420	1322	1232	930	1459					1335
Strecker A #4	29 sw ne nw	11	14	1796	1638	1613	1398	1296	1206	904	1404					
Strecker A #3	29 s2 nw nw	11	14	1827	1624	1597	1357	1267	1207	900	1371					
Stielow #1	33 se ne ne	11	14	1787	1637	1609	1389	1298	1227	929	1425					1317
Fuller #2	34 ne ne se	11	14	1726	1654	1624	1388	1316	1234	930	1453					
Chrisler B #7-7	7 ne ne sw	11	15	1902	1652	1612	1339	1242	1127	842	1417			1422	1482	1250
Cook #3	9 se se nw	11	15	1973	1683	1662	1348	1303	1213	923	1387			1473	1483	
Reich C #2	15 sw ne sw	11	15	1845	1670	1644	1383	1309	1215	920						
Reich C-2	21 nw nw se	11	15	1869	1709	1682	1409	1309	1219	931	1419	1469	1446	1505	1551	
Eulert C #2	26 nw nw sw	11	15	1847	1690	1649	1397	1287	1217	915		1457	1432			1313
Abbott #2	32 nw sw ne	11	15	1841	1729	1699	1431	1321	1241	953	1445	1486	1471	1559	1591	1348
Thurston #1	18 sw-se-nw	11	16	1797	1672	1637	1297	1229	1087	817	1355			1492	1507	1240
Potter #1	21 sw ne sw	11	16	1788	1668	1630	1348	1255	1118	835	1398					1263
Chrisler #1	25 ne nw nw	11	16	1776	1671	1646	1371	1238	1146	844	1461					1276
Shaw #1	26 ne ne ne	11	16	1756	1668	1646	1363	1243	1136	848	1450					1273
Bowlby #1	27 nw se se	11	16	1765	1687	1657	1357	1273	1145	850	1450			1525		1282
Nielsen #5	28 sw sw nw	11	16	1760	1666	1633	1371	1261	1115	823	1401					1275
Chrisler #1	33 nw se se	11	16	1839	1695	1654	1398	1257	1134	832	1464					1301
Chrisler #1	34 sw sw se	11	16	1835	1683	1650	1390	1260	1135	835	1410					1295
Bar S Ranch #2	4 nw ne nw	12	14	1785	1648	1619	1375	1303	1235	925	1402					
Roda B #1	5 se nw se	12	14	1800	1658	1630	1410	1320	1268	943	1450			1515	1545	
Weilert #1	6 c sw se	12	14	1715			1390	1285	1255	935	1340					
Roda A #1	7 sw sw se	12	14	1710	1680	1660	1360	1290	1240	933	1478					1310
Steckel E #2	17 nw sw ne	12	14	1623			1383	1303	1233	936	1413					
Mellard #1	18 c nw se	12	14	1634			1384	1309	1254	929	1444	1474	1464			
Becker O #1	21 se sw ne	12	14	1776	1676	1650	1356	1291	1246	941	1396			1501	1526	
#1 Hopper	28 sw se	12	14	1601			1376	1296	1256	966						
Newman B #1	1 ne sw nw	12	15	1788	1688	1662	1326	1252	1228	936	1375	1448	1388	1518	1533	1261
Oswald #11	8 c se sw	12	15	1858	1766	1733	1438	1348	1268	970	1512			1583	1598	
Oswald #25	8 sw se nw	12	15	1840	1760	1728	1450	1355	1275	985	1466	1522	1472	1590		
Sutton #3	9 se se sw	12	15	1819	1722	1691	1364	1294	1243	939	1394	1484	1411			1309

Foster #1	10 sw sw se	12	15	1642			1401	1304	1257	947	1419	1456	1429			1321
Newman Trust #1	13 nw sw nw	12	15	1642			1382	1292	1252	942		1312				1532
Haberer	14 ne se ne	12	15	1680	1700	1670	1372				1510					
Collins SWD	16	12	15	1792	1739	1708	1402	1302	1242	952	1532					1302
Kuha #1	17 ne nw se	12	15	1842	1747	1714	1431	1310	1252	962	1462	1522	1474	1586	1602	1322
O-W B #22	17 w/2 ne nw	12	15	1874	1739	1705	1429	1339	1264	972		1489	1446			
Rusch A #6	19 nw sw sw	12	15	1903	1748	1714	1390	1313	1242	938	1469					
Milke #1-20	20 nw nw sw	12	15	1887	1736	1703	1412	1317	1249	947	1444					
Schmeidler	22 sw	12	15	1814	1720	1688	1364	1284			1384	1468	1442	1566	1576	
Meckel #1	27 sw nw sw	12	15	1831	1712	1681	1419	1331	1243	941				1551	1573	1336
Meckel #1	29 ne sw sw	12	15	1871	1728	1699	1408	1318	1241	941		1481	1471			1331
Deckert #8A	30 ne ne nw	12	15	1892	1732	1702	1426	1332	1270	972	1462					1332
Rogg #1	31 sw se se	12	15	1864	1750	1718	1426	1324	1239	936		1510	1494			1330
Oswald B #1	2 se se nw	12	16	1809	1667	1641	1369	1291	1121	848						1297
Dreiling F #21	3 c sw ne	12	16	1777	1686	1657	1352	1237	1142	839				1479	1507	1247
Dreiling F #15	3 ne ne nw	12	16	1810	1677	1649	1350	1240	1140	840						1250
Chrisler 0	6 c se ne	12	16	1921	1701	1668	1351	1251	1131	833	1406	1460	1418	1528	1538	1266
Chrisler #1	9 nw nw ne	12	16	1847	1712	1672	1365	1275	1143	847	1377	1484	1477			1312
Dickenson # 1	10 nw sw nw	12	16	1857	1716	1683	1427	1292	1142	847	1507					1305
Oswald swd	11	12	16	1867	1703	1671	1373	1287	1145		1440					1293
Oswald D #4	11 sw sw nw	12	16	1849	1679	1654	1349	1269	1114	834		1429	1379	1509	1524	1279
Smith A #6	14 se nw sw	12	16	1900	1715	1686	1350	1265	1138	858	1362	1460	1404			1268
Dickenson #1	15 sw sw se	12	16	1910	1725	1694	1386	1270	1148	855	1460					1300
Dickenson #2-15	15 nw se nw	12	16	1855	1725	1695	1401	1280	1150	855	1454			1533	1565	1302
Chrisler #1	16 se ne nw	12	16	1901	1721	1686	1401	1291	1146	846	1501			1541		1321
Brunghardt C #1	19 se sw ne	12	16	2103	1733	1703	1418	1293	1143	853	1531					1318
# 1-20 Burgardt	20 nw nw sw	12	16	2122	1730	1693	1392	1272	1137	842	1499			1567	1585	1302
Chrisler #1	21 ne nw se	12	16	1971	1713	1680	1381	1267	1144	846	1479			1552	1565	1301
#4 Dreiling Q	23 se ne nw	12	16	1855	1705	1675	1345	1255	1165	855	1449					1280
Furth #2	26 sw ne nw	12	16	1920	1707	1680	1382	1264	1152	855	1420	1445	1429	1512	1540	1280
Furth #1	26 sw sw nw	12	16	2063	1711	1683	1383	1283	1163	860	1418			1503	1548	
Frolich E #8	27 nw ne se	12	16	1970	1712	1683	1380	1265	1155	855	1410	1460	1430	1515	1585	11275
Frolich E #10	27 nw se se	12	16	2027	1701	1666	1377	1274	1162	860	1432			1547	1587	
Dickenson #2	28 se sw nw	12	16	2055	1715	1678	1425	1270	1145	845	1460			1521	1559	1285
Miller #1	31 se se ne	12	16	2015	1725	1688	1405	1278	1145	845	1430	1475	1451	1535	1543	
Windholz #2	32 nw nw sw	12	16	2030	1725	1687	1405	1277	1160	866		1472	1457			1293
Klotz B #2	33 sw ne se	12	16	2023	1717	1686	1393	1268	1157	855						1287
Frolich A #5	34 ne nw nw	12	16	2071	1717	1685	1371	1261	1155	858	1437					1286
Sitz B #5	35 se se nw	12	16	1965	1697	1665	1385	1247	1140	840						1265
Mac #1	6 w/2 ne se	13	14	1610			1340	1272	1230	960		1450	1392	1470	1587	1292
Woelk #1	6 ne nw se	13	14	1606			1356	1276	1251	964		1446	1411	1496	1546	1306
Sellens A #1	12 nw sw nw	13	14	1649			1406	1322	1299	998	1517					1345
Mayers swd	15 nw nw sw	13	14	1800	1736	1708	1416	1350	1298		1422	1474	1431	1557	1599	

Boxberger #2	32 nw nw nw	13	14	1870			1432	1354	1270		1440					
Krug #1	1 se sw se	13	15	1793	1727	1697	1413	1333	1258	943	1470			1500	1541	1345
Mermis #1	4 sw ne sw	13	15	1838	1732	1692	1408	1318	1230	926	1476					
Dumler #1	5 ne sw sw	13	15	1853	1748	1714	1393	1298	1233	925	1421	1493	1440	1563	1573	
Mermis B #2	8 se ne se	13	15	1857	1743	1712	1435	1319								1329
Mermis #1-8	8 nw nw se	13	15	1859	1744	1713	1419	1309	1239	939				1543	1574	1324
Stoppel-Schant #1	12 sw ne se	13	15	1810	1725	1697	1425	1327	1264	958	1443					1350
Cassity #1	13 se sw nw	13	15	1813	1731	1707	1413	1313	1248	941	1473	1490	1478	1547	1578	1328
Bieker #1	13 ne nw sw	13	15	1819	1734	1707	1399	1319	1264	944	1459	1505	1484	1571	1594	
#1 Brunghardt	14 c se sw	13	15	1829	1739	1707	1429	1349	1229	944	1514			1569	1595	
Brungardt #1	15 se se se	13	15	1873	1745	1712	1436	1333	1233	928		1499	1451	1565	1583	1343
Nowak #2	18 nw nw ne	13	15	1895	1737	1705	1459	1375				1503	1490			1383
Polcyn D #1	19 c ne se	13	15	1881	1779	1746	1469	1381								1401
McConnell #2	21 nw se nw	13	15	1853	1748	1716	1443	1343	1253	958		1488	1478	1543	1555	1353
Kilian #1	24 c ne sw	13	15	1844	1747	1724	1419	1324	1254	944	1444	1524	1464	1569	1599	
Johnson C #1	26 w/2 w/2 nw	13	15	1901	1746	1716	1431	1339	1246	941	1456			1571	1593	1353
#1 Nowak G	30 sw sw sw	13	15	1927	1765	1734	1489	1377	1227	935	1512			1602	1615	
Mermis #1	32 sw sw ne	13	15	1905	1805	1772	1485	1360	1255	955		1575	1535	1612	1651	1400
Baxter swd	32 sw	13	15	1950	1858	1828	1560	1450				1634	1596	1670	1682	1464
Speer #3	32 sw nw nw	13	15	1903	1788	1757	1496	1383	1253			1567	1540	1606	1617	1393
Aley #1	33 s/2 sw nw	13	15	1906	1792	1766	1476	1366	1258	956						
Aley B #1	33 sw se nw	13	15	1901	1781	1753	1431	1351	1261	962						1361
Mai #5	34 nw ne se	13	15	1908	1763	1734	1448	1358	1258	958	1468					1378
Coady #1	34 sw se sw	13	15	1900	1782	1750	1478	1391						1596	1616	1395
Johnson #1	35 se sw sw	13	15	1904	1776	1746	1464	1386	1270	967	1482			1614	1676	1405
Johnson #3	35 sw nw sw	13	15	1902	1761	1732	1457	1352	1262	957	1477					1382
Patterson #2	36 nw nw sw	13	15	1886	1744	1716	1426	1356								1368
Boxberger #2	36 s/2 se se	13	15	1876	1764	1735	1456	1361	1288	981	1471					1376
Wieland B #1	1 nw nw ne	13	16	1863	1763	1731	1443	1333	1253	943	1459	1500	1483	1578	1591	
Weiland A #7	1 w/2 ne ne	13	16	1865	1755	1720	1445	1325	1255	955	1460			1545	1585	1330
Schmitt A #1	1 ne ne sw	13	16	1904	1749	1724	1442	1309	1234	968	1459	1511	1499	1562	1574	1329
Boxberger #2	2 sw nw se	13	16	1967	1725	1702	1377	1282	1177		1387	1489	1467			1297
Boxberger #3	2 sw se nw	13	16	1985	1722	1687	1385	1270	1175	880	1415			1525	1553	1306
Miller #1	3 se ne se	13	16	1991	1738	1708	1381	1281	1191	888	1391	1431	1416			1298
Froelich A #2	4 e/2 nw se	13	16	1994	1724	1689	1364	1274	1174	878						1294
Sanders #1	7 sw nw sw	13	16	2017	1756	1717	1385	1279	1147	857				1521	1612	1299
Weigel #1	8 c se ne	13	16	1965	1725	1694	1375	1275	1155	861	1392					1292
Windholz #2	9 ne se se	13	16	1977	1745	1713	1427	1331	1177		1445			1549	1559	
Windholz V-1	9 sw nw se	13	16	1973	1723	1698	1403	1273	1163	861	1453			1543	1548	1311
Frank #1	10 sw ne sw	13	16	1956	1746	1708	1431	1306	1176	844	1441					1330
Witt #2	10 ne nw nw	13	16	1868	1738	1698	1358	1278	1168	874				1514	1583	
Riedel #1	11 nw nw sw	13	16	1957	1747	1712	1392	1287	1187	893	1403					1318
Schmitt B #1	12 ne ne nw	13	16	1944	1774	1741	1444	1339	1234	939	1464	1512	1474	1582	1604	

Reidel #1	15 se se sw	13	16	1935	1725	1705	1440	1345	1175	875	1455					1362
Hammerschmitt #3	17 nw se se	13	16	1992	1750	1718	1404	1326	1166		1408					1334
Linte B #1	18 nw sw ne	13	16	1995	1740	1710	1435	1300	1155	855						
Larker #2	26 c nw sw	13	16	1936	1796	1762	1474	1386	1220	924				1610	1627	1398

T-3818 **Plate 1 Beaumeister core description and well log calibration**

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T-3818 **Plate 2 Haberer core description and well log calibration**

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T-3818 **Plate 3 Bounds core description and well log calibration**

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R. BOUNDS (Amoco well in western Kansas) se ne sec 17 T 18S R42W

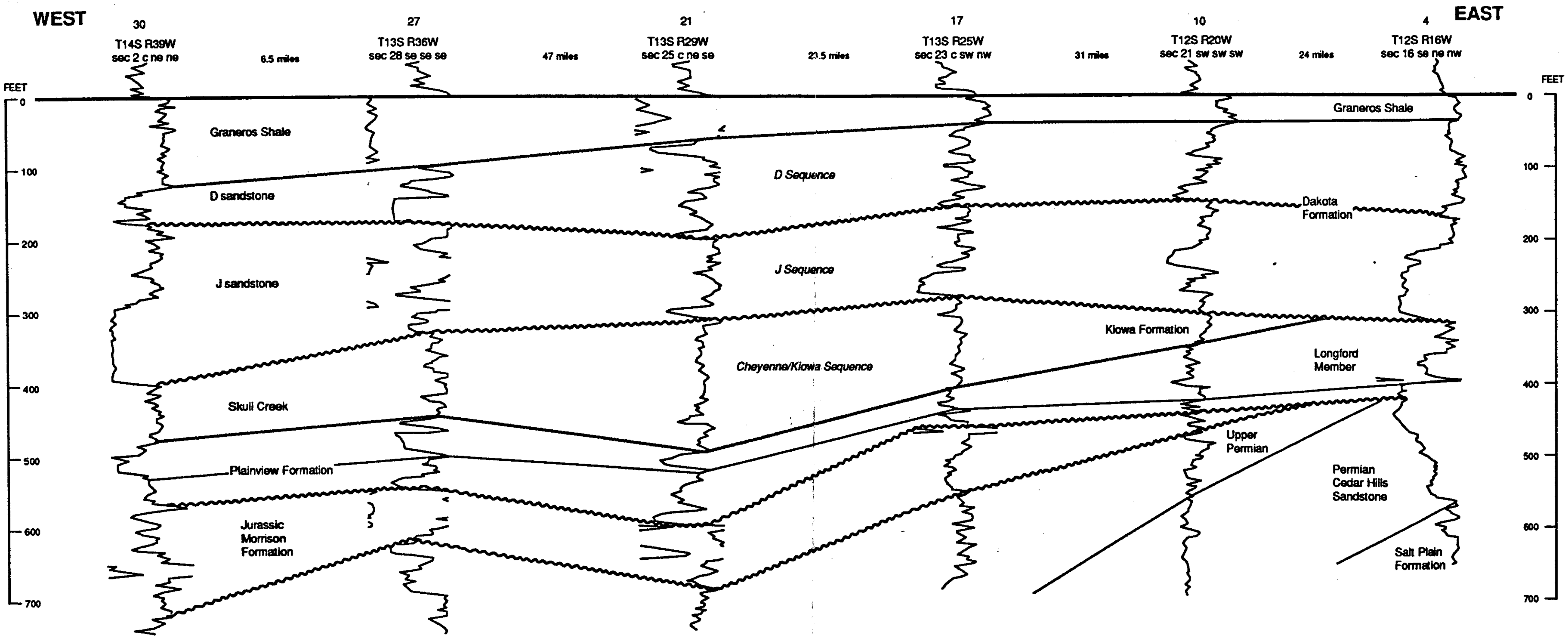

Plate 4 Representative gamma ray well log cross section Z-Z'

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