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STRUCTURAL AND TECTONIC STUDY OF THE CENTRAL WILLISTON BASIN,  
NORTHEAST MONTANA AND NORTHWEST NORTH DAKOTA

by

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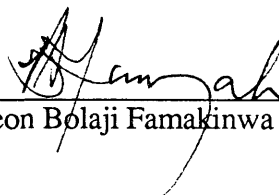
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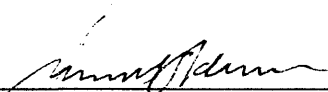
  
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## ABSTRACT

Detailed subsurface mapping of the central Williston basin utilizing over 3000 geophysical well logs documents various fault/fracture patterns and periods of major structural activities between the Paleozoic and Triassic. Major structural movements are documented in the Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Permian and Triassic. Good agreement between paleostructures interpreted from isopach maps and current structural elements indicates that recurrent structural movement of basement blocks along preexisting zones of weakness was the dominant style of deformation.

Geological and geomorphological evidence suggests that the Culbertson-Grenora, (C-G) feature identified in the study area as a northeast-trending anomaly may be part of the broad zone of the Brockton-Froid-Fromberg fault complex. Several fault blocks are documented along its trend. The modern rectilinear drainage pattern in the area coupled with the straightness of some of the streams, implies a fault-block tectonic control. In Montana, structural activity along the C-G trend controlled Prairie salt dissolution in the Prairie Evaporite.

The geologic development of the Nesson anticline was controlled mostly by recurrent structural movement on a mosaic of at least six fault-bounded blocks. The Beaver Lodge fault block is bounded to the west and east by northwest-trending West Nesson and East Nesson faults respectively. Temple fault block is to the north, and is bounded to the west and east also by northwest-trending West Temple and East Temple faults. The two fault blocks are separated by, and offset in the middle section by an intermediate Southwest Tioga block which is bounded to the north and south by northeast-trending faults. Structural movements of the fault blocks differed with time. Faults along the flanks of the Nesson anticline appear not to be straight and continuous as postulated by previous workers.

Rather, they are series of smaller dimension, northwest and northeast-trending faults, all of which may be genetically related.

Phanerozoic recurrent movement on these faults, and at least one episode of Absaroka structural reversal along the trace of the C-G feature and on the East Nesson fault on the Nesson anticline are documented.

Most of the oil and gas fields along the Nesson anticline are proximal to fault block boundaries instead of being centered on the blocks, a testimony to the influence of recurrent movement and fracturing in hydrocarbon accumulation. The increased current wave of horizontal drilling in the Bakken Formation by petroleum industry practitioners emphasizes the importance of fracturing in the creation of the Bakken reservoirs. The interpreted fault block model for the Nesson anticline in this thesis could thus be used as a predictive exploration tool for oil and gas occurrence.

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## INTRODUCTION

Through subsurface stratigraphic analysis of the Paleozoic and Mesozoic strata in the central portion of the Williston basin, northeast Montana and northwest North Dakota, recurrent structural movement on basement fault zones is demonstrated. The stratigraphic analysis consisted of identifying and correlating twenty-five formation tops from the Cretaceous Greenhorn Formation to the Ordovician Red River Formation from 3010 geophysical well logs in the primary study area and additional 95 well logs from Cow Creek/Weldon area in Montana. Isopach and structure maps of stratigraphic units as well as geologic cross sections were constructed in order to study the paleostructural history of the area and document any possible recurrent structural movement. This involved the analysis of stratigraphic thickness variations on the isopach maps and detailed stratigraphic cross sections prepared.

The Williston basin is a large intracratonic basin with a dominantly circular outline and an area of about 130,000 km<sup>2</sup> (Figure 1). The basin is bounded on the west by the Miles City Arch and the Bowdoin Dome, on the southwest by the Black Hills, on the southeast by the Transcontinental Arch and on the north side by the Canadian Shield. The basin contains several prominent structural features, notably the Nesson anticline, Cedar Creek anticline, Billings nose, Little Knife anticline, Poplar Dome and the Brockton-Froid-Fromberg fault zone. Structural trends of these features seem to follow three major directions, northeast-southwest, northwest-southeast and north-south.

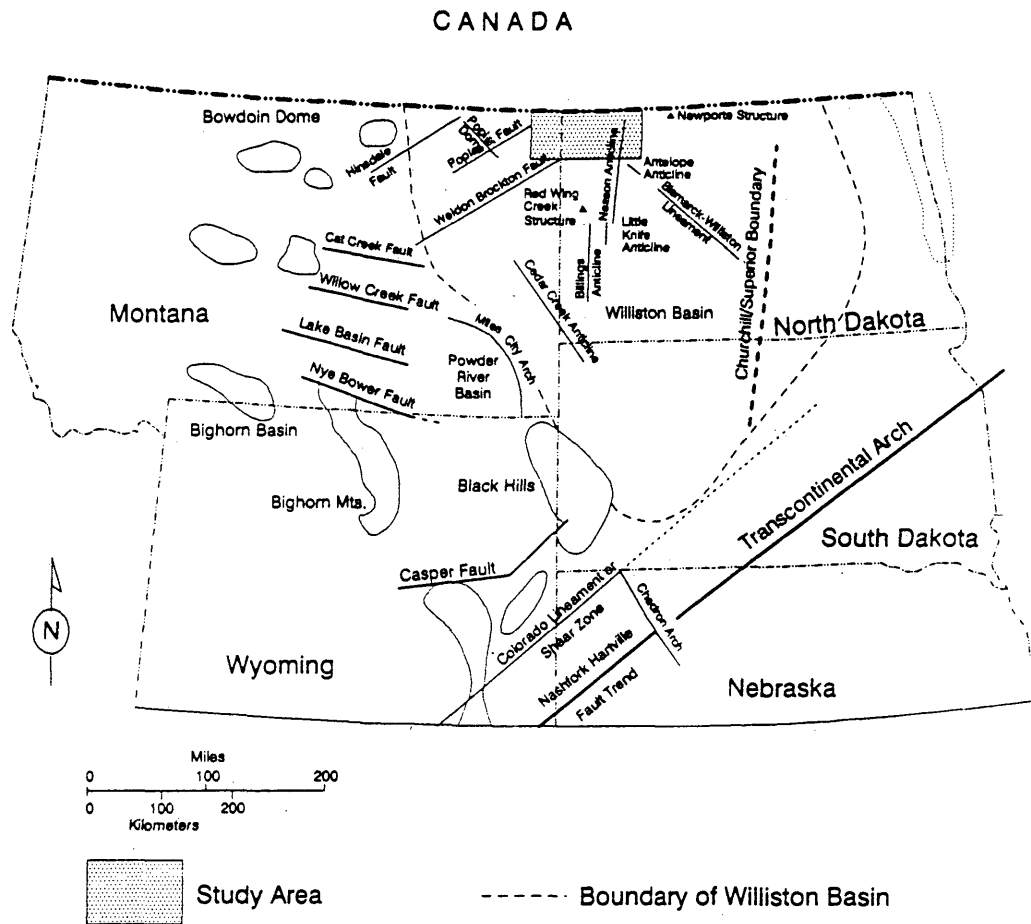


Fig. 1 Outline of the Williston basin showing major structural features and the study area (modified after Gerhard et al, 1986)

Isopach maps of the Devonian Prairie evaporite and Bakken to Charles interval were instrumental in identifying a northeast-trending anomaly referred to as the Culbertson-Grenora feature. The latter trends from the southwest portion of the study area in Culbertson, Roosevelt County, Montana (T27N, R57E) to the northeast around Grenora in western North Dakota, traversing a Prairie salt dissolution area in Shotgun Creek, Roosevelt County, Montana (Figure 2). Detailed stratigraphic cross sections constructed across the Culbertson-Grenora feature indicate episodic recurrent structural movement. The Culbertson-Grenora feature may be part of the Brockton-Froid-Fromberg fault system.

In the Nesson anticline area, a series of faults/fractures was interpreted from the trend and pattern of isopach maps. Closeness of contours or "tightening" was taken to indicate likely faulting. The Nesson anticline is bounded on both flanks by faults which are found not to be straight, long and continuous faults as postulated by past workers including Le Fever et al, (1987), but consist of northwest, northeast and east-trending faults intersecting at varying angles to form a mosaic of fault blocks along the structural trend.

The geologic development of the Nesson anticline was mostly controlled by recurrent structural movement on fault blocks, at least six of which are recognized in the study area. The fault blocks seem to have different and separate histories of movement. Not all fault blocks may have moved recurrently through time. Those blocks that moved stand a better chance of generating potential hydrocarbon accumulation. Recurrent movement along basement controlled fault blocks, usually propagate upward into the overlying sedimentary strata to create structures and control facies distribution and sedimentation processes. As a result, porosity distribution, hydrocarbon migration pathways and accumulation are influenced. Sediments which underwent recurrent movement along zones of weakness in

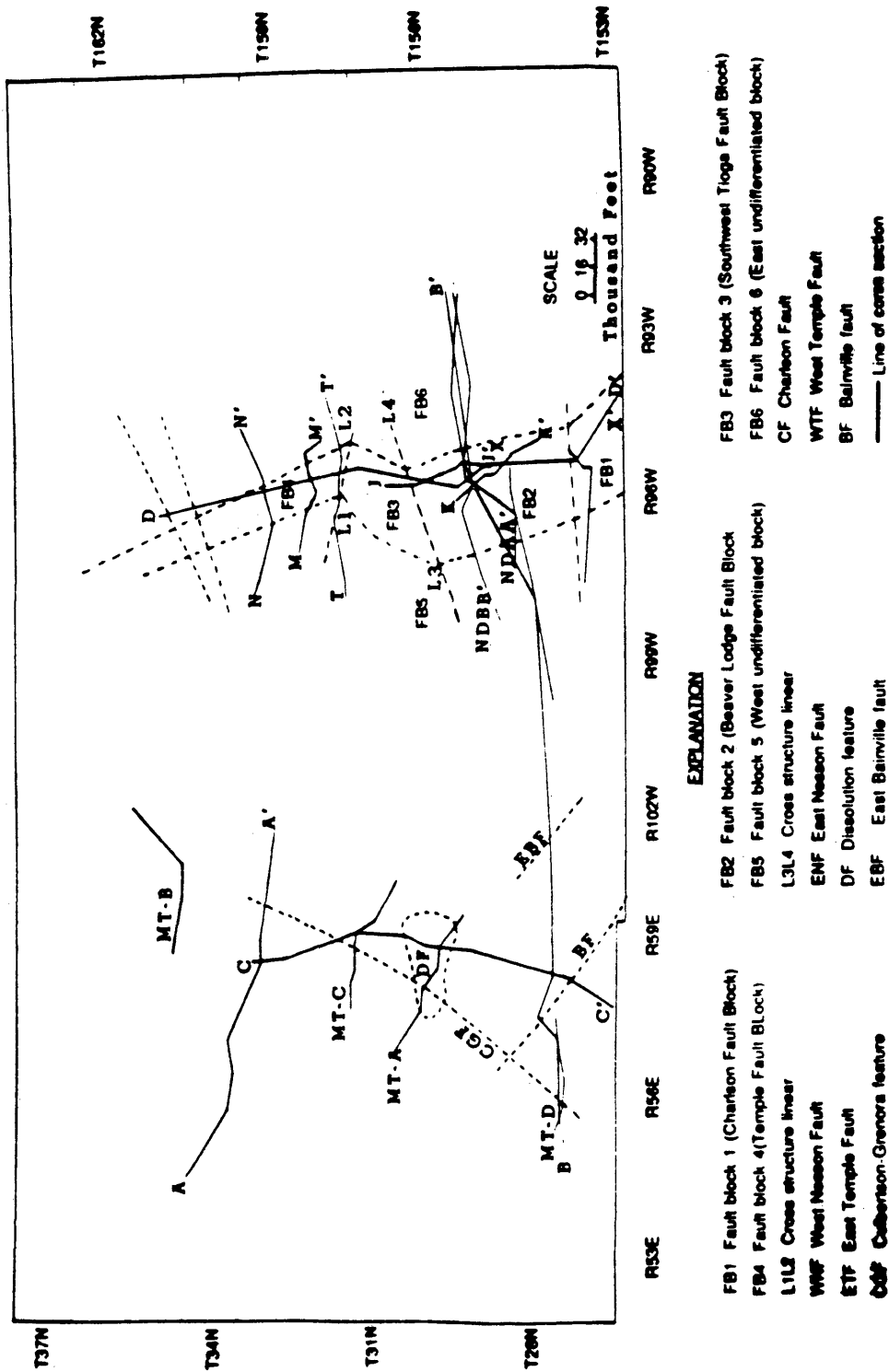


Fig 2. Index map of study area showing structural features and lines of section.

the basement will often display higher porosities and permeability, and consequently, greater reservoir potential than those which did not. This is due in part, to erosion, leaching and most importantly, dolomitization of sediments along the conduits created by block movement and within the displaced fault blocks. Migration of fluids necessary for dolomitization and leaching may occur along fractures formed by basement activity. These fractures also provide conduits along which hydrocarbons can migrate.

### *Purpose and Scope*

Weimer (1980) writes: "Recurrent movement on Precambrian-age basement fault systems has influenced the origin, thickness and distribution of Phanerozoic strata in Colorado and adjacent areas". Of the Powder River basin, Weimer et al (1982) write : "Recurrent movement of the basement fault blocks in the east-central Powder River basin has controlled thickness variations and the distribution of porous and permeable reservoir sandstones within the lower Cretaceous strata..". Gerhard et al (1982), said that the Nesson anticline was formed by the rejuvenation of Precambrian strain fields and that its sporadic structural growth throughout Phanerozoic has been controlled by movement on a major normal fault system on the west side of the anticline.

It is difficult to separate structure and sedimentation in basin analysis. Brown and Brown (1987), maintain that even though the deformational patterns in the Williston basin area reflect structural weaknesses in the Precambrian basement blocks, the jostling effect of these blocks on the broad Paleozoic shelf areas in the basin have been predominantly expressed as vertical movement along fracture zones. In a shallow basin, minor vertical movement can have a tremendous effect on depositional systems. Positive structural movement may be expressed in terms of thinning in the sediment package, subaerial

exposure phenomena and other physical sedimentary features associated with a shallow environment of deposition. On the other hand, subsidence of the same area is likely to cause that area to be covered with a relatively thicker sediment package because of the increased accommodational potential.

Documentation of the paleostructural history, various fault/fracture alignments and recurrent movement throughout Phanerozoic time is the major objective of this study. This was achieved by preparing and interpreting a series of isopach maps of stratigraphic intervals, from the Cretaceous Greenhorn to the Ordovician Red River Formation, structure contour maps of prominent stratigraphic horizons and several stratigraphic and structural cross sections, across the anomalous areas suspected to be involved in recurrent structural movement.

This study also set out to investigate the possible northern extension of the Brockton-Froid-Fromberg fault zone. The Brockton-Froid-Fromberg fault zone of as yet undetermined age (Gerhard, 1985, personal comm.), is a northeast-trending major fault system that extends from the southwest portion of Montana along the general trend of the Yellowstone River to the northeast. Parts of the system in Cow Creek/Weldon field area, Mc Cone County, Montana (T21-23N, R46-48E), have been studied and established by Hicks (1985). However, it remains to be verified how far north or northeast the feature extends. Gerhard et al, (1982) attribute the origin of the Williston basin to left-lateral movement on both the Brockton-Froid-Fromberg fault zone and the Colorado-Wyoming shear zone the south.

The sporadic structural growth throughout the Phanerozoic on the structural features may have been controlled by recurrent movements on their bounding faults. Stratigraphic



and porosity development in the overlying stratigraphic interval is presumably related to fault block movement.

### *Geographical Location*

The study area is located in the central part of the Williston basin at the northeast corner of Montana and northwest corner of North Dakota, incorporating townships T27 - 37N, ranges R52 - 59E in Montana, and T153 - 163N, R88 - 103W in North Dakota (Figure 3). A total area of over 9000 square miles is covered by the study utilizing over 3000 geophysical well logs. The following counties are covered: Sheridan, Richland and Roosevelt in Montana, and Williams, Burke, Divide and Mountrail in North Dakota.

### *Previous Investigations*

There is an appreciable volume of previous work generally related to the proposed study. However, these past works differed from one another in scope of study, specific area of investigation, methodology and resolution.

Very early work in the area was done by Chamberlain (1919) and Wilson (1936). In essence, these early works recognised some of the structural discordance of the region. Thomas (1974) identified prominent surface lineaments from photo geologic-photogeomorphic maps in the Williston basin and adjacent areas. He proposed a tectonic model which visualizes the lineaments as series of basement-weakness zones subdividing the crystalline basement into discrete blocks and representing a structural framework of Blood Creek and Williston basins. He also believed that the weakness zones defining the block framework adjusted laterally by simple shear to regional compressional forces during the Laramide orogeny.

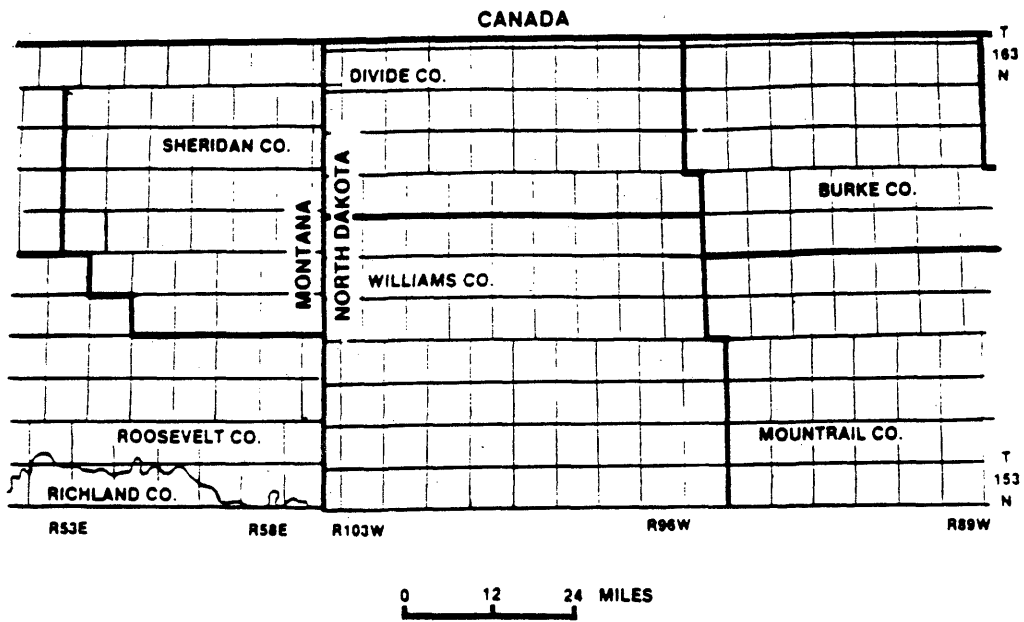


Fig.3 Geographic location of the study area showing townships, ranges and counties covered in North Dakota and Montana.

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Brown (1978) interpreted structural style and Paleozoic tectonic history from a series of isopach maps prepared for the southern portion of the Williston basin. He believed that the tectonostratigraphic framework is indicative of a wrench fault system in the area, although timing and sense of motion was not discussed. He also attempted to demonstrate the influence of basement tectonics on stratigraphic development in this area. Shurr (1978) used unenhanced satellite images to map lineaments in the western South Dakota portion of the Williston basin and tried to relate the lineament trend to Cretaceous facies patterns and potential gas occurrence.

Weimer and Sonnenberg (1981) mapped at least four paleostructural trends in the northern Denver basin and related the stratigraphic thinning in the Niobrara Formation and the distribution of the Cretaceous J Sandstone, to recurrent movement on basement fault systems. Sonnenberg(1981) concluded that both northwest and northeast -trending fault systems of Precambrian age are present in the Denver basin. He identified four major northeast-trending and three major northwest-trending paleostructures which had recurrent movements at various times during the Phanerozoic.

Gerhard et al (1982) theorized on the origin of the Williston basin by considering it as a downdropped block caught between two major left-lateral zones, the Brockton-Froid fault zone, and the Colorado- Wyoming shear zone of Archean or early Proterozoic age. Gerhard et al, (1982) suggested that tectonic movement of basement blocks along the Nesson anticline, near the center of the Williston basin, was caused by wrench faulting, and influenced Paleozoic deposition there. A similar relationship was described by Clement (1987) for the Cedar Creek anticline, which he claimed developed through recurrent tectonic movements along a northwest-striking fault zone. Clement documented

four major periods of tectonism in the Cedar Creek area from early Paleozoic to middle Tertiary time.

Gerhard (1987), recognized the significance of the West Nesson fault in the geological development of the Nesson anticline. Soeripto (1987), documented the paleostructural framework of the Williston basin using large rock packages for correlation and interpretation in an area adjacent to and slightly overlapping the current study area.

Kent (1987), studied the paleotectonic control on sedimentation in Saskatchewan in the northern part of Williston basin and concluded that the Mississippian strata are the first stratigraphic units to show a distinct relationship between facies distribution and present basin configuration. He also discussed salt solution collapse as a local structural control on sedimentation. LeFever, et al (1987), concluded from their study of the central and southern portions of the Nesson anticline that nine distinct areas (probable structural elements) exist on this part of the structure and that structural activity in each area was independent of the other areas.

#### *Data Base and Methods*

Over 3000 geophysical well logs from the study area were examined and 25 formation tops, from the Cretaceous Greenhorn Formation to the Ordovician Red River Formation, were picked for each well. Priority was given to the deep wells so that the earliest geologic history of the area could be understood. Distribution of wells within the basin is not uniform. Some areas have high well density while others have low density. In the former, only high quality, relatively new and deep wells were used, whereas, in the latter, one was constrained to utilize all available wells.

An additional suite of 95 well logs from Weldon-Cow Creek field area in McCone County, Montana (T21 - 22N, R46 - 48E), was examined and used to construct stratigraphic cross sections, structure and isopach maps.

Well data consisting of well name, kelly bushing (KB) elevation, formation name and top were entered into a database on computer. A Lotus 1-2-3 worksheet program was used to calculate stratal thickness and subsea depth values. The complete data set is stored on floppy diskettes and retained in the geology and geological engineering department library. All maps were hand contoured.

Because of the huge amount of plates accompanying the thesis, only a selected few considered most critical to the interpretation of data are enclosed in the pocket. Most of those not contained in the pocket are presented in the thesis as page-size figures. All plates, however are available on file in the department for detailed viewing.

A typical well log showing most of the formations used in the mapping, is shown in Figure 4. Depth to top of the following formations were recorded from each well log - Greenhorn, Dakota, Swift, Rierdon, Spearfish, Opeche, Minnelusa, Tyler, Otter, Kibbey, Charles, Mission Canyon, Lodgepole, Bakken, Three Forks, Nisku (Birdbear), Duperow, Souris River, Dawson Bay, Prairie, Winnipegosis, Elmpoint (Ashern), Interlake, Stonewall and Red River Formations.

Six isopach maps, of the Red River - Interlake, Prairie, Dawson Bay - Bakken, Bakken - Charles, Charles - Spearfish and Spearfish - Greenhorn intervals, were constructed in order to gain an understanding of the paleostructural history. Five additional isopach maps of thinner stratigraphic intervals, those of the tectonic-sensitive Devonian strata - Souris River, Duperow, Nisku, Three Forks and Bakken Formations, were also prepared so as to

Marvin-Iverson No. 22-18  
 Sec 18, T155N, R95W

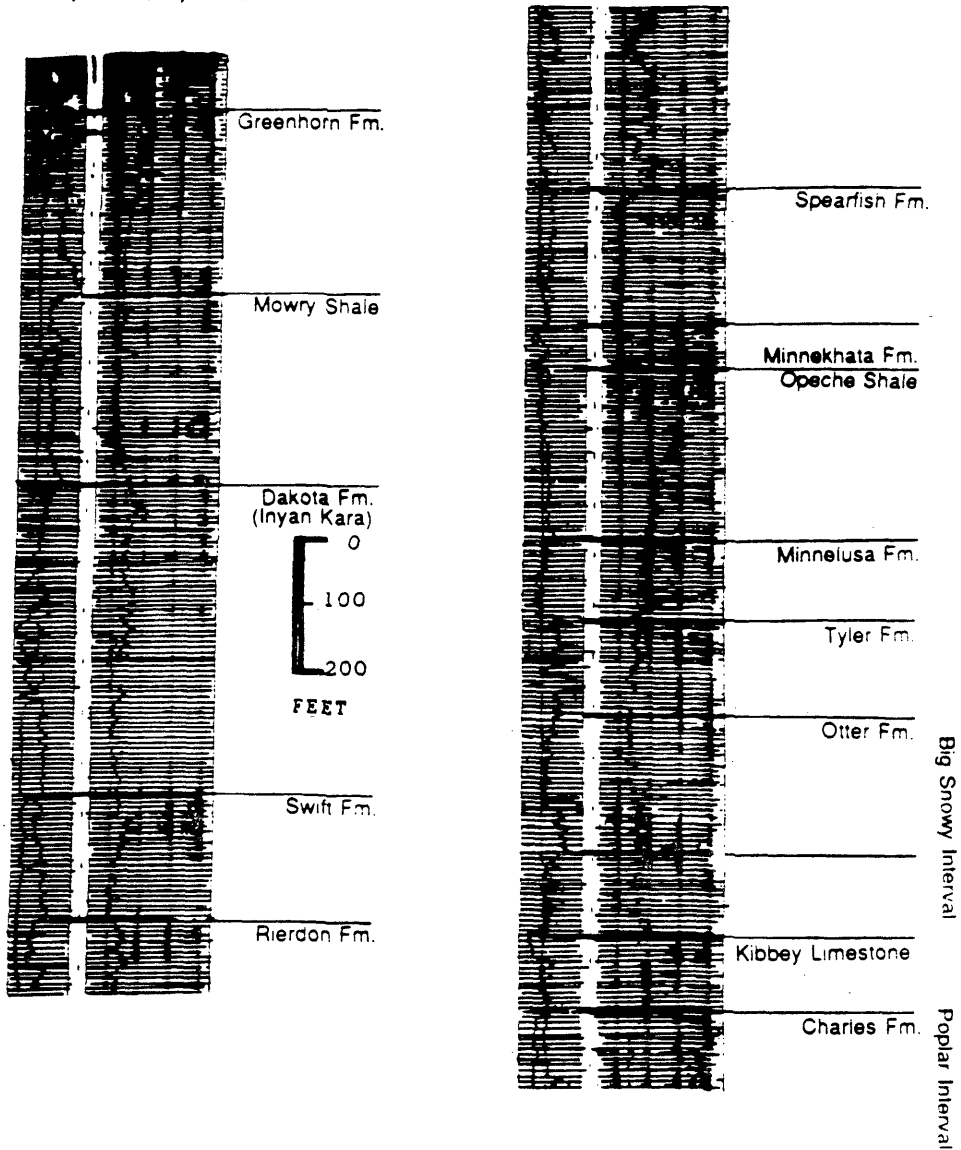


Fig. 4A Type log (Dual laterolog microfl) of the study area (upper section) from the Amerada Hess Marvin-Iverson No.22-18 well (18-155N-95W), Williams County, North Dakota

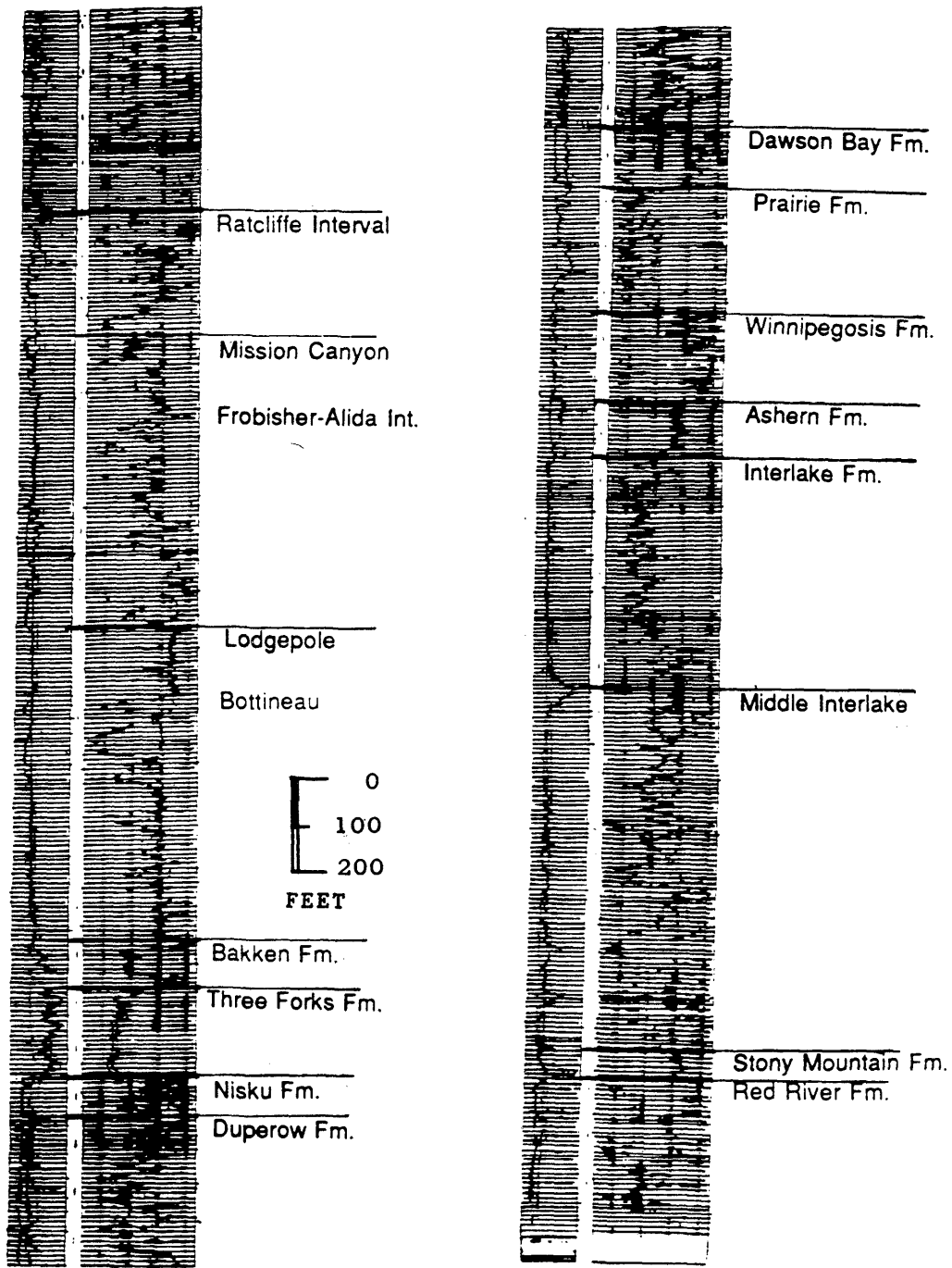


Fig. 4B. Type log of the study area (lower section) ... contd from previous page

better define the fault/fracture alignments and refine the paleostructural history of the area. The Prairie evaporite was mapped separately because of its anomalous thinning and thickening characteristics. It would then be possible to see if local abrupt thins and thicks show any relationship to the paleostructural trends identified on the maps. Structure contour maps were drawn on tops of four key stratigraphic horizons: the Red River, Bakken, Charles and Greenhorn formations.

Anomalous stratigraphic thinning and thickening trends were noted and considered to be indicative of structural activity. Across such anomalous areas, several detailed cross sections were constructed. The cross sections were useful in demonstrating that structural activity resulted in stratal thickness changes. Additionally, they provided a means of dating those movements and better defining the fault zones and their limits. Occasionally, facies changes interpreted from well log signatures were detected across inferred structural features. Other subsurface features such as erosional truncations, salt dissolution and facies changes as interpreted from well logs, were studied.

The subsurface study reveals at least six fault blocks along the Nesson anticline in the North Dakota portion of the study area and one major northeast-trending feature in Montana. These features are located and named on the index map (Plate 1 (Figure 2)).

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## REGIONAL TECTONIC SETTING

The western cratonic shelf in the United States and along the southern border of western Canada can be divided into several principal lithostructural terranes based upon the Precambrian genesis of this part of the North America continent. Figure 5 illustrates the major tectonic elements in the northern Rocky Mountain region. The Cordilleran miogeosyncline exists to the west and its axis seems to be parallel to the Paleozoic continental margin, trending N40E in Nevada and making a right angle bend in southern Idaho to trend approximately N30W in central and northern Idaho (Maughan & Perry Jr., 1987). The Canadian shield extends under the Williston basin to the Cordilleran geosyncline. The Transcontinental Arch is a prominent Paleozoic feature which borders the Williston basin to the southeast. The trend of this structure is parallel to the northeast leg of the miogeosynclinal axis in Nevada. The northwest curvilinear edge of the Precambrian exposures of the Canadian shield to the north of Williston, also parallels the northwest leg of the miogeosynclinal axis in Idaho (Figure 5).

The Williston basin, a large intracratonic basin with a dominantly circular outline, thus forms a large depression in the western edge of the shield occupying much of North Dakota, northwest South Dakota, northeast corner of Montana, a significant portion of Saskatchewan and part of Manitoba. Other tectonic boundaries of the basin are the Black Hills Uplift to the southwest and the Miles City Arch and Bowdoin Dome to the west.

Many other tectonic elements abound in the immediate vicinity of the Williston basin, the most prominent of which is the Central Montana trough, an early Paleozoic feature which developed along the trend of the Precambrian Belt basin and projected eastward

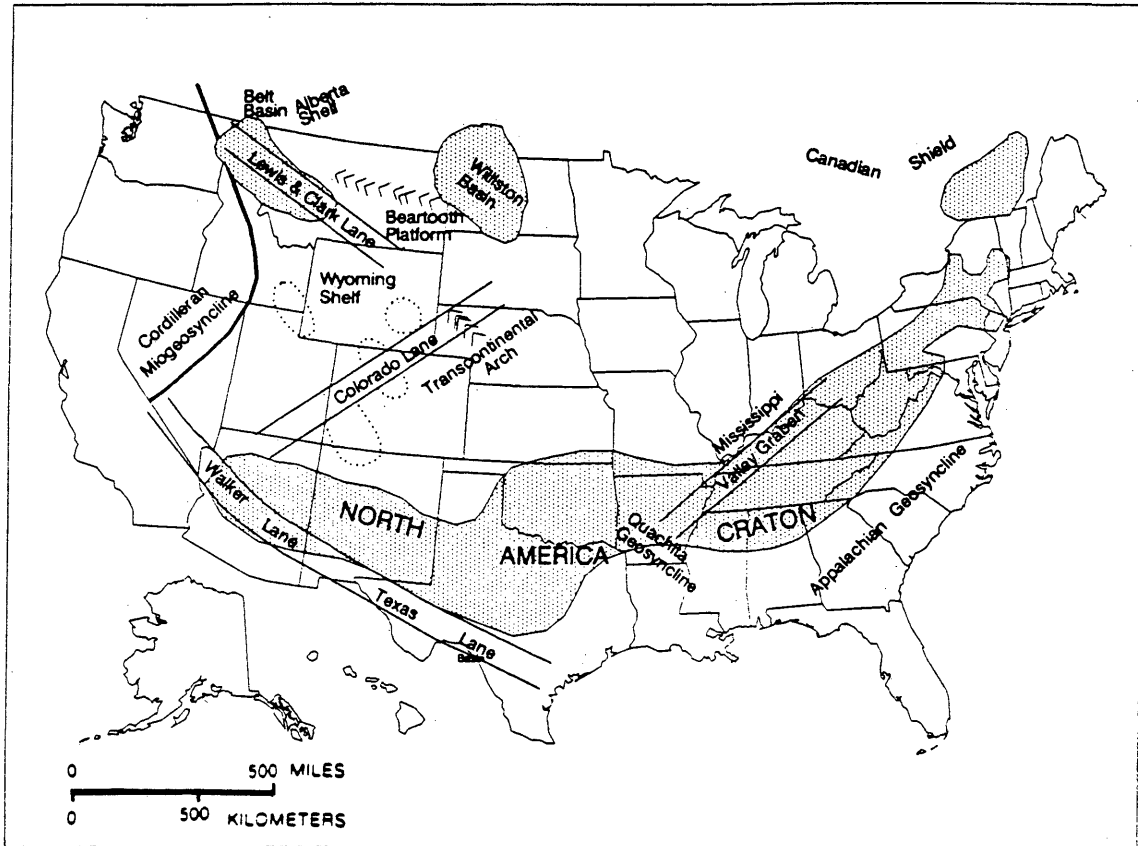


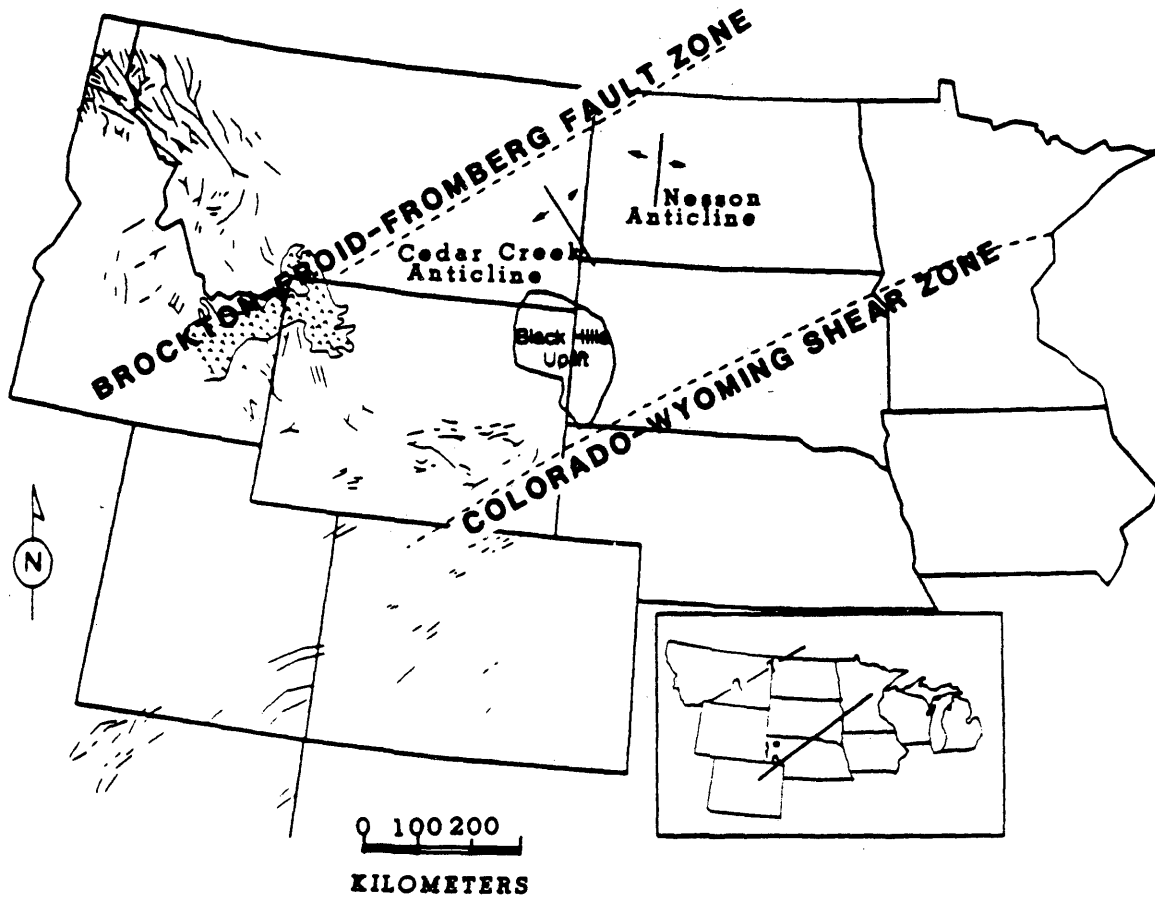
Fig. 5 Outline of the western interior of the United States showing major tectonic elements (after Maughan and Perry, 1987)

through western Montana toward the Williston basin. The Central Montana Uplift grew out of the Central Montana trough in middle Devonian time and had practically the same trend as the trough. The Big Snowy Trough developed along the same trend during the Mississippian and Pennsylvanian periods.

The Williston basin is thought to be directly related to two parallel trends, the Brockton-Froid-Fromberg fault zone and the Colorado-Wyoming shear zone, both of which trend northeast-southwest and bound the central Rockies, including the Williston basin, catching and deforming the basin (Gerhard et al, 1982) (Figure 6). The central Rockies appears to be a trapped block caught between the Brockton-Froid-Fromberg fault zone and the Colorado-Wyoming shear zone. The Central Rockies have a sinusoidal expression linking the slightly offset-to-the west, northwest-trending Northern Rockies with the north-trending Southern Rockies. The Black Hills, located within this apparently trapped block and limiting the Williston basin to the southwest, also shows this curvilinear expression. The northern portion of the hills is curved to the west from the major north-trending Black Hills.

A significant hingeline, outlined by Ballard (1963) for the eastern part of the Williston basin in North Dakota, is the lithostructural boundary between the provinces of Churchill (1.8 - 2.5 b.y) and Superior (> 2.5 b.y) (Figure 1). This north-south trending Precambrian structural boundary is an important factor in Phanerozoic basin development serving as tectonic hinge and causing rapid dip and facies changes across the boundary (Gerhard et al, 1982). This tectonic hinge line is interpreted as a continental suture during the Trans-Hudsonian orogeny (Bickford et al, 1986).

Timing and sense of motion on the prominent lineaments discussed above are not clear. In a wrench-fault hypothesis alluded to by Gerhard et al, 1982, left-lateral movement



**Fig. 6** Diagram showing the relationship of the Brockton-Froid-Fromberg fault zone and Colorado-Wyoming shear zones to the structural features of the Rocky Mountain and Williston basin (modified after Gerhard et al, 1982)

along the northeast-trending shear systems is conjectured. Basin evolution is thought to have resulted from the drag along the left-lateral shear systems which formed a depressed block in which the Williston basin and some part of the Central Rockies exist. Tensing of the downdropped block during Phanerozoic orogenic stresses created the present day structures.

The present structures within the Williston basin include the north-trending Nesson anticline, Little Knife anticline and the Billings nose, northwest-trending Cedar Creek anticline and the Antelope anticline. The Poplar dome is domal in shape but with a predominantly northwest grain. The Bismarck-Williston zone is an extension of the northwest-trending Antelope anticline mapped by Gerhard et al (1987).

Even though there is strong controversy as to the sense of motion on the lineaments, there is little problem in viewing the majority of Phanerozoic movement on these weakness zones as predominantly of a vertical nature. The jostling effect of the lineament blocks as they respond to stress on the broad Paleozoic shelf areas in the Powder River and Williston basins has been expressed predominantly as vertical movement along the fracture zones, resulting in subtle horsts, grabens and tilted half-grabens (Brown and Brown, 1987). Apart from the wrench-fault model of origin for the Williston basin other theories of origin include thermal flexing of the crust beneath the Williston basin, inducing subsidence by Turcotte and Ahern (1977) and intracontinental rifting, forming an east-west trending aulacogen extending from the Big Snowy trough by Peterson (1981).

## REGIONAL STRATIGRAPHY

The Williston basin is a structural-sedimentary intracratonic basin in parts of North Dakota, South Dakota, Montana, and southern Canada. Sedimentary rocks of all Phanerozoic periods from Cambrian through Tertiary are present in the deepest parts of the basin, where they attain a thickness of about 16,000 feet. Rock thickness decreases to less than 10,000 feet in eastern Montana and to 5,000 feet along the basin margin (Peterson and McCary, 1987). Similarity between the geologic development of the Williston basin and other cratonic areas affords a simple division of its stratigraphic record into time-bounded groupings using the sequence concept of Sloss (1963).

Carlson and Anderson (1965), recognized six major unconformity-bounded, transgressive-regressive cycles of basin deposition based on the Sloss concept. These are the Sauk (Cambrian - Lower Ordovician), Tippecanoe (Ordovician - Silurian), Kaskaskia (Devonian - Mississippian), Absaroka (Pennsylvanian - Triassic), Zuni (Jurassic - Tertiary) and Tejas (Tertiary - Quarternary). Gerhard et al (1982) and Gerhard (1987) have subdivided the Kaskaskia sequence into two units; Lower and Upper Kaskaskia, based on the development of a regional unconformity overlying a widespread anoxic sedimentation event near the close of the Devonian. This anoxic condition is marked by deposition of the Bakken Formation, a major petroleum source rock in the Williston basin (Gerhard, 1987). Carbonate sedimentation dominated in early and middle Paleozoic time but was replaced primarily by clastic deposition in late Paleozoic, Mesozoic and Tertiary time. The basinal configuration remained essentially the same throughout the Paleozoic although basin center experienced minor shifts in location through time. Description of the basin stratigraphy

and sedimentary facies given below is summarized from Carlson and Anderson (1965), Gerhard et al (1982), Gerhard (1987), Peterson and MacCary (1985).

### *Sauk Sequence*

The initial Phanerozoic sedimentary deposits in the Williston basin are the Sauk sequence (Figure 7), which is represented by the Deadwood Formation (Upper Cambrian - Lower Ordovician). The Deadwood Formation is about 1000 feet thick in the central part of the basin and thins eastward reaching a zero edge in eastern North Dakota and central South Dakota. The Deadwood consists mostly of clastics and minor carbonate deposited on a rather irregular surface.

The Nesson anticline may have had a Precambrian ancestry as Cambrian strata are absent on the feature and most of the thinning in the Deadwood Formation accounted for on the structure, occurs in the lower part as against the upper part indicating syndepositional uplift. The Deadwood is unconformably overlain by the Winnipeg Group, the basal unit of the Tippecanoe sequence.

### *Tippecanoe Sequence*

The Tippecanoe marks the beginning of the Williston basin as a discrete structural depression with marine connection to the southwest. This transgressive-regressive cycle includes the middle Ordovician through Silurian rock record in the basin. The sequence is made up of the Winnipeg Group (Black Island, Icebox and Roughlock formations), the Big Horn Group (Red River, Stony Mountain and Stonewall formations) and the Silurian Interlake Formation (Figure 7).

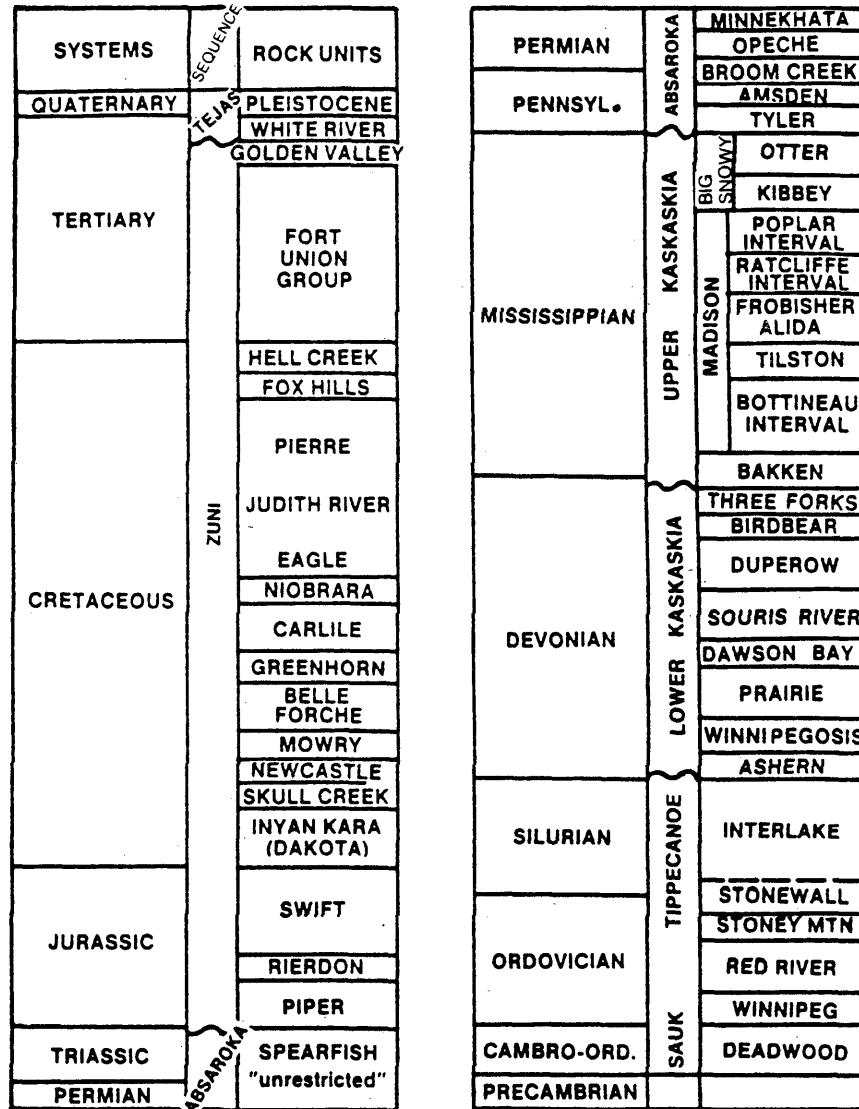


Fig. 7 Generalized stratigraphic section of the Williston basin (modified after Gerhard et al, 1987)



The transgressive phase of the Tippecanoe is the Winnipeg Group which consists of a clastic basal unit, the Black Island, a clean quartz sandstone member which is overlain by the Roughlock Formation, a mixture of green-gray shale, calcareous siltstone and silty carbonate. The Roughlock is in turn overlain by the Icebox Formation, a predominantly carbonate unit.

Carbonate rocks of the Red River Formation were deposited under shallow marine and sabkha environments. The lower unit, consisting of basal shaly to sandy carbonate, burrowed, fossiliferous, dolomitic limestone and dolomite with skeletal materials, was deposited as normal marine subtidal to intertidal carbonate during a widespread marine transgression. The upper Red River Formation is regressive unit comprising of at least three carbonate-*evaporite* cycles. Dolomitization is the most significant control on porosity development within the Red River Formation. Carroll (1979) suggests that sedimentation and subsequent dolomitization appear to have been controlled by buried Precambrian hills associated with pre-existing structures, and that porosity is commonly developed on the periphery of the "highs".

The Red River Formation is overlain by the Stony Mountain which consists of a basal argillaceous, crinoidal limestone and interbedded shale unit and an upper unit of fossiliferous, burrowed limestone and dolomite. This is capped by a thin widespread anhydrite which is in turn overlain by the Stonewall Formation with which it is very similar.

Cyclic sedimentation continued through the Silurian when the Interlake Formation (late Silurian), was deposited. The Interlake is divisible into three members, based on shale bed markers into lower, middle and upper Interlake. The lower Interlake is composed of light-colored, very fine grained, laminated and non-laminated stromatolitic dolomite with

nodules of thin interbeds of anhydrite and is presumed to have been deposited under intertidal and supratidal conditions. The middle Interlake is a more marine, subtidal unit of fossiliferous dolomite or skeletal limestone. The upper part of the Interlake Formation, which is mostly restricted to the central part of the basin where it was relatively unaffected by Devonian erosion, contains widespread beds of porous oolitic, algal and coralline dolomite deposited under intertidal and supratidal conditions. Regression after Silurian deposition resulted in karstification at the top of Interlake.

### *Kaskaskia Sequence*

Kaskaskia sequence (early Devonian - late Mississippian) rocks are perhaps the most significant of all the sequences in terms of their natural resources. They also represent a period of relative tectonic stability or subsidence. Limestone deposition, coupled with two episodes of evaporite deposition (Devonian Prairie and Mississippian Charles), dominated the Kaskaskia sequence. Gerhard, et al (1982) divided this sequence into the Lower and Upper Kaskaskia based on the intra-Kaskaskia unconformity near the top of the Devonian. This unconformity is marked by anoxic conditions that favored deposition of the Bakken Shale.

### *Lower Kaskaskia*

Seven different formations make up the lower Kaskaskia sequence. These are, in ascending order, the Winnipegosis, Prairie, Dawson Bay, Souris River, Duperow, Nisku (Birdbear) and Three Forks formations.

Regional transgression began in middle Devonian with the Winnipegosis Formation whose initial deposits are red dolomite, siltstone and shale beds that constitute the lower to middle Devonian Ashern Formation and culminated in the mound and reef-bearing carbonates of the middle Devonian Winnipegosis Formation. Both deep-water and shallow-water environments are recognised in the Winnipegosis. The deeper facies consists of laminated limestone and stromatoporoid, tabulate-coral pinnacle reefs, and the shallow facies consists of shallow-marine patch reefs, lagoonal and intertidal deposits.

Activity on the Transcontinental Arch in middle Devonian time caused the Elk Point basin, consisting of the Williston and Alberta basins, to be tilted northwestward before basin restriction increased salinity and induced Prairie deposition (Figure 8). The Prairie evaporite is over 400 feet thick in the basin center, but thins toward the margins by onlap or dissolution or both. The lowest member of the Prairie, the Ratner Anhydrite is overlain by thin shale and halite which are in turn overlain by three cycles of potash and interbedded halite (Figure 9). The potash members, easily recognisable on electrical logs as offscale kicks on the gamma ray, are named, in ascending order, Esterhazy, Belle Plaine and Mountrail. They record the shallowest and most saline depositional conditions within the Prairie. The Prairie Formation is capped by the Second Red Bed, a red to green, non-fossiliferous dolomite and calcareous shale.

Detailed intra-formational correlation within the Prairie afforded Oglesby, (1988) the capability to distinguish between the two processes. Progressive increase in areal extent of the formation from bottom to top is a major characteristic of onlap or depositional thinning and the reverse is true for top-to-bottom salt dissolution.

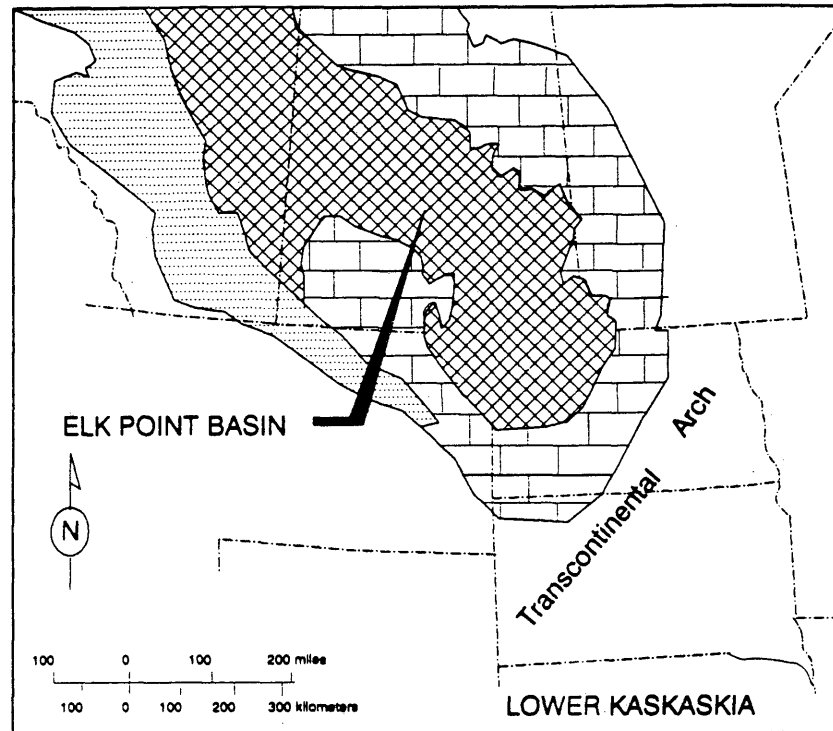


Fig. 8 Paleogeography of the Elk Point basin during the time of deposition of the Winnipegosis Formation. Basin restriction was caused by the reefs to the north leading to the Prairie deposition in the Devonian (modified from Gerhard et al, 1982)

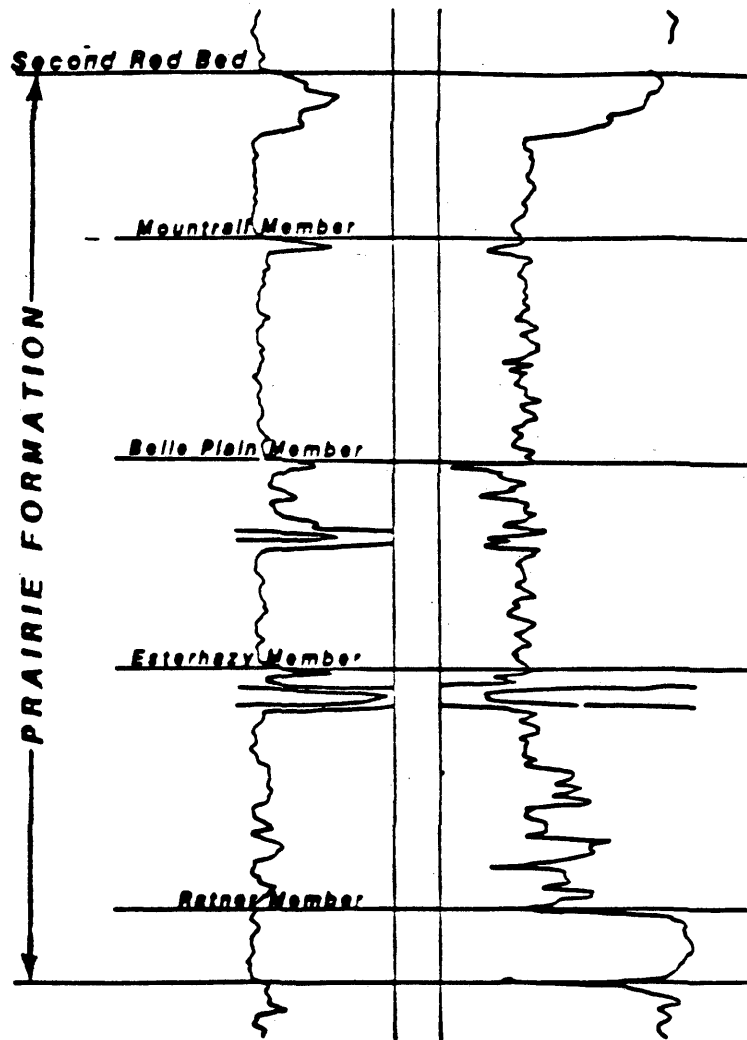


Fig. 9 Electric log of the Prairie Formation showing the constituent members (after Oglesby, 1988)

The Prairie is overlain, with minor disconformity, by the Dawson Bay Formation, a single carbonate-evaporite cycle consisting of basal argillaceous dolomite and limestone that grades upward into skeletal dolomite and stromatoporoid reefs capped by anhydrite.

The early Devonian transgression reached its peak in late Devonian time with the deposition of several carbonate-evaporite cycles that make up the bulk of Upper Devonian rocks. The Souris River Formation, which overlies the Dawson Bay, consists of several depositional cycles of fine clastics grading upward into argillaceous and fossiliferous dolomite or limestone, capped by anhydrite and anhydritic dolomite.

The Souris River Formation is overlain by the Duperow Formation which is similar except that the latter contains more complete shoaling upward cycles than the former. A typical cycle within the Duperow consists of a subtidal, open marine facies of stromatoporoid and tabulate corals which is overlain by a lime mudstone, lagoonal facies and supratidal carbonate facies with anhydrite. The final series of carbonate-evaporite cycles of the Devonian make up the Nisku (Birdbear) Formation, which directly overlies the Duperow. Overlying the Nisku Formation is the Three Forks Formation, a marine and non-marine clastic sequence of red and green shale, siltstone, sandstone and carbonate-evaporite cycles. These clastics cover Nisku carbonates marking a hiatus in the middle of the Kaskaskia sequence and may be related to westward transport of clastic material from the active Transcontinental Arch. Angularity between Upper Devonian and Lower Mississippian rocks along the eastern basin margins is suggestive of crustal instability (Gerhard et al, 1982).

### Upper Kaskaskia

Upper Kaskaskia sequence rocks (Figure 7), comprise the Bakken Formation and the major Mississippian groups, the Madison and Big Snowy Groups. The Lower Mississippian Bakken Formation was deposited down following a brief shelf emergence at the end Three Forks deposition. A reorientation of the seaways ushered in Mississippian sedimentation as the Williston basin was opened to the west through the central Montana trough. The Mississippian sea way may be related to the development of shear systems in central Montana (Gerhard et al, 1982).

The Lower Mississippian Bakken Formation can be divided into three units, a lower unit of organic-rich, black shale and minor siltstone, a middle unit of dolomitic siltstone, and an upper unit of black shale similar to the lower unit. On electric logs, the Bakken is easily recognised by the double-prong fork log motif and the offscale readings on both the gamma ray and resistivity logs (Figure 10). The Formation base is placed at the base of the lower prong representing the offscale metered, lower rich shale. The Bakken Formation is a major source rock for petroleum in the Williston basin. Bakken deposition was followed by another period of cyclic shelf carbonate sedimentation in the Mississippian, with a major change in faunal and floral assemblages. Crinoid and bryozoan skeletal remains and oolitic bank deposits became the dominant feature of the Mississippian carbonate cycles. The cycles are generally more evaporitic upsection culminating in the deposition of the halite-bearing Charles Formation. The Mississippian Madison Group comprises of three major formations named, in ascending order, the Lodgepole, the Mission Canyon and the Charles. In the subsurface, especially in the

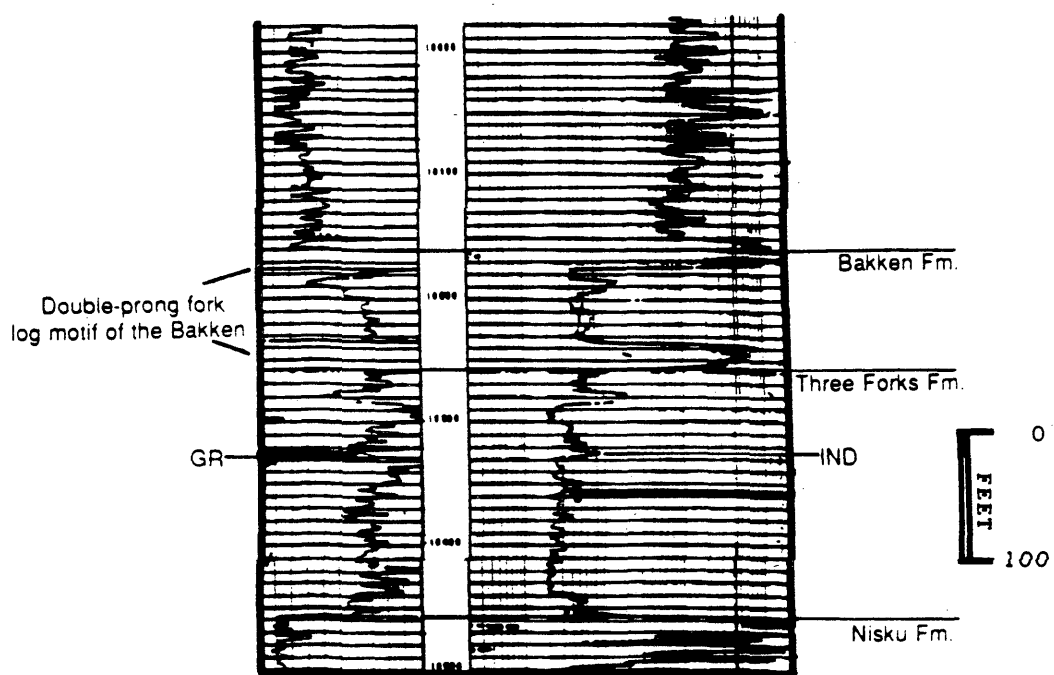


Fig. 10 Electric log of the Getty Oil 19-13 Owen well (19-157N-96W), Williams County, North Dakota showing the double-prong, offscale readings on gamma ray and induction logs

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central part of the basin, the Madison is separable into five marker-defined units, based on widespread evaporite and associated fine clastic beds, recognisable on gamma ray and other electrical logs. These units are, in ascending order, Bottineau, Tilston, Frobisher-Alida, Ratcliffe and Poplar intervals (Carlson & Anderson, 1965). The Lodgepole Formation is the basal unit of the Madison Group and is composed of thinly bedded, argillaceous or cherty, dark gray limestone, interbedded with a few dark gray calcareous shales.

Maximum transgression probably occurred at the end of Lodgepole deposition or early in the deposition of the Mission Canyon. The Mission Canyon rocks consist of predominantly skeletal wackestone, becoming oolitic toward the basin margin. Sub-aerial weathering of the skeletal wackestone has produced a variety of pisolitic and fenestrate porosity fabrics which form important oil reservoirs (Gerhard et al, 1982).

Madison sedimentation came to a close with the deposition of the regressive Charles Formation, a predominantly halite unit with interbedded anhydrite and shale. Common occurrences of solution breccias and karst surfaces at the upper Madison Charles surface is indicative of the widespread emergence that followed Charles deposition. The top of Charles is considered to represent the upper boundary of the Tamaroa sequence of Wheeler (1963), (Meissner, 1978). Wheeler's sequences (1963) are essentially similar to Sloss' (1963) in that they both recognize six major sequences which are bounded top and bottom by interregional unconformities. The main disagreement between them lies in the Kaskaskia sequence of Sloss. Wheeler, (1963) subdivides the Kaskaskia sequence into two sequences namely the Pankasha Holostrome and the Tamaroa sequence. The former corresponds to the Lower Kaskaskia and the latter to the Upper Kaskaskia of Gerhard, et al

(1982). Figure 11 is an illustration of the relationship between Wheeler sequences(1963) and Sloss sequences(1963). The carbonate depositional cycles in the Madison reflect relative tectonic stability. Lack of coarse or medium grained clastics and the widespread nature of individual stratigraphic units may suggest eustatic sea level control, although minor epeirogenic movements cannot be ruled out.

The Kaskaskia sedimentary record came to a close with deposition of the Big Snowy Group of Chesterian age. The Big Snowy Group comprises the Kibbey, Otter and Heath Formations, which are a mixture of terrigenous clastics and minor carbonate rocks. The sudden influx of these extra basinal clastic sediments mark the influence of the Ancestral Rocky Mountain orogeny, beginning in Late Mississippian west and south of the Williston basin.

The basal unit of the Big Snowy Group is the Kibbey Formation - a mixture of red shale, siltstone, and sandstone of near shore marine origin, very famous for its middle member, the Kibbey limestone. The latter is generally used as a marker unit because of its widespread nature and easy recognition on electrical logs. Overlying the Kibbey is the Otter Formation which consists of marine, nearshore and tidal flat beds of green shale and siltstone. The Otter is overlain in some places by the Heath Formation, presumed to have been deposited in a restricted marine environment. The Heath Formation is composed of dark gray, organic, marine shale and limestone with minor interbeds of siltstone.

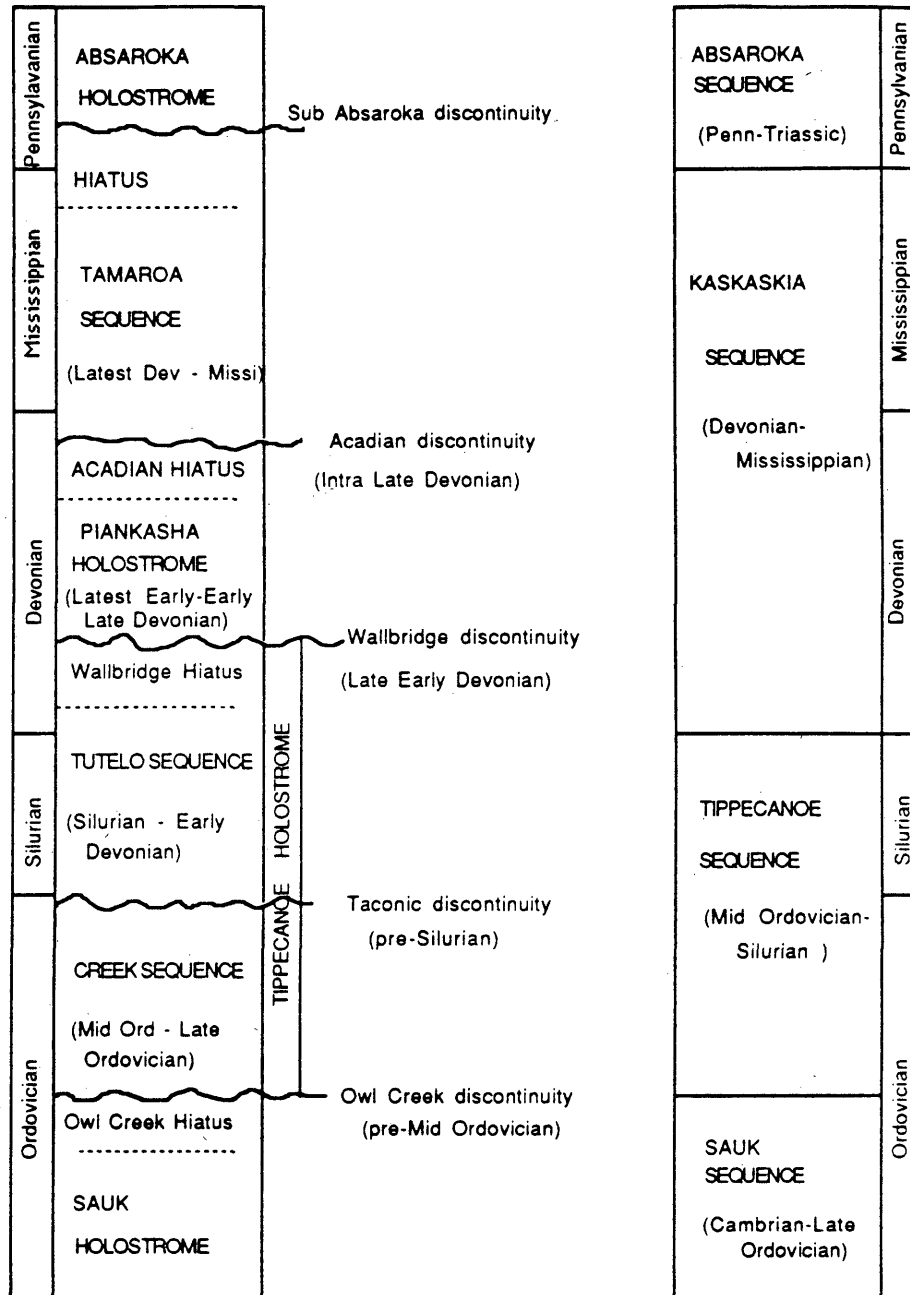


Fig. 11 Relationship of Wheeler sequence (1963) to Sloss' (1963)

### *Absaroka Sequence*

Several orogenic events during late Mississippian to Pennsylvanian time resulted in new uplifts and basins, and growth of many other features. Absaroka sequence rocks consist predominantly of silicilastics with minor carbonate and evaporite beds. Basal Absaroka rocks are included in the Tyler Formation (Lower Pennsylvanian) which is composed of marine, deltaic and fluvio-lacustrine quartz sandstone, shale and minor limestone (Peterson & MacCary, 1987), estuarine bar and marine sands and shale (Ziebach, 1964 in Gerhard et al, 1982).

The Tyler Formation is overlain by red and brown shale, siltstone and sandstone interbedded with dense, microcrystalline carbonates of the Amsden Formation, which was deposited in a more restricted environment. This sequence is capped in places by the Broom Creek Formation. An unconformity at the top of the Broom Creek records a period of subaerial exposure and weathering during the Permian. Hypersaline conditions developed at the close of Absaroka sedimentation, giving rise to the deposition of the Permian Opeche salt and Pine salt. Deposition of the Triassic Spearfish Formation concludes Absaroka sedimentation. The Spearfish is composed of red shale and sandstone with some halite beds at the approximate boundary of the Permian-Triassic systems (Peterson & MacCary, 1987).

### *Zuni Sequence*

Jurassic and Cretaceous sedimentary rocks make up the bulk of the Zuni sequence (Jurassic-Tertiary), which rests unconformably on Absaroka rocks. Basal Zuni rocks are the middle and late Jurassic Piper, Rierdon and Swift formations. The Piper Formation consisting of predominantly red beds, evaporites, halite and marine limestone is

overlain by shallow marine shale, glauconitic sands and oolitic carbonates of the Rierdon and Swift formations. This is in turn overlain by the Morrison Formation which is famous for its dinosaur remains.

In the Williston basin, the top of the Jurassic is marked by a subaerial regressive exposure surface. This was followed by continental and nearshore marine sandstone and vari-colored shales of the Inyan Kara Formation (lower most Cretaceous) of the Dakota Group, and then by the marine transgressive phase of the upper Inyan Kara. Progressive deepening of the Western Interior Cretaceous sea way, provided for the deposition of the remainder of the Cretaceous section. The Newcastle Formation is overlain by the marine Mowry Shale, which is in turn overlain by marine, dark gray shale, marl and limestone of the Colorado Group (Belle Fouche, Greenhorn, Carlile and Niobrara formations). The Colorado Group is composed of a sequence of well defined fossiliferous, marine transgressive-regressive deposits. The top of the Greenhorn Formation is a very good regional marker and is used as the upper stratigraphic control in this thesis, partly for this reason and partly because most wells are logged from Greenhorn downward.

Increasing coarse siliciclastics in the upper part of the sequence indicate tectonic activity related to the Laramide orogeny

### *Tejas Sequence*

Tejas sequence (Tertiary-Quaternary), is a record of very few indurated stratigraphic units. The Fort Union Group is overlain by lacustrine and fluvial clastics of the Golden Valley and the White River Formations. The White River Formation of South Dakota has been correlated with scattered limestone and ash-bearing, shaly sandstones from the top of

the Killdeer Mountains. Unnamed remnants of the Miocene and Pliocene consisting mostly of lacustrine-fluvial deposits and minor limestone, are present in the Williston basin. Continental Pleistocene glacial sediments cover more than 75% of North Dakota, and a great part of the Montana portion of the basin.

## REGIONAL STRUCTURAL MECHANICS

The major structural features in the Williston basin, as well as the surrounding areas show three dominant orientations, northwest, northeast and north. Lineaments also trend essentially the same direction defining what Thomas (1974) call lineament blocks. These weakness zones may be boundaries between Precambrian lithologic units, shear zones or faults. Enigmatic as they may seem to be, the lineaments display such a regularity of pattern that basement involvement is hard to discard. This, of course, has a lot of ramifications in the structural mechanics of the area as well as in the stratigraphic development. Even though most writers lean toward a wrench fault model of origin for the Williston basin and the structural features contained, the actual structural mechanics involved is still controversial. Two main deformational processes, pure shear and simple shear mechanism are often invoked in attempting to explain the origin of the structures contained in the Williston basin area.

### *Pure Shear Deformation*

Pure shear deformation is an online compression mechanism by which forces are directed toward one another along the same line of action causing flattening. (Figure 12). Two of the major works that consider pure shear compressional deformation as a major cause of the basement-related structures and the structural grain of the Williston basin and adjacent areas, are Brown (1978) and Brown & Brown (1987). In their study area, which included 200,000 mi<sup>2</sup> of area in eastern Montana, western North and South Dakota, parts of Nebraska and northeastern Wyoming, they concluded that at least three potential stress

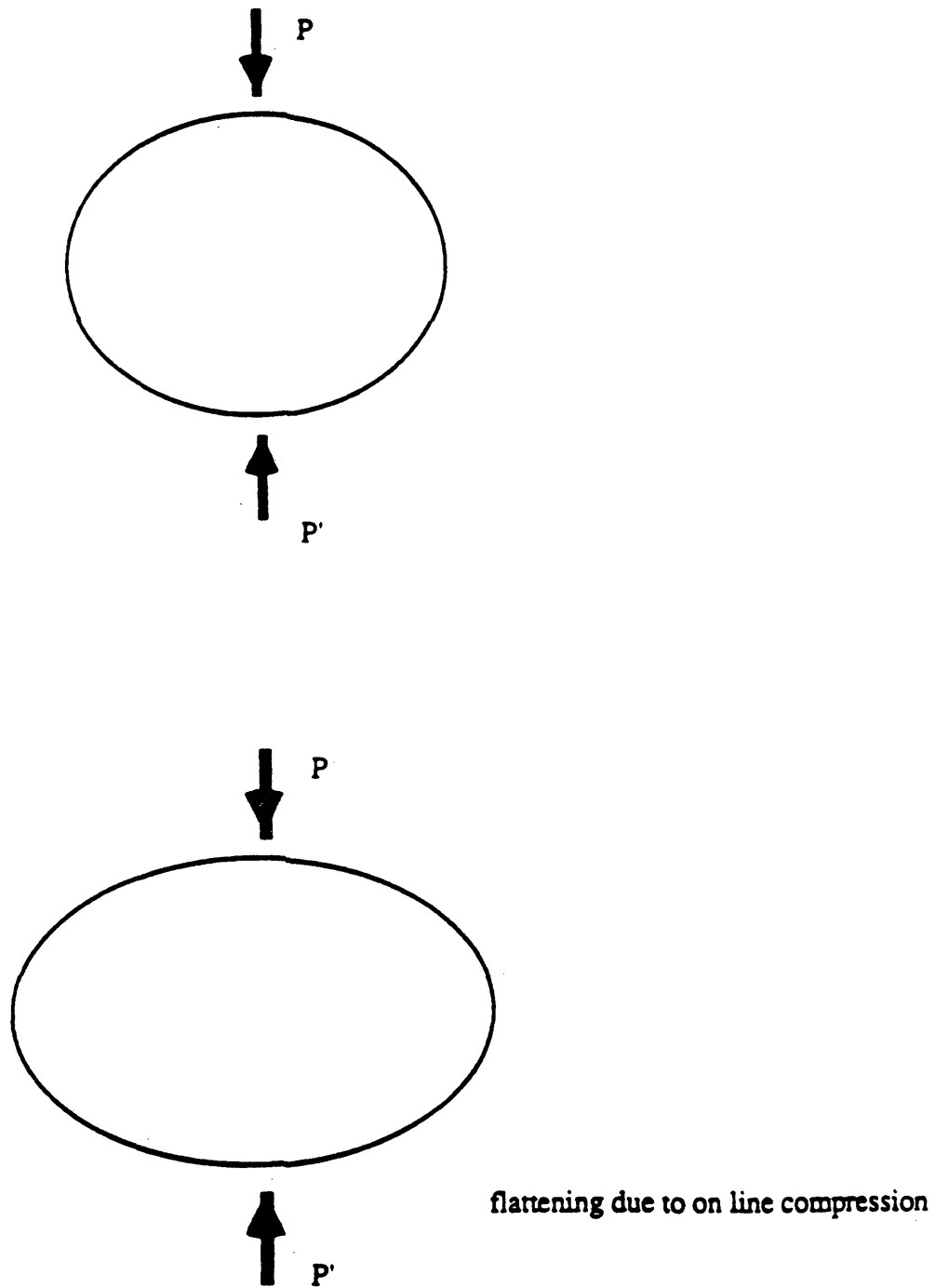


Fig. 12 Pure shear deformational mechanism (on line compression)



orientations influenced the structural architecture. One involved a regional stress P-P' greater than resistance R-R', another involved equal regional stress P-P' and resistance R-R' and the third involved a situation in which the stress and the resistance are transposed.

#### *Regional Stress $P > Resistance R$*

When the regional stress PP' is greater than the resistance RR' as shown in figure 13, a pair of conjugate shears always develops at some angle to the direction of maximum compressive stress. This angle is usually about  $45^{\circ}$  but could vary appreciably depending on several physical properties of the rock, for example the internal friction and rock particle acceleration. Rocks are far from being homogenous and isotropic. This makes it difficult to predict the angle at which shearing will develop as a result of pure shear wrench fault tectonics. However, there is a primary fault direction and a complementary fault direction developed in response to pure shear mechanics. In addition, tension fractures and faults will develop parallel to the maximum direction of maximum compressional stress and perpendicular to the orientation of the folds thereby generated.

#### *Regional Stress $P = Resistance R$*

When the regional stress PP' is equal to the resistance RR' in a situation where the block boundaries are rigid or frozen, a resultant of these two equal forces will develop either in a northeasterly direction or a northwesterly direction, depending on the rock fabric and resistance. Brown and Brown (1987) concluded that the northwest resultant was most

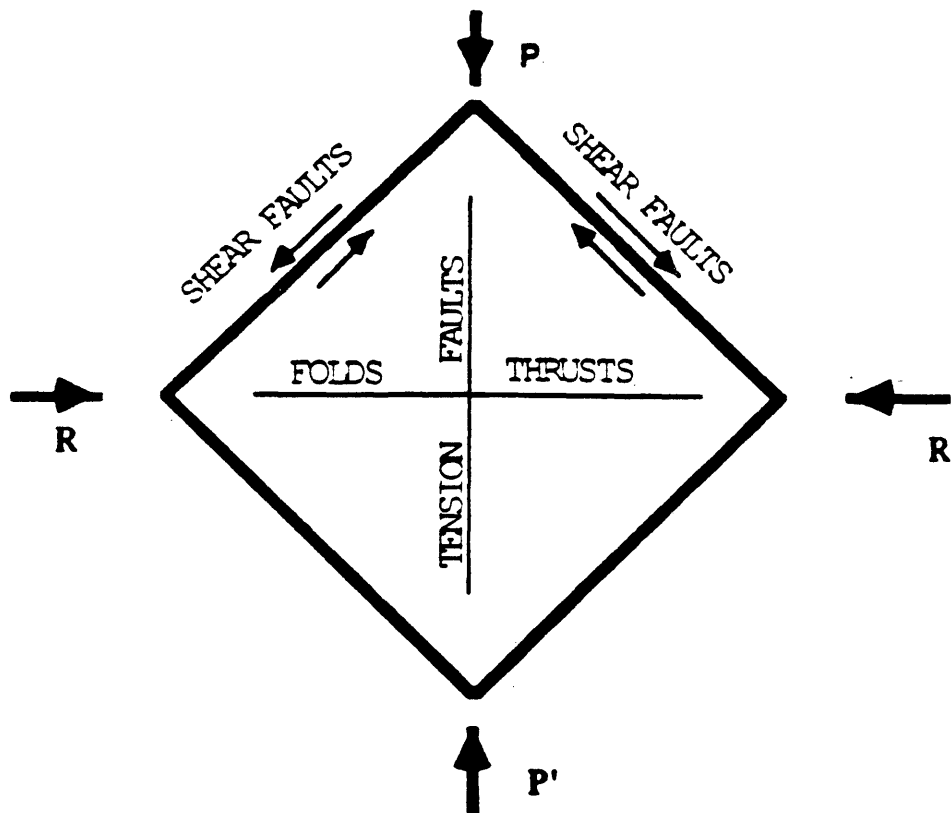


Fig. 13 Potential stress orientation when regional stress  $PP'$  is greater than resistance  $RR'$  (modified from Brown and Brown, 1987)

likely dominant in their study area (Figure 14). In this situation, boundary shear faults would trend north-south and east-west, tensional faults would be parallel to the direction of maximum compressive stress  $SS'$  and folds would trend in a northeasterly direction.

In the third category, the compressive stress and the resistance are transposed and the results are similar to the first case except that the sense and direction of motion are now reversed (Figure 15). Brown (1978) concluded that the sediment geometric patterns, angular relations and boundary conditions deduced from their paleostructural maps are consistent with the predicted wrench fault tectonic configuration of Moody and Hill (1956); McKinstry (1953) and others. They maintain that shearing along a wrench fault system was responsible for structural deformation in the Williston basin, and that the primary northeast shear direction and the complementary northwest direction were alternately dominant during the Paleozoic deposition.

### *Simple Shear Block Couple*

Thomas (1974) is in total disagreement with compressional pure shear mechanism as being responsible for the wrench fault origin of Williston basin's major structural features. His main contention is that the inhomogeneity and anisotropy of the basement will not permit it to propagate orogenic forces uniformly, hence pure shear compressional mechanics is unlikely. Instead, he said the weakness zones in the basement would deflect orogenic forces and set up a system of structure mechanics called lineament simple shear, block coupling or lineament block tectonics (Figure 16).

Lineament simple shear produces block coupling which results in drag fold uplifts with associated flank faults and cross fold tension faults. Coupling progresses through

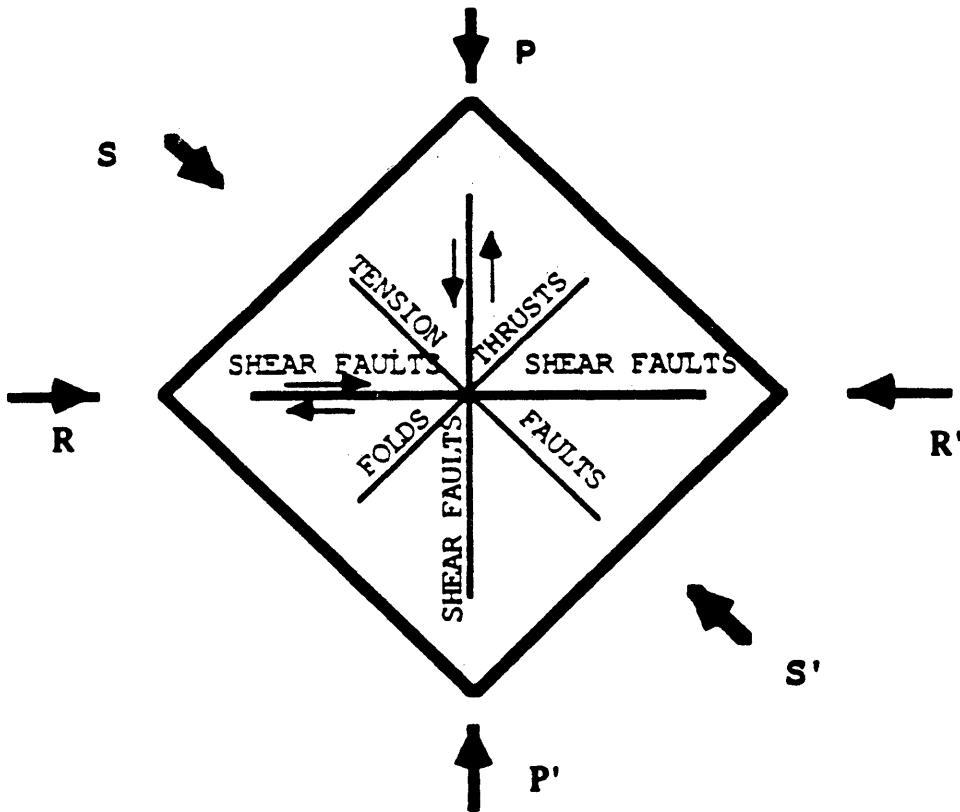


Fig. 14 Potential stress orientation when regional stress  $PP'$  is equal to resistance  $RR'$  (modified from Brown and Brown, 1987)

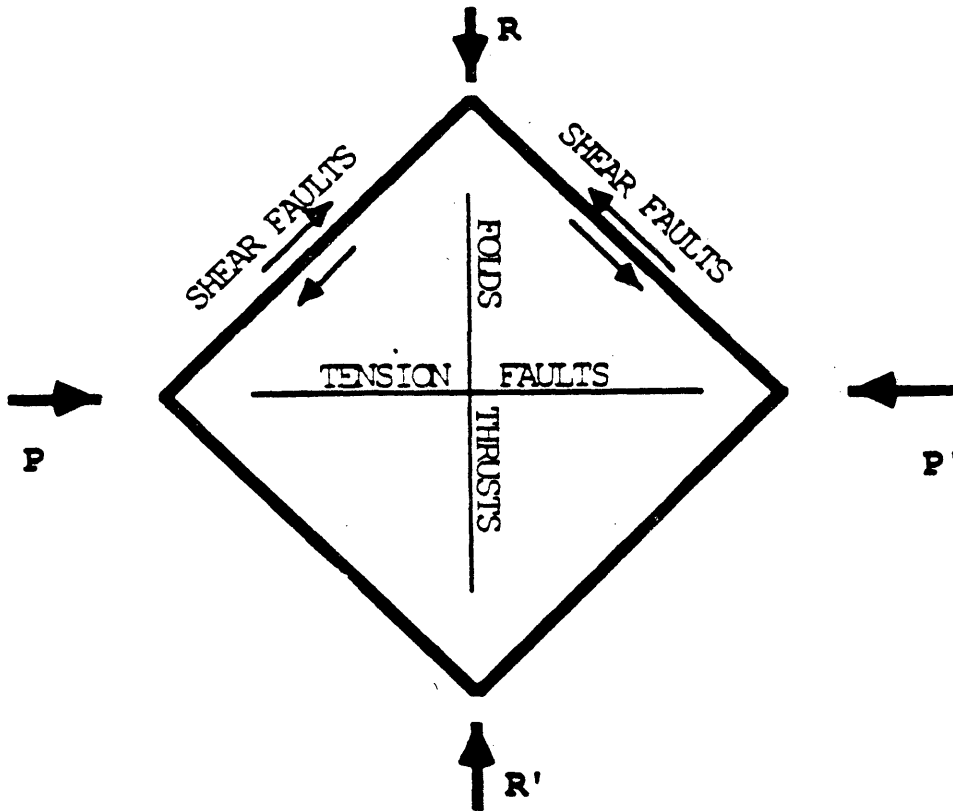


Fig. 15 Potential stress orientation when regional stress  $PP'$  and resistance  $RR'$  are transposed (modified from Brown and Brown, 1987)

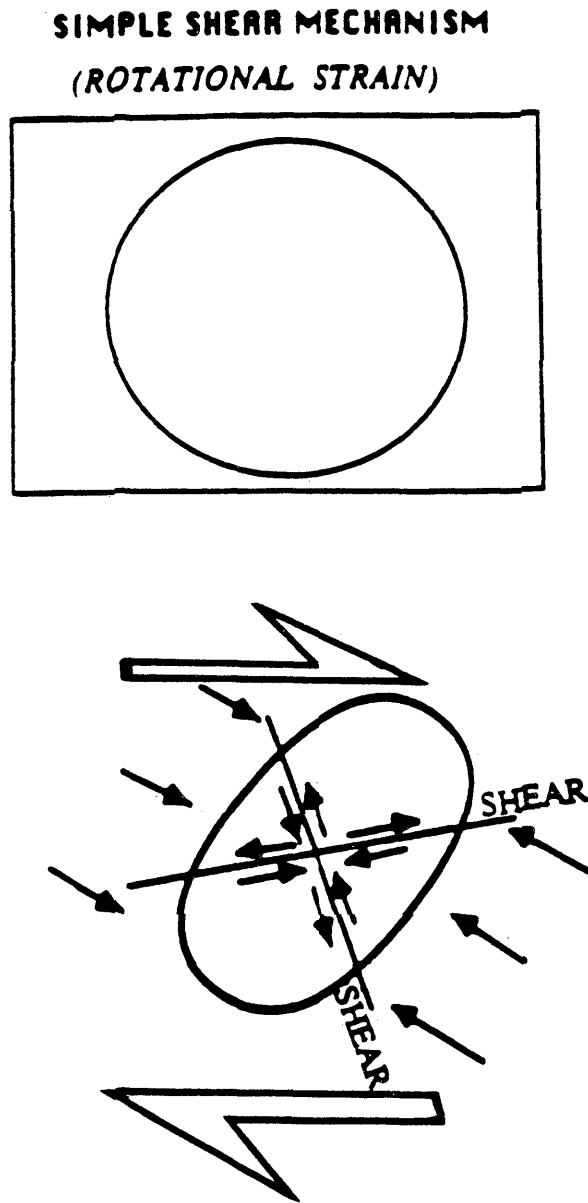


Fig. 16 Simple shear (rotational) deformational mechanism or coupling

time to yield more and more degree of drag fold rotation (Figure 17). The structural products of block coupling are identical to those of pure shear mechanics except for the following factors:

- (1) Block couple-generated structures like drag folds, flank and tension faults, cross fold tension faults and fractures are all confined to the coupled block in which they were formed.
- (2) Rotation is always associated with simple shear mechanics. The rotation is in the direction of the shear couple and goes through different stages of complexity. If the basement is strongly involved in the coupling, rotation is limited.
- (3) Characteristic en echelon arrangement of drag folds is produced by block coupling, being clockwise in a right-lateral setting and counter-clockwise in a left-lateral setting.
- (4) At the incipient stage of block coupling, cross-fold tension faults or fractures are inclined at angle of about  $45^{\circ}$  with the boundary weakness zone.

Gerhard, et al (1982) shared the view that structural lineaments are surface expression of basement weakness zones which had become reactivated through time. Their contention is that the Williston basin formed as a downdropped block between two northeast-trending lineaments, the Brockton-Froid-Fromberg and the Colorado-Wyoming shear zones which they believe originated by left-lateral shearing in the edge of the pre-Phanerozoic continental plate. The shearing, they maintain, is responsible for the offsets and displacement between the northern and southern Rockies. The Central Rocky Mountain block including the Black Hills and the Big Horn uplifts was consequently caught in between as a slice with left-lateral drags.

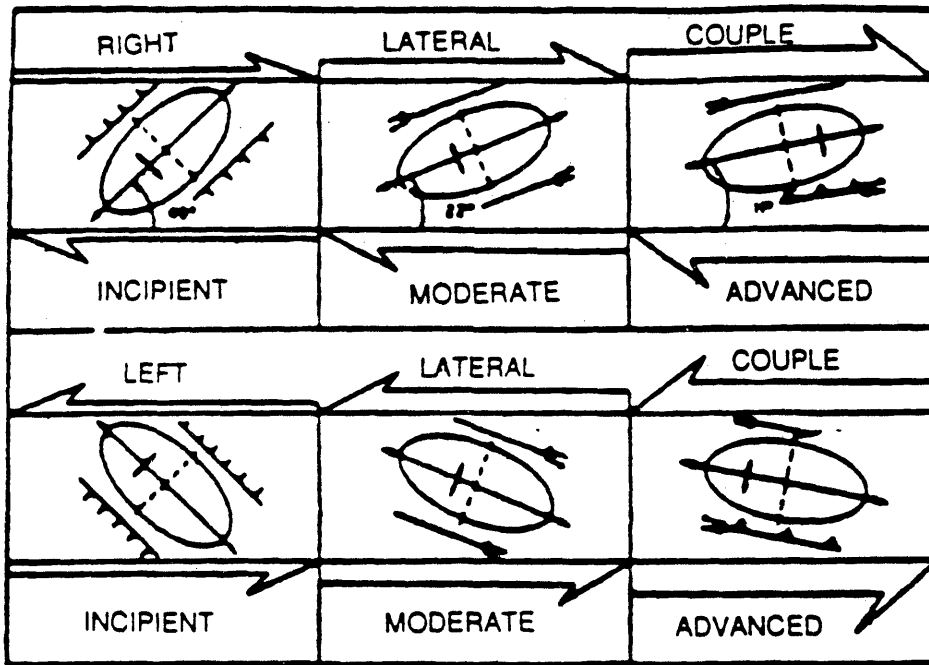


Fig. 17 Block coupling as a result of lineament simple shear mechanism producing various degrees of drag-fold rotation for both left-lateral and right-lateral motion (after Thomas, 1974)



The shearing generated numerous basement-rooted faults within the Central Rockies and the Williston basin, and further tensing of the shear system has resulted in dip-slip motion along the basement planes of weakness. It is questionable whether any significant motion on the two major shear zones has occurred since Precambrian time. Alternately, left-lateral shearing on the bounding shear zones may have induced tensional stress resulting in a large-scale pull apart basin (Figure 18 ).

### *Salt Solution Structures*

Structural noses resulting from stratal flexing as a result of recurrent movement on basement weakness zones are not the only structural expression of the Williston basin. Many other structures abound that may not have a direct relationship to basement movement. Some of these structures are responsible for large amounts of hydrocarbon in the basin. Swenson (1967) and Kent (1973) discussed salt solution structures in the Nisku (Birdbear) Formation. They reported that these structures resulted from multi-stage solution of the middle Devonian Prairie evaporite. Swenson (1967) reported that the upper Devonian Nisku production at Tule Creek field, Montana, is genetically related to Prairie salt dissolution. Structure generation from salt solution mechanics takes at least two stages. The first stage of salt solution results in the creation of local depression which allows for anomalously thick sediments to accumulate. Later, the second stage salt solution removes the remaining salt from the areas surrounding the local depression. The effect of this is to make the first depression assume a positive disposition and cause draping of younger sediments over the thickened area (Figure 19A). Oil fields resulting from salt solution tectonics are characterised by flat tops with relatively steep sides. Most of the oil fields of this type are located in Roosevelt County, Montana, e.g. Tule Creek, Tule Creek

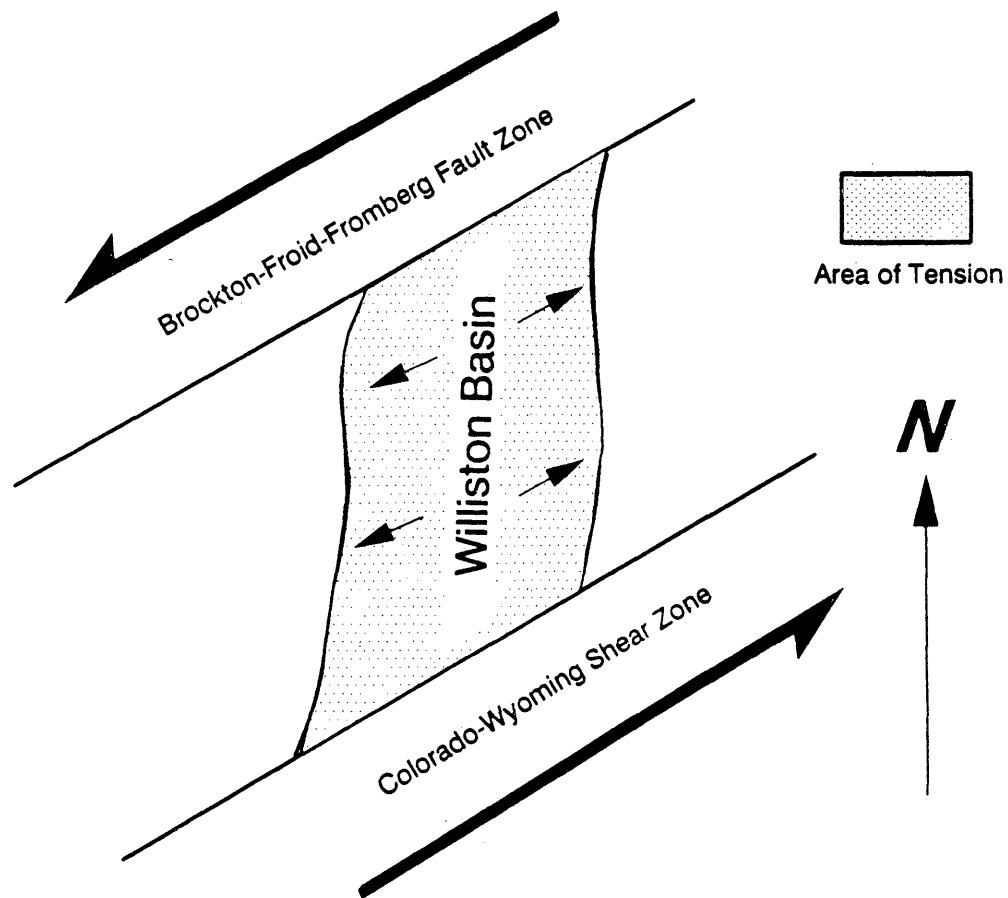


Fig.18 Williston basin considered as a downdropped block between two major shear zones, the Brockton-Froid-Fromberg and Colorado-Wyoming shear zones as a result of tension created by movement along both shear zones (after Gerhard et al, 1982).

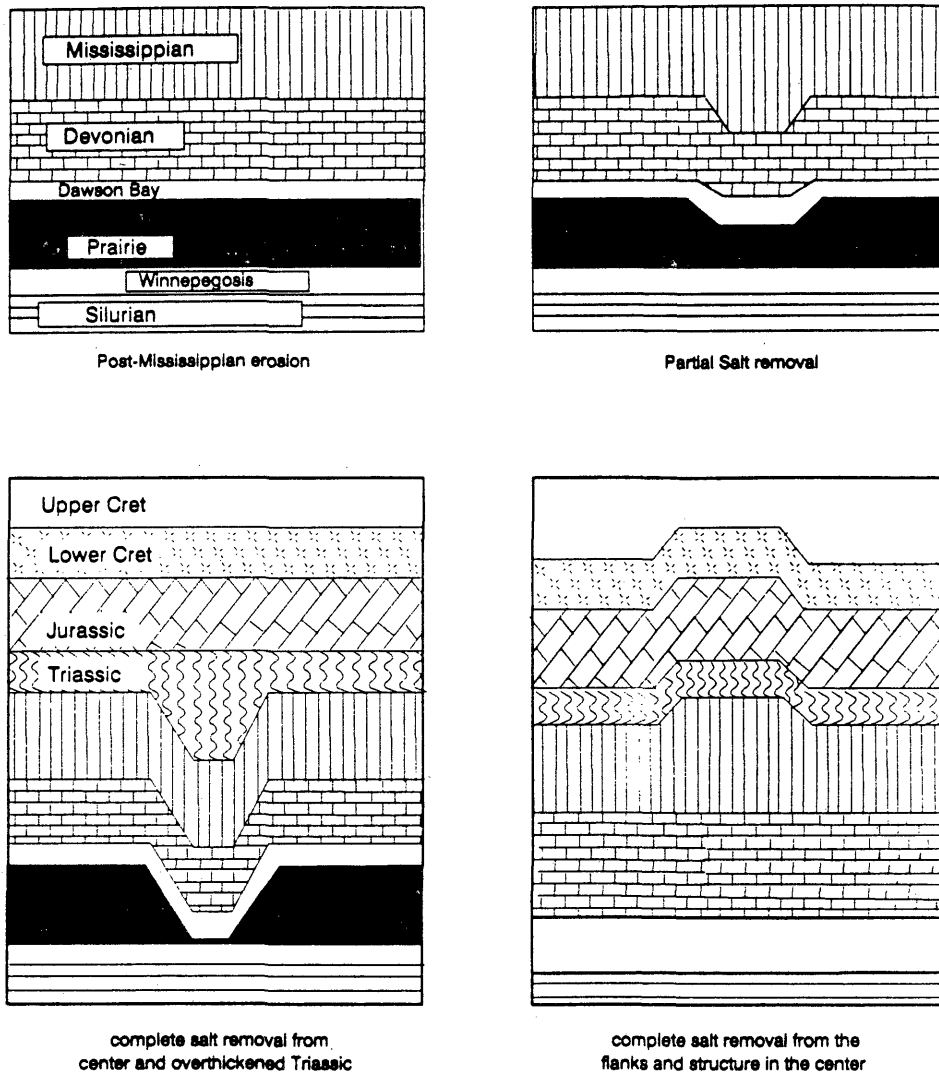


Fig.19A Salt solution structure formed after multi-stage dissolution . Hydrocarbon production is from the overlying thickened structure in some Montana oil fields (modified from Oglesby, 1988)

East, Volt, Benrud, Benrud East, Benrud Northeast and Red Fox. These fields produce from dolomite with intercrystalline porosity (Oglesby, 1988). Volt Field (T30N, R46E) was one of four Nisku (Devonian) field discoveries completed in Roosevelt County, Montana in 1964 with an initial potential of 145 BOPD. The structure contour map (figure 19B) shows a northeast-southwest trend with a relatively flat top and steep sides especially at the northern end.

Salt dissolution is related to fracturing and possibly to basement tectonics. This implies that the periodicity of salt dissolution may be attributed to rejuvenation of these structures, resulting in the opening of fractures along which formation waters are able to move to dissolve the salt.

### **Non-Basement Structures**

Other structures in the Williston basin whose origin remains controversial, but probably unrelated to basement tectonics are the Red Wing Creek and the Newporte structure. The Red Wing Creek field was discovered in 1972 as a structural and seismic anomaly that fits no pattern in the Williston basin. It produces oil from abnormally thick Mississippian strata, the top of which is 2200 feet structurally higher than the top of a similar horizon in a well just three miles away from the structure (Soeripto, 1986). Exhibits presented to the North Dakota Industrial Commission during the spacing hearing for the Red Wing Creek field, interpreted the structure to be an astrobleme (Gerhard et al, 1982). The interpretation has been supported by Brennan et al, (1975) and Parson et al, (1975).

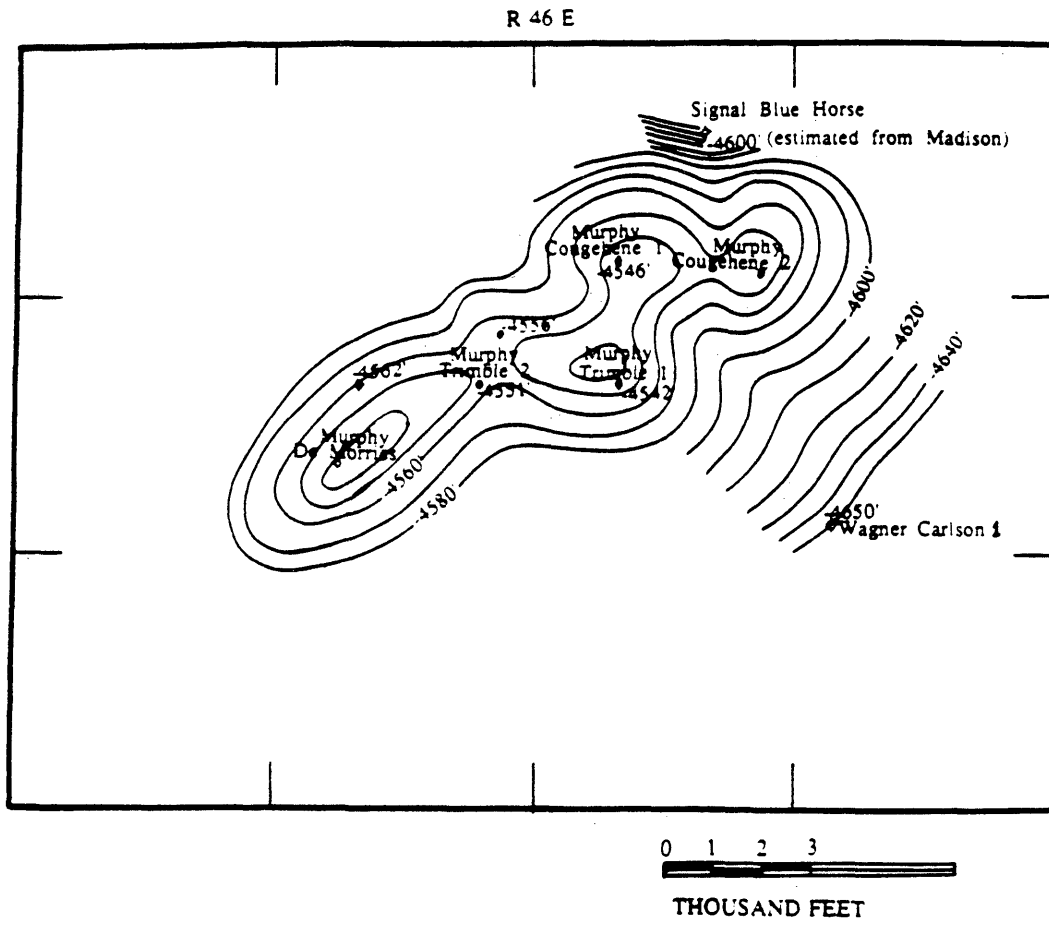


Fig.19B Structure contour map of Volt Field (T30N, R46E), Roosevelt County, Montana (Williston Basin Field Summaries, 1978)

Meteorite impact is considered responsible for the origin of this ring-like depression with a centrally located uplifted block (Figure 20). The major structural disruption is evident in the Jurassic before the deposition of the Piper Formation. The Newporte structure located in north-central North Dakota is another structure whose origin and complexity had continued to pose questions to different workers. Donofrio (1981) suggested that the Newporte structure is possibly a meteorite impact feature.

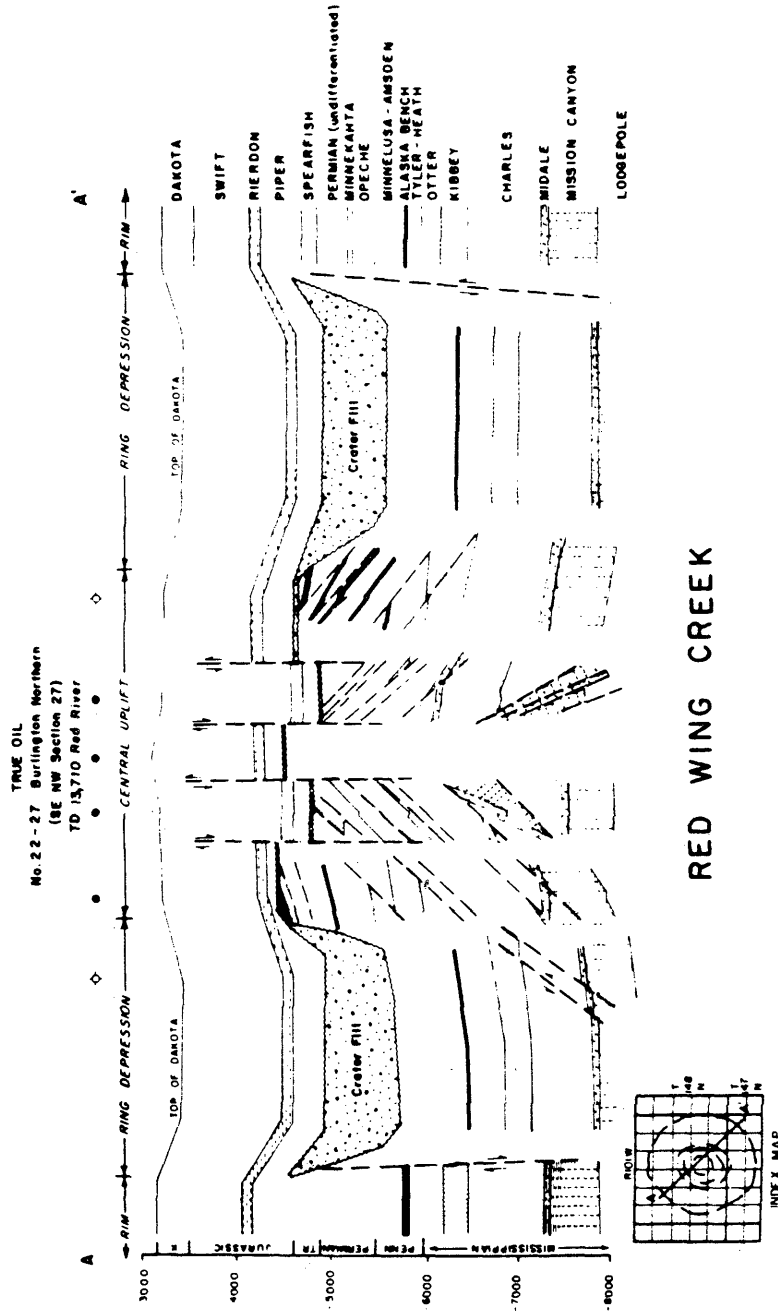


Fig.20 Cross section through Red Wing Creek structure, McKenzie County, North Dakota showing two crater fills presumed to have been formed as a result of meteorite impact (after Gerhard et al, 1982)

### ***Recurrent Fault Block Tectonics***

The style of deformation in which the basement fails under stress, and fragments into a mosaic of fault blocks which are bounded by faults or fracture zones, is referred to as fault block tectonics. These faults and fractures are usually oriented in various directions as determined by, amongst other things, the direction of the stress field that generated them. Faults of different orientations may owe their origin to one or more orogenic movements. A hypothetical illustration of mosaic of fault blocks generated by three different directions - northwest, northeast and north, is shown in Figure 21. Generally, the faults are a few tens of miles wide and long or even smaller with very high angle fault planes, often times, vertical especially when the principal stress field direction is horizontal.

Further tensing of the crust initiates movement along the pre-existing planes of weakness and causes the fault blocks to be differentially offset from one another. Accompanying such structural movement is, often times, fault block rotation and tilting creating what is termed scissor blocks by Brown (1978), and which plunge at varying degrees of dip so that the relation between the sediments deposited in the elevated and depressed blocks vary not only across the fault zone but also along strike in each block because of the differences in water depth.

The sediments deposited over basement faults respond passively and mimic the mosaic pattern by faulting or draping. In the elevated blocks, sediment thickness is usually smaller than in the depressed block. In addition, the sedimentary facies in both blocks may be different. For example, the elevated blocks may be areas of high energy deposits such as algal mounds and grainstones while the relatively depressed blocks may be site of low energy sediments such as wackestones and shales. The latter may also contain high percentage of fragmental material apparently dumped from the adjacent highs.



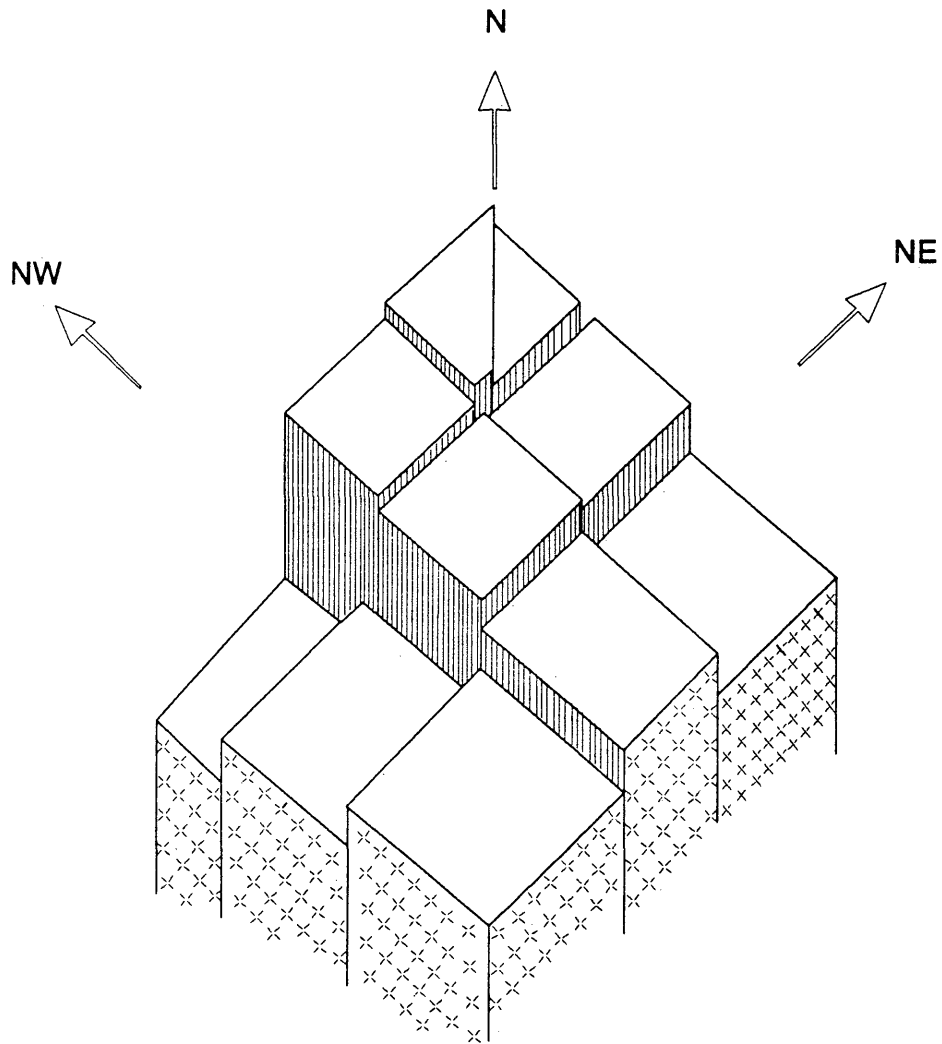


Fig. 21 Mosaic of fault blocks generated by three major directions of faulting , north, northeast and northwest (modified from Sonnenberg, 1981)

Not all fault blocks moved recurrently through time, and the sense of motion along a particular fault plane may vary from time to time. A block may be depressed, say in the Paleozoic and become elevated in the Mesozoic. Stress field orientation during an orogenic episode is a major determining factor as to which fault blocks move and in what sense.

## Stratigraphic Thickness Analysis and Structural Interpretation

Stratigraphic thickness analysis of time bounded intervals is critical to interpreting paleostructures in a given area. Generally, thick accumulation of sequences imply large accommodation potential and conversely, thin sequences imply small accommodation potential. Anomalous thickening or thinning of stratigraphic units over the regional trend is by far more important than the thick or thin intervals themselves, and often times may reflect paleostructural movement. However, great caution must be taken in such structural analysis since various other phenomena such as folding, erosion, salt solution, block rotation and others may possibly cause anomalous thickening or thinning within a time-bounded stratigraphic unit.

Onlap is a depositional geometry in which regular and successive stratigraphic units pinch out or thin toward the basin margin, over structures or paleotopography (Figure 22). This phenomenon is usually associated with an overall water-deepening or transgressive event. Conversely, offlap normally results from an overall water-shallowing or regressive event in which successive younger time-stratigraphic units are deposited farther away from the shore and the older units exposed near the updip terminations (Figure 22). Deltaic progradation which generates inclined foreset beds is a good example of the offlap relationship.

Erosional truncation is a post-depositional feature in which the sedimentary units, usually inclined, become laterally terminated.

Variable sedimentation rates might also cause thinning/thickening patterns in time-stratigraphic units giving rise to what is referred to as convergent strata. The phenomenon

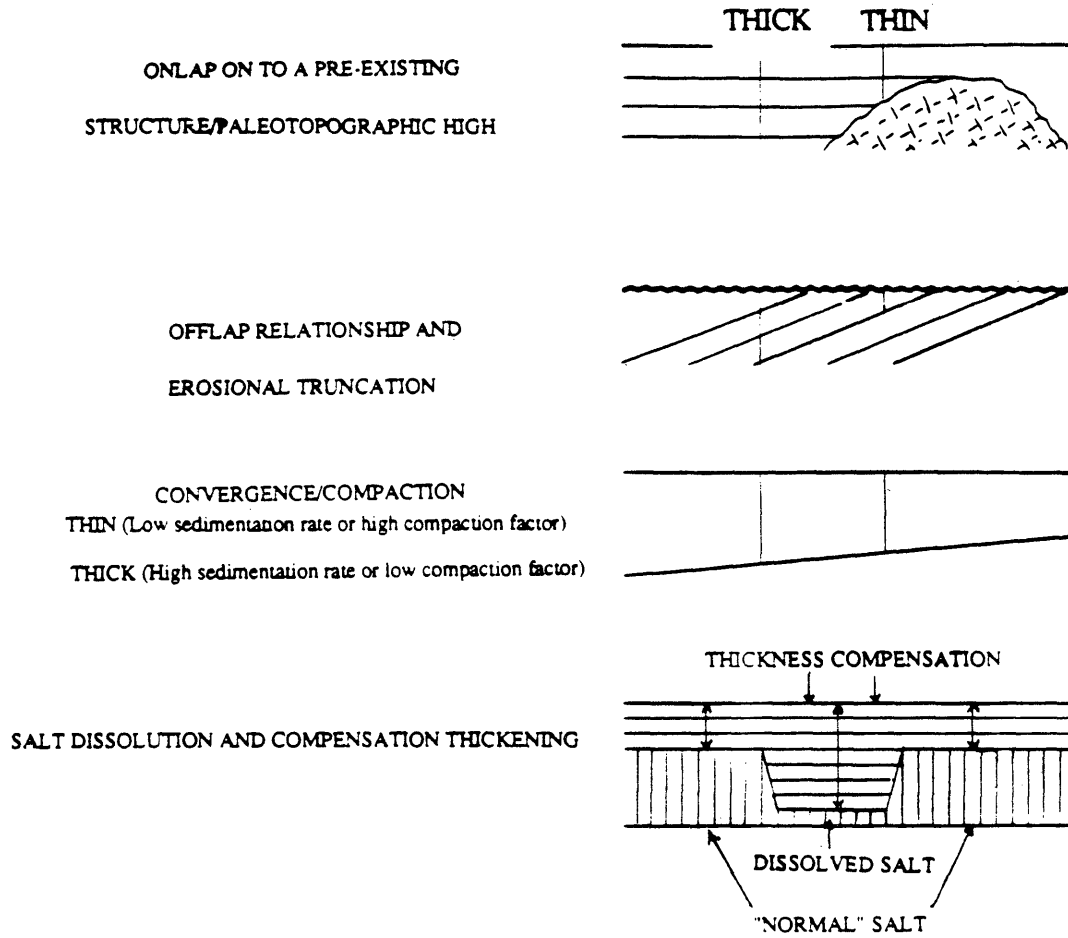


Fig. 22 Schematic illustration of thickness variations in time-stratigraphic units and their causes (modified from Sonnenberg, 1981).

of convergence may also be attained by differential compaction of the deposited units under the influence of an overburden. This feature is also shown in figure 22. Different types of shales, for example, compact differently because of their differing capacities to hold interstitial waters, and shales, in general, compact more than sands.

Salt dissolution such as that which affected the Devonian Prairie evaporite and which is considered to be a multi-stage process, has been known to generate anomalous thickening in younger stratigraphic intervals that overlie the dissolution areas (Figure 22). Such thicks are referred to as compensation thickness. Times of salt dissolution can be analyzed by evaluating and dating the anomalous thickening in overlying strata.

Above all, faulting has been known to be responsible for quite a large number of cases in which counter regional thinning or rapid anomalous thickening of stratigraphic units are significant. Figure 23 shows the cases in which departure from the regional thickening trend may imply structural movement. Depending on the type of fault and dip of the fault plane, faulting may produce additional features such as missing sections in the upthrown block or repeated sections and abnormal stratigraphic thickening. The thickening/thinning pattern may be complicated by rotation and tilting of fault blocks. Counter regional thinning may result from normal faulting in which the fault plane is vertical or very high angle. When the fault plane is inclined thinning as well as missing sections may result from normal faulting, whereas in reverse faulting, bed repetition and abnormal thickening are the main features.

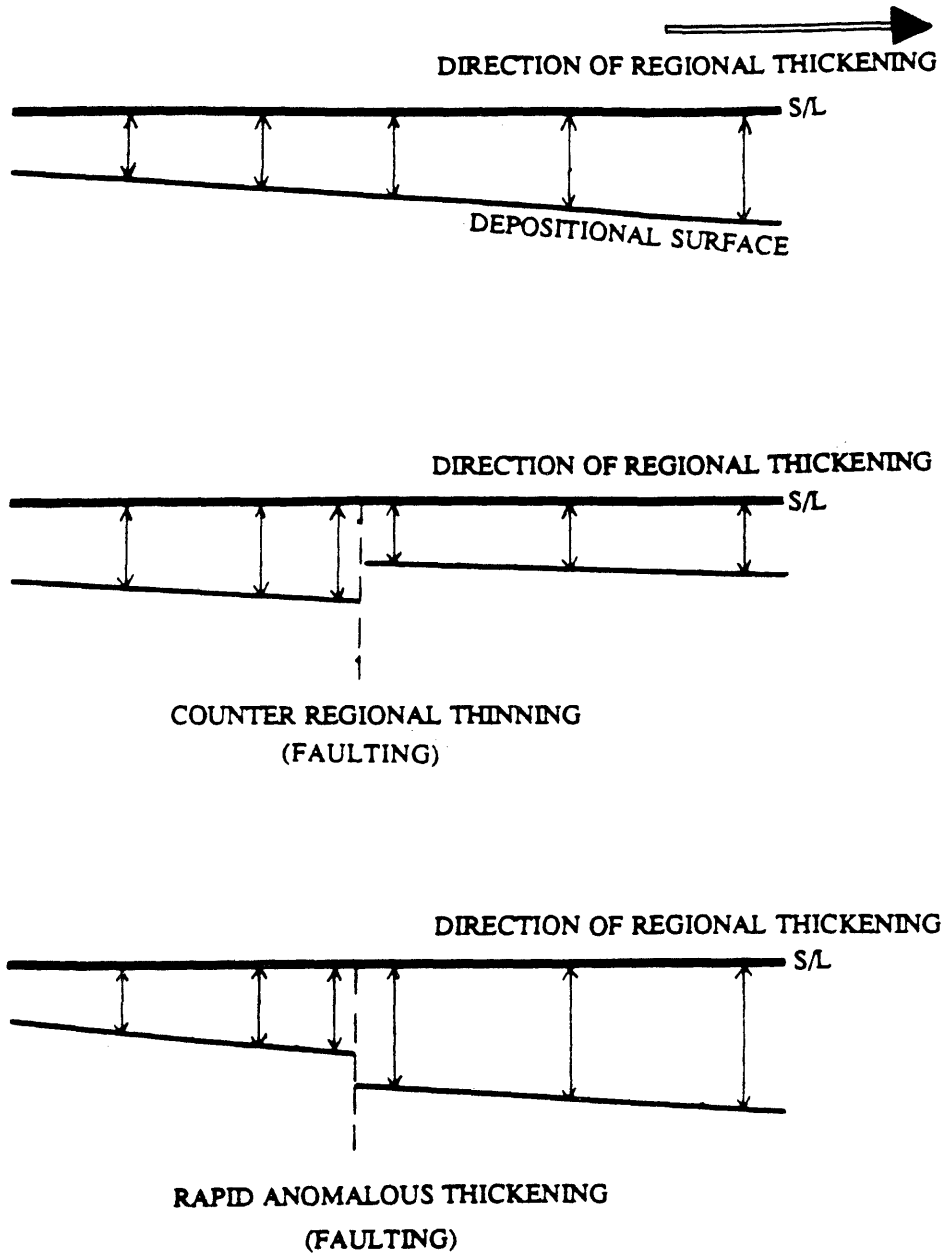


Fig. 23 Stratigraphic thickening and thinning patterns suggestive of faulting

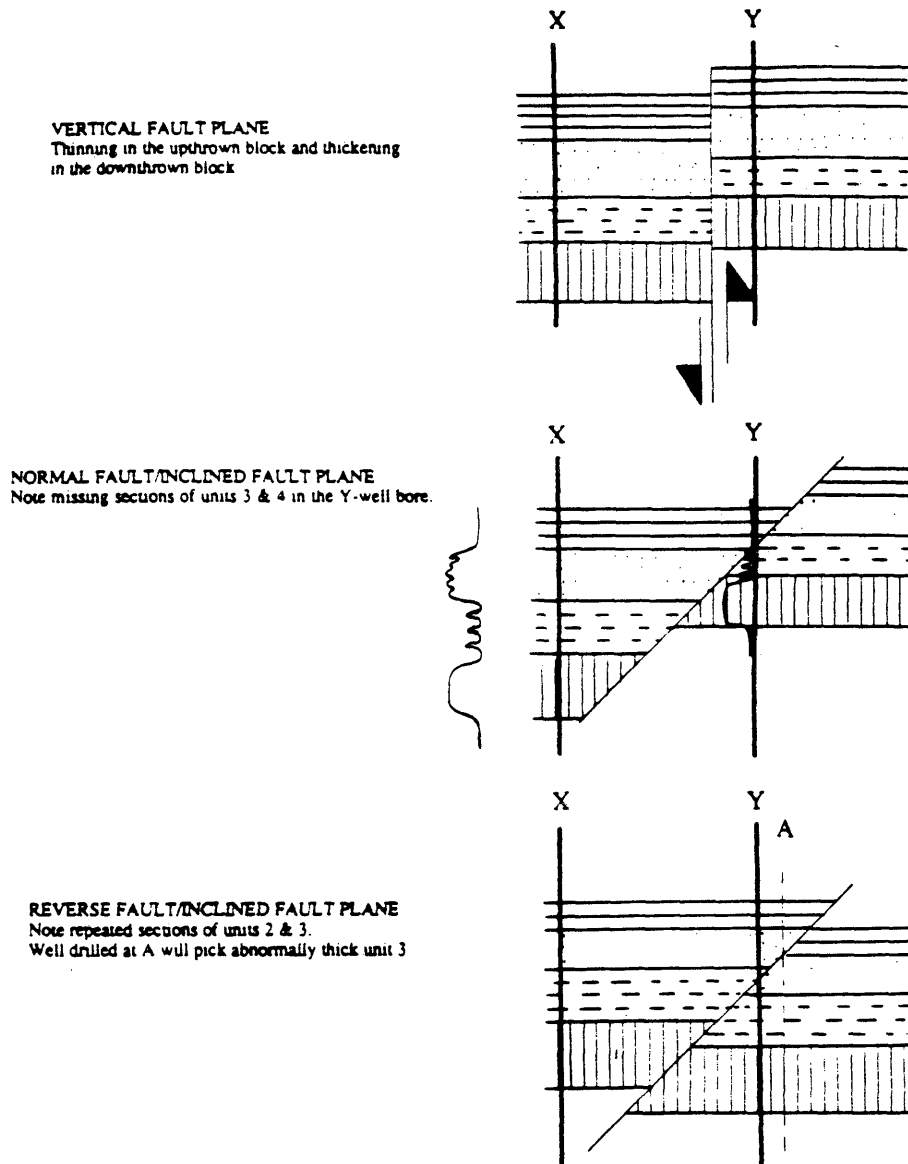


Fig. 24 Schematic diagram showing different fault types and features generated.

## STRUCTURAL GEOLOGY

Several periods of tectonic activities between the Paleozoic and late Mesozoic to early Cenozoic are identified by this study from detailed subsurface mapping. Paleostuctural lineations characteristic of each period of tectonism was noted and found to carry on, for the most part, to other periods of tectonic activity. Northwest and northeast paleostuctural lineations are dominant in the region, especially along the trend of the Nesson anticline, while northerly trends are rare. In Montana area, northeast structural trends are common, the most prominent of which is the Culbertson-Grenora feature, a tectonic feature thought to be related to the northeast-trending Brockton-Froid-Fromberg fault system. The repetitiveness of the paleostuctural trends as determined from isopach maps of stratigraphic intervals, suggests that structural deformation in the study area was predominantly recurrent movement along pre-existing zones of weakness in the basement. It should be noted that the accuracy of paleostuctural interpretation deduced from isopach maps depends on, amongst other things, how much the intervals chosen for isopaching meet certain set of conditions as outlined by Lee, (1954). One of such conditions is that surfaces of isopached stratigraphic units should approach a state of flatness on near horizontality for the isopach map to be able reveal true paleostuctures. The further away the departure from this condition, the less accurate the isopach map is in paleostuctural analysis. In the study area, the lower bounding surfaces of the isopached intervals are selected at basal transgressive units hoping that they represent originally flat depositional surfaces, while the upper bounding surfaces are placed at erosional bevelling surfaces.

The structural geology of the area was studied from a subsurface stratigraphic thickness analysis perspective. The subsurface study consisted of identifying and



correlating twenty-five formation tops from the Cretaceous Greenhorn Formation to the Ordovician Red River Formation from over three thousand well logs scattered throughout the study area. Stratigraphic intervals were then carefully selected for isopach mapping. Such isopach maps are very useful in revealing paleostructural deformation. In the study area, six isopach maps of the Red River - Interlake, Prairie, Dawson - Bakken, Bakken - Charles, Charles - Spearfish and Spearfish - Greenhorn were initially prepared together with four structure contour maps at the tops of Red River, Bakken, Charles and Greenhorn formations. In addition, four regional stratigraphic cross sections, north-south trending AA' (Plate 3) and BB' (Plate 4) and east-west trending CC' (Plate 8) and DD' (Plate 9). The regional cross sections were useful in identifying anomalous areas suspected of having undergone recurrent structural movement. Across such anomalous areas, detailed stratigraphic cross sections utilizing larger scale well logs and closely spaced data were used in documenting the paleostructural history and timing of structural events.

A prominent northeast-trending feature extending from the southwest in Culbertson area, Roosevelt County, Montana (T27N, R57E) to the northeast area around Grenora in western North Dakota (T161N, R102-103W) across a sub-circular Prairie salt dissolution area in Shotgun Creek, Roosevelt County, Montana, was identified first as a salt-thin linear on the Prairie isopach map (Plate 5), and subsequently on the isopach map of the Bakken - Charles interval (Plate 7). The feature is referred to as the Culbertson-Grenora feature in this thesis. In addition, several areas along the trend of the Nesson anticline are suspected to have experienced recurrent structural movement at different times because of the stratigraphic thinning along the axial trace of the anticline. Multiple and probably complex faulting on both flanks of the Nesson anticline was interpreted from the isopach maps.

These preliminary findings prompted a more detailed study of the structural geology of the area concentrating most efforts on the Culbertson-Grenora feature in Montana and the Nesson anticline in North Dakota. To this effect, five isopach maps of tectonic-sensitive intervals - the Devonian units of Souris River, Duperow, Nisku, Three Forks and Bakken were prepared to better define the structural configuration and how paleostructures changed with time. Also several stratigraphic and structural cross sections were constructed across the anomalous features in order to determine the timing of structural movement.

Several fault blocks are identified from the detailed stratigraphic cross sections MT-A (Plates 17a, b & c), MT-B (Plates 19a, b & c), MT-C (Plates 18a, b & c) and MT-D (Plates 16a, b & c) prepared across the Culbertson-Grenora feature at various locations along its trend. Episodic recurrent movement of fault blocks was the dominant style of deformation. Times of major structural movement were Devonian, Mississippian, Permian and Triassic. In the salt dissolution area in Montana, structural movement seems beclouded by Prairie salt dissolution and compensation thickness phenomenon in overlying stratigraphic units. Careful analysis of the thickness anomaly observed in younger stratigraphic intervals across the dissolution area, indicates that the cause of the extra stratal thickness is not just thickness compensation as a result of salt dissolution, but a combination of that and structural movement. Calculation of stratal thickness of the dissolved Prairie salt versus the extra stratal thicknesses observed in the overlying Tyler, Minnelusa and Spearfish formations between the No. 2 Jacobsen Estate well and the Picard A#1 well, indicates that there is more rock thickness than compensation thickness can account for. Faulting may thus have localized the dissolution trends and created additional accommodation potential for the extra stratal thicknesses.

In addition, the rectilinear surface drainage pattern observed in the area (Plate 1) coupled with the straightness of some of the streams, imply strong tectonic control and lends support to a structural interpretation.

When it appeared that Prairie salt dissolution was overshadowing or beclouding any possible structural movement along the trend of the Culbertson-Grenora feature in the salt dissolution area, an area out of the limit of Prairie salt deposition in Mc Cone County called Cow Creek/Weldon, was studied with a view to learning the structural characteristics of the Weldon-Brockton fault where it had been established by previous work such as Hicks (1985). Isopach and structure maps of producing Kibbey interval and four NW-SE stratigraphic cross sections C1-C2 (Plate 23), C3-C4 (Plate 24), C5-C6 (Plate 25) and C7-C8 (Plate 26) prepared in the Cow Creek/Weldon field area (T21-23N, R46-48E) demonstrate structural movement on the Weldon-Brockton fault. Times of major movement were Pennsylvanian and Permian during the time of deposition of the Heath, Tyler and Amsden (Minnelusa). No deep well data are available for documenting earlier structural history. Similar strata are affected in the study area but with reduced intensity. It thus seems that major activities on the Culbertson-Grenora feature, a probable branch of the Brockton-Froid-Fromberg fault system were concentrated to the southwest and attenuate generally to the northeast. The near constancy of the Second Red Bed member capping the Prairie evaporite on most of the cross sections across the area, indicates that thinning within the Prairie was not a dissolution process but a structurally controlled phenomenon. This study thus sheds more light on the possible northern extension of the Brockton-Froid-Fromberg fault zone.

Isopach maps were interpreted with regard to structural elements. Basic indication of structural elements is stratigraphic thinning/thickening pattern. Alignment of isopach thicks

and this is indicative of paleostructure. Close spacing of isopach contours or "tightening" may be used to delineate fault/fracture trends or draping over deep-seated fault zone.

Abrupt changes in contour pattern or trend may also suggest faulting. Based on the above criteria the Nesson anticline was interpreted into a mosaic of fault blocks consisting of at least six blocks. These fault blocks are of varying sizes and are bounded on all sides by faults or fractures. Five prominent faults are documented along the trend of the Nesson anticline. These are the West Nesson fault which bounds Charlson fault block or block 1 and Beaver Lodge fault block or block 2 to the west, the East Nesson fault bounding fault block 2 to the east, the West Temple fault which bounds Temple fault block or block 4 to the west, the East Temple fault which bounds fault block 4 to the east and the Charlson fault which separates the Charlson fault block from Beaver Lodge fault block. Lack of adequate data and inavailability of closely spaced well data do not permit proper resolution of fault block 3, which to my mind, may even be broken up into at least 2 or more smaller fault blocks. Fault block 5 is the western flank of the Nesson anticline and fault block 6 is the eastern flank, each of which may also contain several fault blocks, but lack of adequate data did not allow this determination.

Paleostructures can be interpreted from thickness variation analysis of time-stratigraphic intervals. Basic premise in tectonics and sedimentation is that fault block movement generally affects topography and bathymetry at the site of deposition, hence thick stratigraphic units accumulate in depressed areas while thin units accumulate in elevated areas. Counter regional thinning or anomalous rapid thickening is often accompanied by facies changes as observed across the major faults interpreted in the study area.

The faults recognized along the flanks of the Nesson anticline appear not to be straight, long and continuous types of faults as postulated by past workers including Le Fever et al, (1987). Rather structural deformation along the Nesson anticline seems to have given rise to a mosaic of fault blocks bounded on all sides by faults or fractures of smaller dimensions, which trend in northwest and northeast directions, and along which recurrent structural movements have taken place.

Detailed E-W stratigraphic cross sections NDAA' (Plates 29a, b & c) and NDBB' (Plates 30a, b & c) constructed in the southern portion of the Nesson in the study area were useful in determining the times of major structural movement on the West Nesson and East Nesson faults, thus differentiating between the Beaver Lodge fault block (Block 2), block 5 and block 6. Stratigraphic cross sections TT' (Plates 34a, b & c), MM' (Plates 35a, b & c) and NN'' (Plates 36a, b & c) were equally instrumental in analysing the history of structural movement across the West Temple and East Temple faults and thus differentiating between the Temple fault block (block 4) and fault blocks 5 and 6. North-south stratigraphic cross section XX' (Plates 37a, b & c) helped in distinguishing between the Charlson fault block (block 1) and the Beaver Lodge fault block (block 2), and analysing the history of structural activities along the interpreted Charlson fault.

Interpreted fault blocks are of varying sizes ranging from about 40 square miles in block 4 to over 130 square miles in block 2. The bounding faults have a semi-rectilinear geometry and are mostly high angle to vertical faults. Evidence for this is gathered from the fact that there are no missing stratigraphic sections between correlated wells on either side of the faults, although well spacing might in part be responsible for this. Also, previously mapped basement-related faults in the same general area have been found to be very steep or vertical (Sonnenberg, 1981). The distinction between fault blocks was based

on the analysis of stratigraphic thickness variations across the features and the general orientation, pattern and fabric of the structures and fields. Phanerozoic recurrent structural movements on these faults with structural reversal in the Absaroka on the East Nesson fault and in the Mississippian on the East Temple fault is demonstrated. Structural activity in each fault block seems to be independent of the other blocks, but the Devonian deformation was ubiquitous and common to them all.

The profound influence recurrent structural movement on basement may have on overlying sedimentary patterns and hydrocarbon accumulation can not be overstated. Draped folds often form in response to basement movement with their shape dictated by the amount of relief across the basement block. These folds may affect a portion of, or the entire sedimentary section, thus creating favorable trapping mechanism for any possible hydrocarbon accumulation. Recurrent structural movement causes intense fracturing in overlying strata, and along these fractures, magnesium-rich fluids can migrate to dolomitize limestone deposits. Dolomitization enhances original porosity and facilitates further fracturing, which also increases porosity, but more importantly, the permeability.

The Antelope field on the Nesson anticline produces from structural closure with permeability changes across the structure in the Devonian. The permeability changes are thought to have resulted from fractures generated as a result of recurrent movement on basement weakness zones (Davis, 1989, personal comm.).

A cursory look at the location of these fields with respect to the positions of the interpreted faults and fractures indicate that the fields are mostly situated around and along the faults or at the intersection of faults or fractures instead of being centered on the different fault blocks. This observation is a manifestation of the role of fracturing,

resulting from recurrent movement , on hydrocarbon accumulation. The model may thus help as a predictive tool for oil and gas occurrence in a relatively unknown areas.

In order to be able to understand the development of paleostructures through time the discussion of isopach maps is arranged from the oldest interval to the youngest.

## INTERPRETATION OF ISOPACH MAPS

### *Red River - Interlake Interval*

Subsurface data control below the Silurian Interlake Formation in the study area is limited and that below the Ordovician Red River Formation is very sparse. For this reason, it was not possible to study the earliest structural history involving units below the Red River. The earliest paleostructural information documented in this study is from the upper portion of the Tippecanoe sequence represented by the isopach of the interval from the top of the Red River to Interlake Formation (Figure 25). The lower limiting surface of the isopached interval is the top of the Red River Formation, or the base of the argillaceous Stoughton Limestone Member of the Stony Mountain Formation. The upper bounding surface is the top of the Silurian Interlake Formation which represents a major unconformity surface, heavily karsted and associated with the early Devonian regression (boundary between the Tippecanoe and Kaskaskia sequences).

The isopach map (Plate 2) shows a general regional thickening of this interval from about 500 feet in Roosevelt County, Montana in the west, to over 1450 feet in Williams County, North Dakota, in the east. Isopach contours trend north-south for the most part in the western part of the study area but change to north-northeast near the Montana - North Dakota state boundary. This north-northeast grain is disturbed in the eastern portion of the study area around the Nesson anticline. An area of thin rocks is observed along the length of the Nesson anticline following two major directions - northwest and northeast and thus indicating its influence as early as Tippecanoe time.



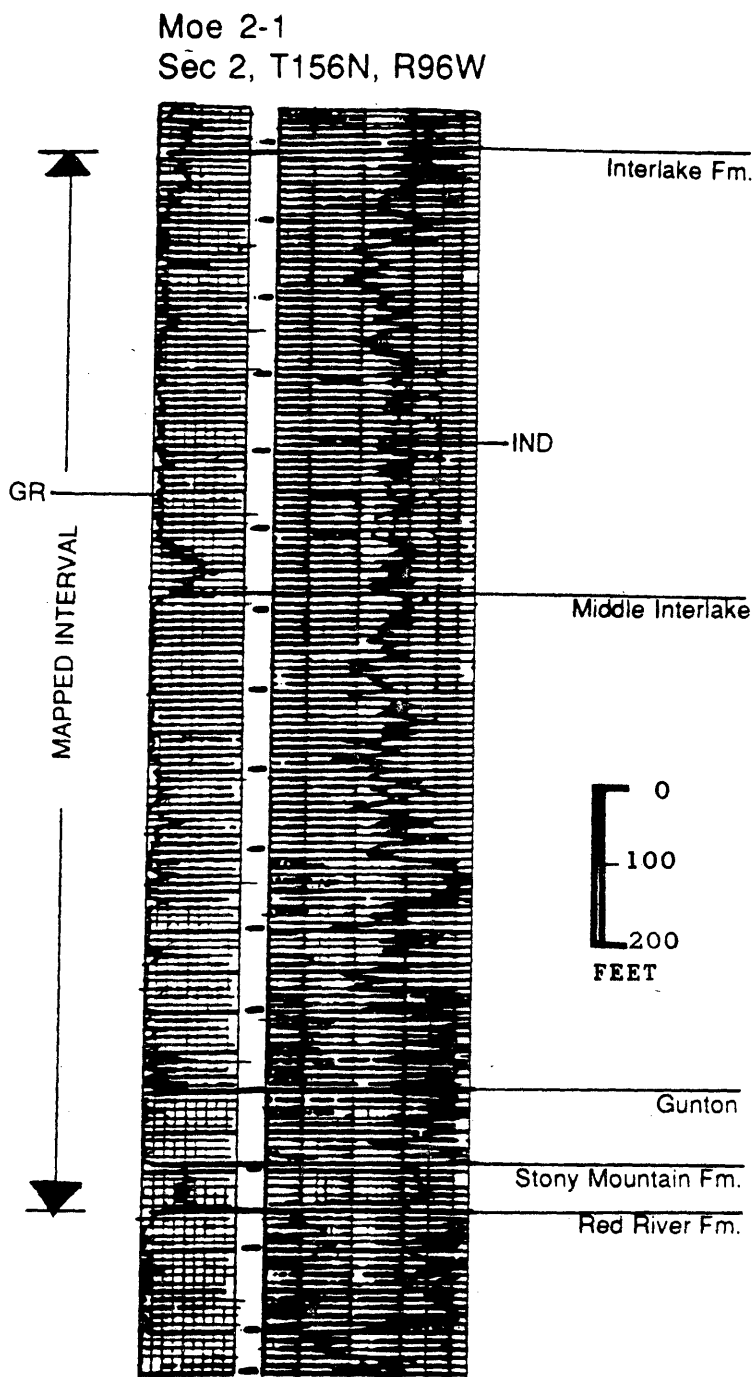


Fig.25 Electric log of the interval isopached from the top of the Red River Formation to the top of the Interlake Formation from well Moe 2-1 (2-156N-96W), Williams County, North Dakota

A secondary northwest trend is observed in the south-southwest portion of the area around Bainville in Roosevelt County, Montana. This trend is associated with small northwest-aligned areas of thin and thick rocks which are oblique to the direction of regional depositional strike. Also in the southeast portion, the Antelope anticline manifests itself as a northwest-trending thin rock area, inclined to the southern end of the Nesson anticline. In Montana, the average rate of stratigraphic thinning is 9 feet per mile. It changes slightly to 8 feet per mile in North Dakota, where north-northeast grain is assumed. These gradients change drastically around the Nesson anticline, being about 25 feet per mile to the west of the thin area around T157-158N, R95W and 22 feet per mile to the east of the same structural feature on the Nesson anticline.

Along the Nesson anticline, several subsidiary portions were active during the deposition of the Tippecanoe Sequence, notably the Beaver Lodge field area (T155 -156N, R96W) which shows up as a northeast-trending thin in the southern part and north to northwesterly linear trend in the northern part. The area west of Tioga field (T157 - 158N, R95W) shows similar linear trends with the Beaver Lodge field, that is, northeasterly - trending area of thin rocks occurs to the southwest portion of Tioga field and northwesterly -trending area of thin rock occurs to the northwest portion. A third area occurs in the north of the study area on the west side of Noonam and Planeview fields (T161 -162N, R95W). The structurally lowest area lies to the southeast of Beaver Lodge field area in Mountrail County, North Dakota. During the Tippecanoe at the time of deposition of the Red River - Interlake interval, the northwest and northeast paleostructural trends appear to be most dominant.

Two regional stratigraphic cross sections AA' and BB' (Figures 26 & 27 (Plates 3 & 4) ) constructed from west to east along the direction of depositional thickening and

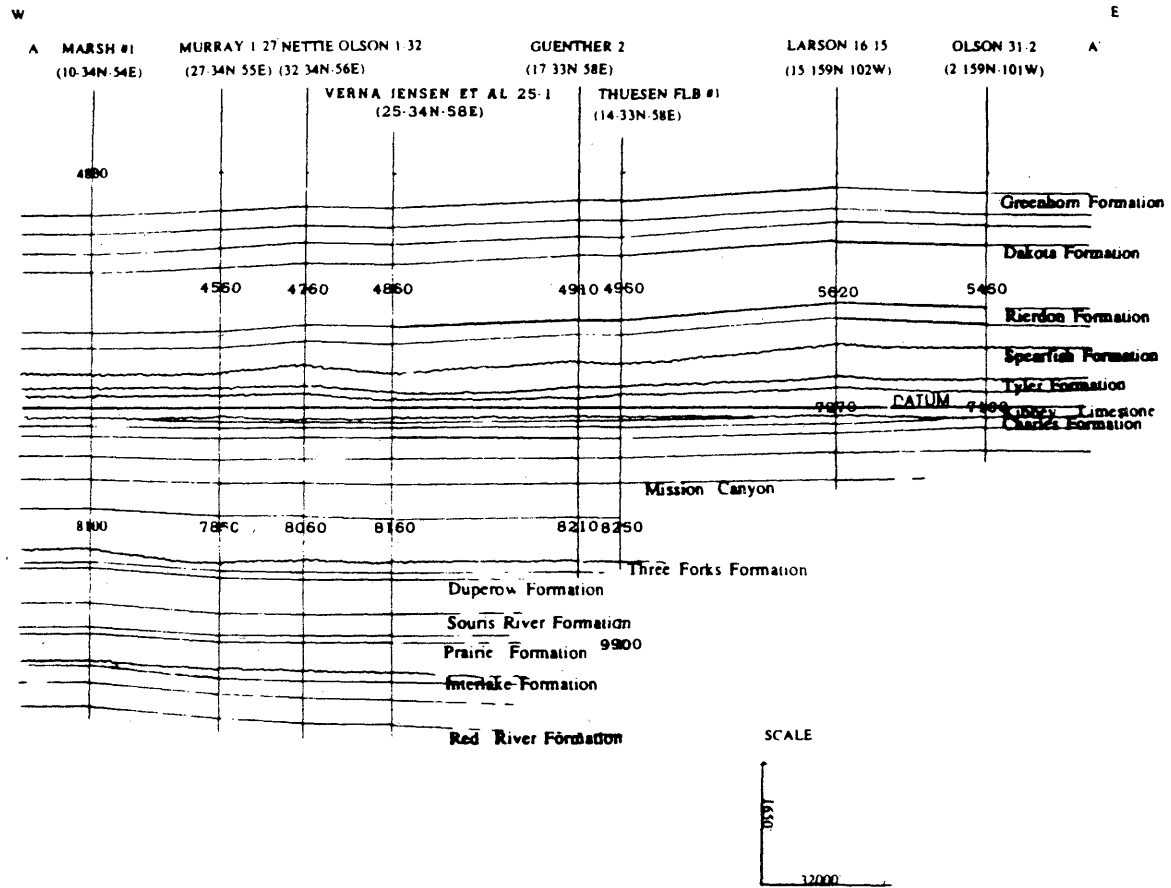


Fig. 26 East-West regional cross section A-A' from Montana to North Dakota

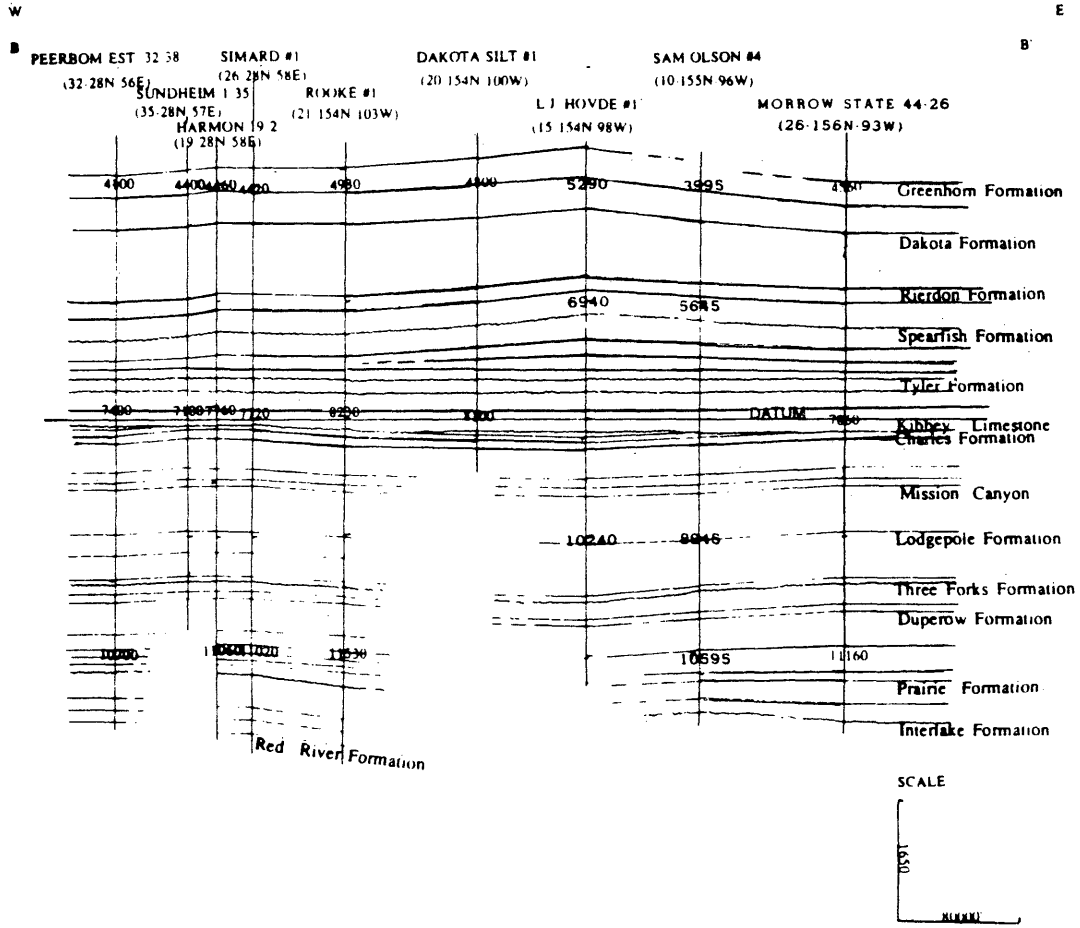


Fig 27 East-West regional cross section B-B' from Montana to North Dakota

apparently that of the dip, support the general features of the isopach maps (Plates 3 & 4). All stratigraphic units within the Tippecanoe sequence thicken to the east as far east as the western side of the Nesson anticline. Positive activity on the Nesson anticline at this time caused thinning in the stratigraphic units. Detailed correlation of the internal units of the mapped sequence indicates that most of the thinning occurs at the top of the Tippecanoe (Upper Interlake Formation). This thinning is probably due to erosional truncation at the top of the Silurian Interlake Formation. A similar phenomenon was documented by Rhoel (1967) in the Cedar Creek area. Erosional truncation at the top of the Interlake may thus have contributed to most of the thinning in the area. Because most of the individual units within the mapped sequence do not change appreciably in thickness across the area, it is believed that paleostructures were essentially created after deposition of the sequence.

Tippecanoe sedimentation also may have been influenced by northeast lineaments especially the Brockton-Froid-Fromberg fault zone as the trend of the contours changes from north-south to northeast in western North Dakota, paralleling the Brockton-Froid-Fromberg fault zone (Plate 2). This change is also accompanied by a slight change in rate of thinning. The change is suggestive of minor reactivation of the lineament or fault zone during Tippecanoe sedimentation. Effects of recurrent movement become more obvious in the younger sequences as shown later on in the discussion.

The drastic change in rate of stratigraphic thinning west of the Nesson anticline in western North Dakota from 8 feet per mile to 25 feet per mile on the western margin of the anticline and 22 feet per mile on the eastern margin, suggests positive activity of the Nesson anticline during Tippecanoe time. Faulting at the margins and on the crestal portions of the Nesson anticline are suggested by the isopach map and cross sections.

Detailed cross sections prepared across this feature at several positions along its length, show this point and is further discussed in the thesis.

Of note is the trace of the axis of the Nesson anticlinal fold as revealed by the areas of thin rocks deduced from the isopach map along its length. The trend of the axis changes from northeast around Planeview field area to northwest west of Temple field and back and forth between West Tioga and Beaver Lodge fields. A very conspicuous change in direction is to the south of the anticline where it seems to split into two folds, the more prominent of which is the Antelope anticline, a northwest-trending satellite feature of the Nesson. Those areas marking changes in paleostructural lineations or might be locations of northeast-trending, cross-structure faults or offset linears.

### *Prairie Evaporite Sequence*

The Devonian Prairie evaporite was mapped as a single entity because of its variable thinning and thickening characteristics. Figure 28 shows the interval isopached from the top of the youngest halite member overlying the Mountrail Potash member to the bottom of the oldest halite member, the Ratner Member. The capping stratigraphic unit of the Prairie Formation, the Second Red Bed, is not included in the isopach because it obscures the thinning/thickening patterns of the salt. Oglesby (1988) concluded that, in top-to-bottom dissolution thinning of the Prairie salt, there is a compensating thickening of the Second Red Bed member as a result of collapse breccias filling the space created by the dissolution. The presence of a thicker Second Red Bed section may result from development of a thicker paleosol on the Winnipegosis carbonates or from the collapse of Prairie evaporite (Figure 29).

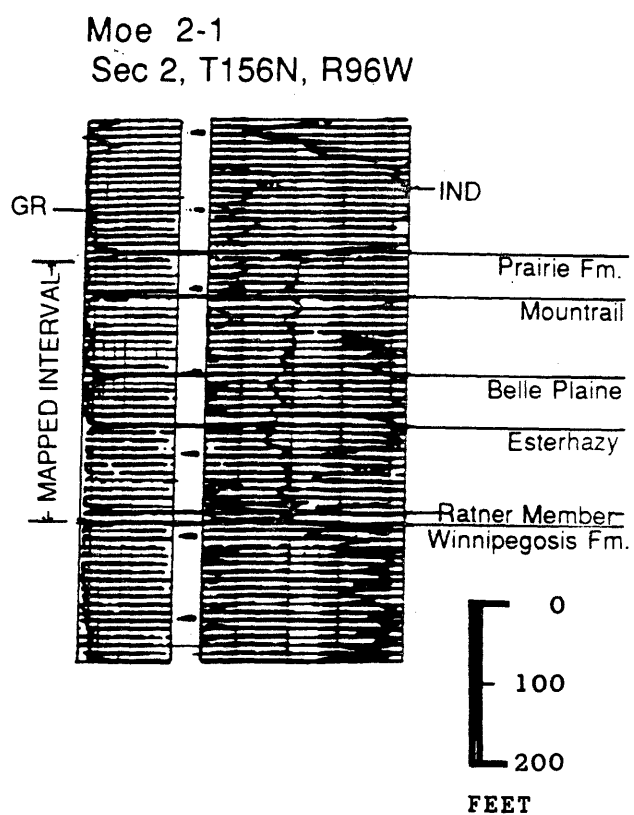


Fig. 28 Electric log of the isopached Prairie Evaporite (the Second Red Bed Member is excluded), from well Moe 2-1, sec2, T156N R96W, Williams County, North Dakota

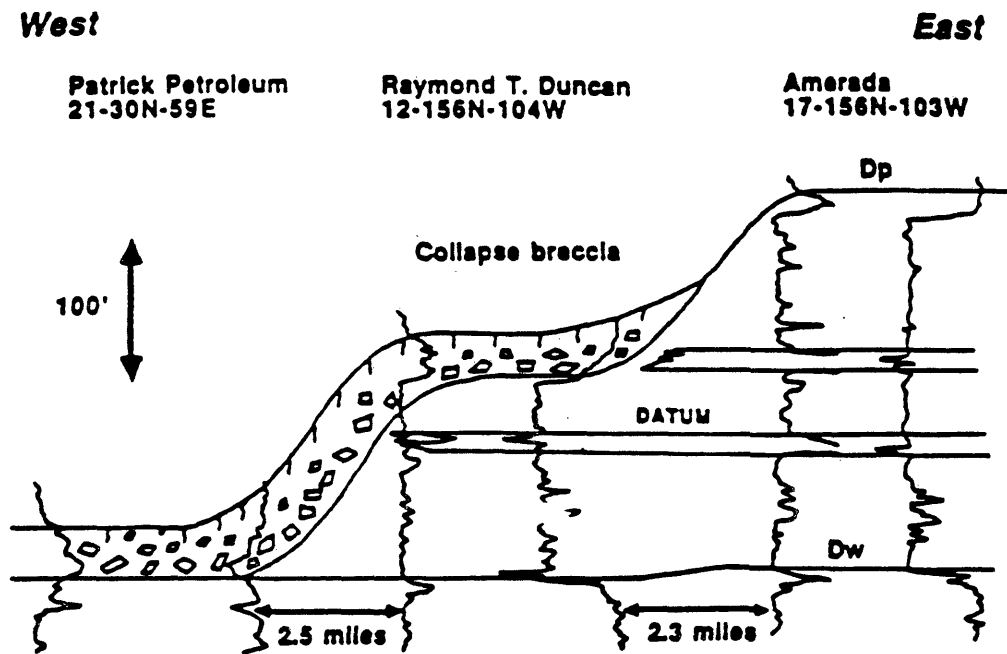


Fig. 29 Thickening of the Second Red Bed due to formation of collapse breccias as a result of top-down salt dissolution (after Oglesby, 1988)



General features of the Prairie evaporite isopach map (Plate 5), indicate that the northwest and northeast paleostructural trends continued to be active throughout the time of deposition of the Prairie, as a linear alignment of narrow thin intervals in two major directions, northeast and northwest is observed. General thinning of the salt is to the west-southwest. To the west of the study area the general trend of the isopach contours is northwest and thinning is generally to the southwest at an average gradient of 10 feet per mile, close to the limit of salt dissolution, and about 4 feet per mile away from this zone. A very prominent northwest-trending area of thin section in the study area occurs to the southwest just north of Bainville in Roosevelt County, Montana. This linear is characterised by a very high thinning gradient of 50 feet per mile. Two other subtle northwest-trending linears occur in the northeastern corner of Montana around Clear Lake and Katty Lake field areas. Perhaps the most striking salt thin noticeable in the area is the northeast-trending linear from Culbertson in the southwest through Shotgun Creek to Grenora in western North Dakota. The trend of this area of thin Prairie salt seems to follow that of the broad zone of the Brockton-Froid-Fromberg fault system. The exact nature of this anomaly was further examined in the study using detailed stratigraphic cross sections (Plates 16a,b & c; 17a,b & c; 18a, b & c & 19a,b, & c).

Also, an area outside of Prairie salt depositional limit, was selected southwest of the original study area in McCone County, Montana (T21 -23N, R46 -48E) to learn the characteristics of the Brockton-Froid-Fromberg fault in an area where it has been identified by other work. The northeast-trending linear is characterised by a thinning gradient of 66 feet per mile around the focus of a big dissolution feature just east of Shotgun Creek, Roosevelt County, Montana (T29-30N, R57-59E). Another northeast-trending area of thin

rocks occurs to the east of this prominent northeast feature. This has a thinning gradient of 13 feet per mile.

Along the Nesson anticline, salt isopach thins occur in linear trends on the anticline. The salt linears generally trend north-south but change direction slightly at a few locations along the Nesson anticline in a similar fashion displayed by the axis of the Nesson anticline on the Tippecanoe sequence isopach map. The average rate of thinning on the Nesson anticline is 17 feet per mile. The general direction of salt thickening is north and northeast. A thick salt accumulation (>410 feet), occurs to the west of the most northerly northwest-trending salt thin around McGregor and Temple field areas.

The narrowness of salt isopach thins, their spatial arrangement, orientation in northwest and northeast directions and sublinear patterns in the area, suggest a strong tectonic influence. The dissolution zones seem to mimic the basement fabric earlier discussed. During later periods of deformation, individual blocks were subjected to stress fields of varying orientations which caused reactivation of the weakness zones. Extensive fracturing along the lineaments may open path ways not only for migration of hydrocarbon, but also for fresh, potent, unsaturated dissolving fluids thus contributing to Prairie salt dissolution. Lateral migration of fluids is also possible which explains the linearity of many dissolution areas. The largest dissolution feature in Roosevelt County, Montana (T29-30N, R57-58E), occurs along a northeast trend which is coincident with a northeast lineament, probably part of the Brockton-Froid Fromberg fault complex bringing in fresh water into the basin. The subsidiary feature that trends northwest from Bainville area was probably caused by unsaturated fluids that got diverted at the lineament intersection northwest of Bainville, in accordance with the theory on groundwater flow pattern in fractured rocks (Figure 30) , (Anna, 1986 in Oglesby, 1988). Consequently, the main

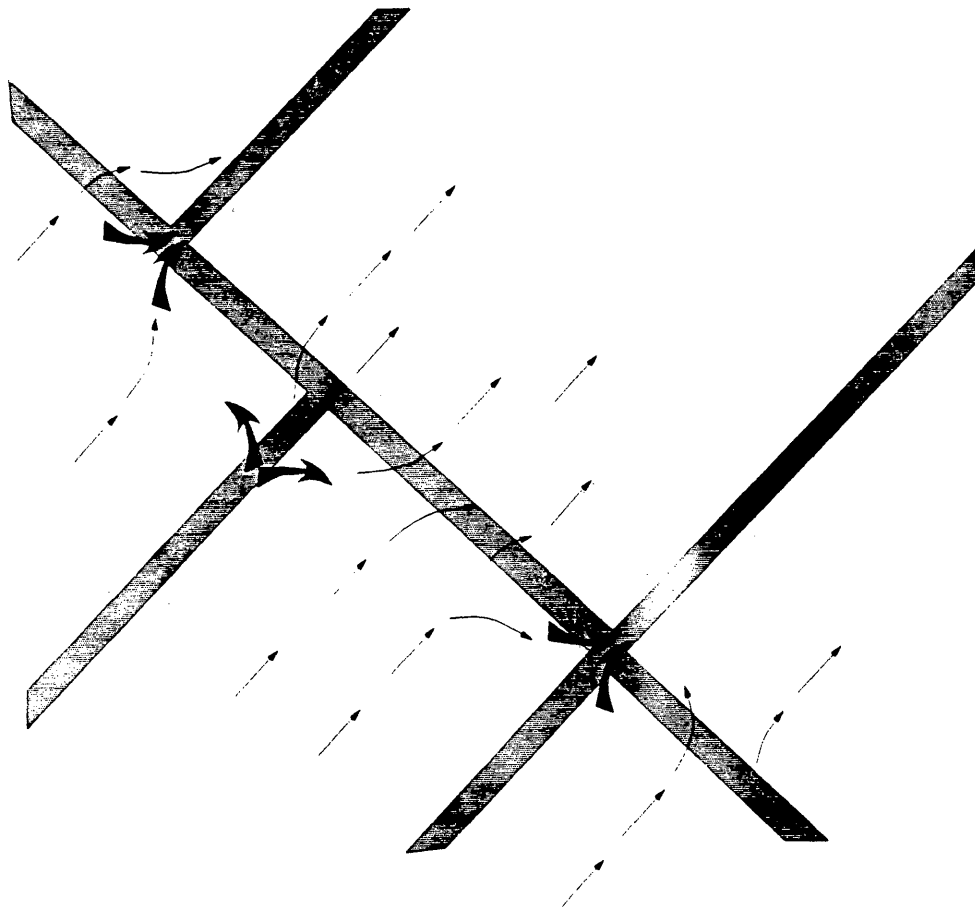


Fig. 30 Theoretical flow directions of groundwater in a fractured system of rocks  
(after Anna, 1986)

dissolution features align with the main flow direction of potent, undersaturated fluids (northeast) and the subsidiary dissolution features align with the subsidiary flow direction of secondary diverted fluids along criss-crossing, northwest -trending lineaments. Regional cross section C-C' (Plate 8 (Figure 31)) and detailed stratigraphic cross section MT-A (Plate 17c (Figure 32c)) prepared across this big dissolution feature were useful in demonstrating not only the abrupt thickness changes in the Prairie salt, but also what mechanism might be responsible for the thinning. Oglesby (1988) used the correlation of the several regionally correlative upward-brining and shoaling sequences within the Prairie Formation across the Williston basin , to demonstrate at least two types of mechanism responsible for Prairie thinning. These are salt dissolution (mostly from top to bottom) and depositional thinning (onlap over Winnipegosis reefs).

Applying a similar genetic stratigraphic correlation to the cross sections prepared in the study area, as the Prairie is flattened on top of Winnipegosis Formation, the thinning of 177 feet between the True Oil well Krogedal 31-5 (T30N, R57E, Sec 5) and Superior well, Jacobsen #1 (T30N, R57E, sec 13) is accounted for mostly by the absence of the potash beds and the top halite members in the Krogedal 31-5 well (Plate 17c ). At the same time, the Second Red Bed increases from 15 feet in the Krogedal 31-5 well to 45 feet in Jacobsen Estate #1 well (13-30N-57E) and 50 feet in the No. 2 Jacobsen Estate well (T30N, R58E, Sec 17). These observations are consistent with Oglesby's interpretation of top-to-bottom dissolution in the Prairie and may suggest a combination of faulting and dissolution. Another observation supporting salt solution is the sharp and high thinning gradient (100 feet in 1 - 3 miles) associated with these features as observed by Oglesby (1988).

Gradual salt removal from the dissolution areas caused abnormal stratal thickening in younger sedimentary units, a phenomenon commonly referred to as thickness

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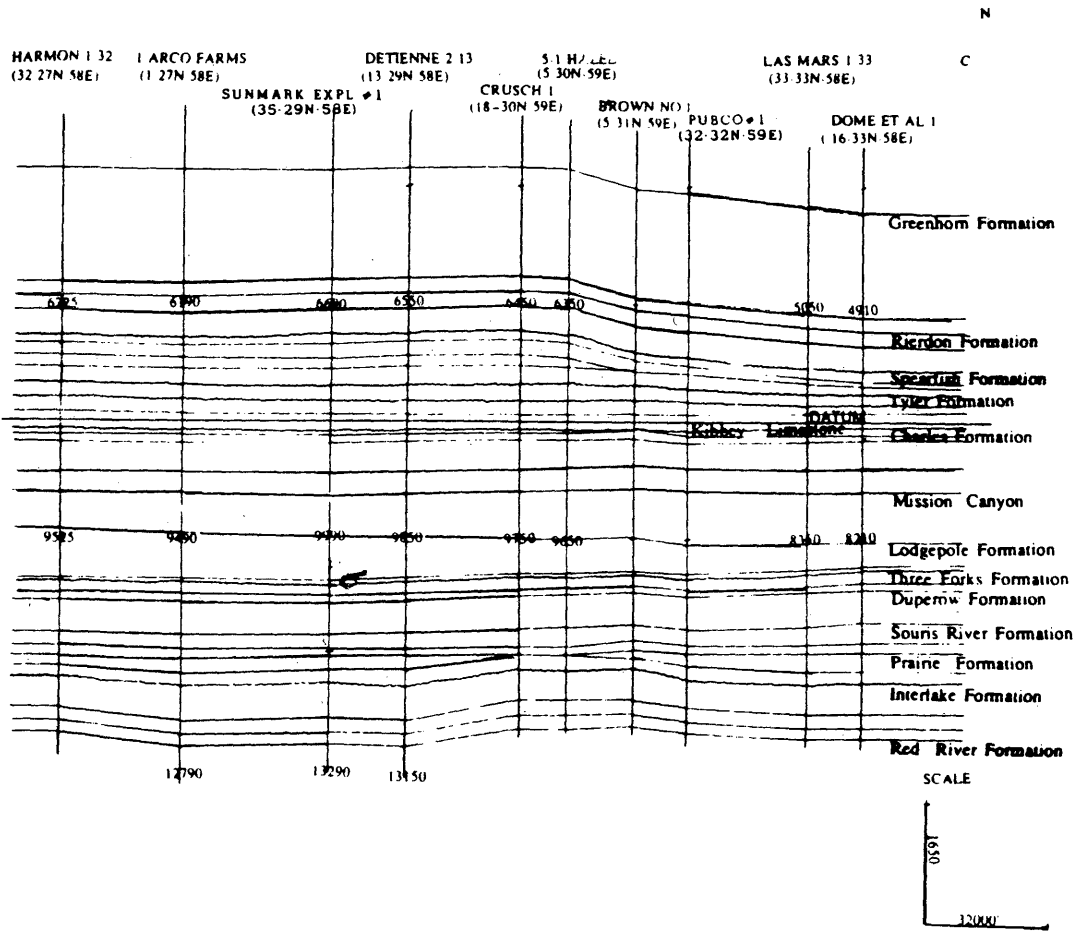


Fig. 31 North-South regional cross section C-C'

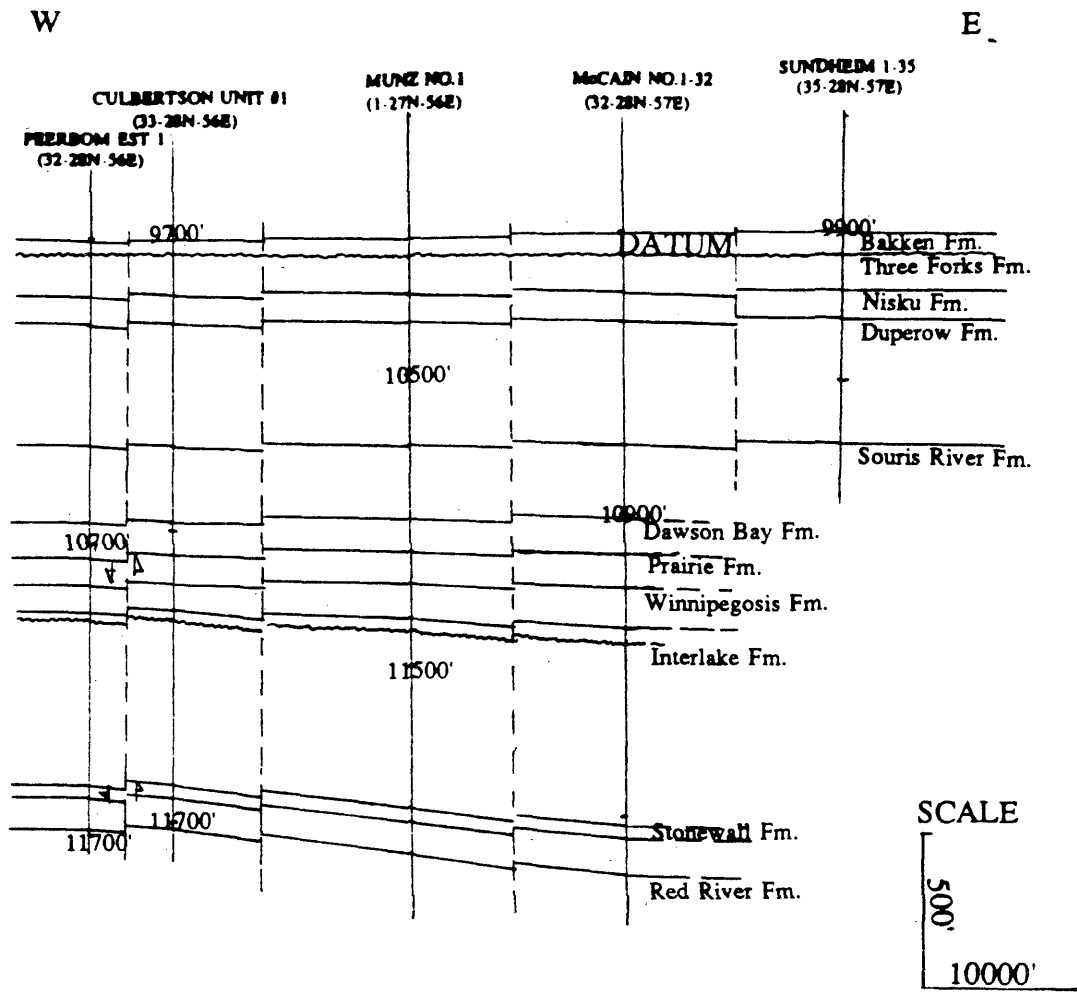


Fig. 32c East-West Stratigraphic cross section MT-A (Red River - Bakken Interval)

compensation. As revealed by the regional cross section CC' (Plate 8 (Figure 31)), the greatest thickness compensation seems to have occurred between the end of Big Snowy deposition and Tyler deposition and sometime during the time of deposition of the Spearfish. Salt tectonics in this area seems to obscure any possible recurrent movement

along the northeast-trending linear from Culbertson to Grenora, and this prompted the recommendation of a separate project to study parts of the same trend in McCone County, Montana (T21-23N, R46-48E) where Prairie salt is non-existent. The presence of the Weldon-Brockton fault was demonstrated for the McCone County study and thereby assumed to be present in the study area where its effects seem beclouded by salt tectonics. This subject is discussed in greater detail later in the thesis.

#### ***Dawson Bay - Bakken Interval***

The Dawson Bay - Bakken isopach map (Plate 6) essentially represents the lower Kaskaskia sequence. The Prairie Formation and underlying sedimentary units are omitted from this interval for reasons already discussed. The lower bounding surface is placed at the top of the Dawson Bay Formation which corresponds to the base of the Souris River series of upward shoaling sequences. The top limiting surface is placed at the top of the Bakken Formation (Figure 33).

The isopach map representing the lower Kaskaskia sequence shows a different structural pattern from the ones discussed earlier. There is a general thickening from about 940 feet in the southwest portion of the study area to 1280 feet in the northeastern portion, east of the Nesson anticline. This thickening trend marks a change in the direction of depositional dip of the basin from south to north, for the most part. Along the Nesson

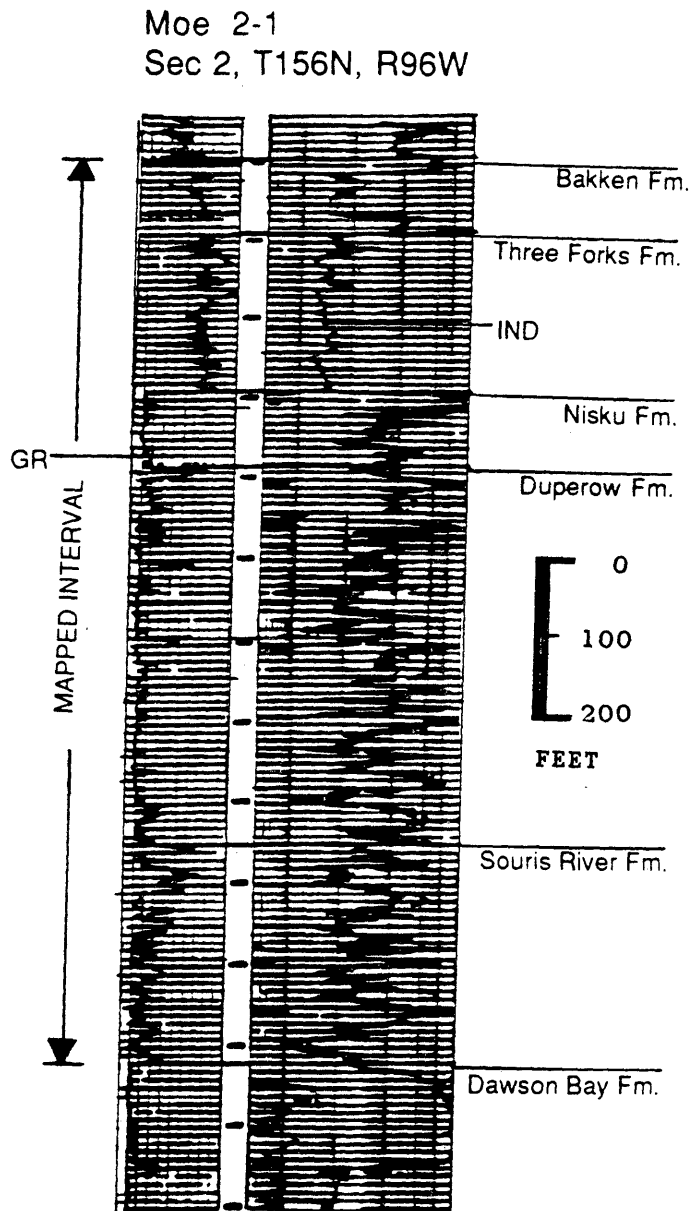


Fig. 33 Electric log of the isopached Dawson Bay - Bakken interval from well, Moe 2-1 (2-156N-96W), Williams County, North Dakota



anticline, a northward thickening rather than southward as shown on Plate 6, is observed. This change in structural pattern was caused by the northward tilting of the Williston basin in early Devonian time as a result of activity along the Transcontinental Arch to the south. The northward tilting forced the previous crestal points of Red River structures and all other pre-early Kaskaskia structures to shift southward from their original positions (Gerhard, 1987).

Isopach contours of the lower Kaskaskia trend generally northwest in the study area, which represents the depositional strike at this time. In northeast Montana and parts of western North Dakota, the contours are uniform for the most part except at a few places where they are interrupted by northwest alignment of thin rock areas. The thin areas around Bainville (T28N, R58E) and Dwyer (T32N, R58E) are good examples. The postulated location of the Brockton-Froid-Fromberg fault zone does not have a prominent expression at this time except for a subtle re-entrant that trends northeast from the southern portion of Rush Mountains (T31N, R59E) (Plate 6).

The northwest-trending paleostructural trends around Bainville area in Montana are again prominent. To the east of the study area along the Nesson anticline, the pattern is a bit more complex. The Beaver Lodge field area shows up as an area of thin rocks with a north to north and east trend. The areas west of Tioga field and along the Temple and McGregor fields (T157 -159N, 95W) as well as the Antelope anticline also show up as northwest -trending areas of thin rock. An area of thick rocks about 4 miles wide mimicing the trend of the axis of the paleostructural trend on the Nesson, occurs to the west of the structure.

The rate of stratigraphic thinning in the vicinity of the Nesson anticline is of the order of 7 feet per mile west of the Beaver Lodge field. This gradient changes to 33 feet per mile

just west of the thin rock area of the Beaver Lodge field around T155N, R97W. This rapid change of thinning rate characterised by "tightening" of contours, is indicative of possible structural activity on the west side of Beaver Lodge. A similar tightening of contours is observed east of Beaver Lodge and Capa fields suggesting an east bounding fault on the Nesson anticline, which is downthrown to the east. These thin trends are offset along the Nesson anticline and they probably reflect recurrent movement on fracture zones. One such offset linear, L3L4 trends northeast from the northwestern portion of Beaver Lodge field through the southern tip of Tioga field, and may be the structural boundary between the two fields. A similar offset linear, L1L2 also trends northeast from an area in T158N, R96W through the southern part of Temple and McGregor fields. In all, at least six fault blocks are recognisable here. The Charlson fault block or block 1 contains Charlson field and is limited to the north by the east-trending Charlson fault. The western and eastern limits are the West Nesson and East Nesson faults respectively. The Beaver Lodge fault block or block 2 contains Beaver Lodge field and is bounded to the north by the northeast-trending, cross-structure linear L3L4. It is also bounded to the west and east by the West Nesson and East Nesson faults. Southwest Tioga fault block or block 3 is capable of being subdivided into two or more fault blocks, but data inavailability does not permit. West Temple fault exists to the north and is bounded on the west and east by the northwest-trending West Temple and East Temple faults respectively. The southern boundary is the northeast-trending, cross-structure linear, L1L2. Fault blocks 5 and 6 are undifferentiated fault blocks to the west and east of the Nesson anticline. The Antelope anticline is also visible as a northwest-trending thin area.

### *Bakken - Charles Interval*

This interval includes the all important Mississippian Madison strata, and can be used to interpret the upper Kaskaskia sequence. The lower limiting surface of the isopached interval is the top of the Bakken Shale or the base of the Lodgepole Formation which is a transgressive carbonate sequence. The upper bounding surface is the top of the Charles Formation which is an unconformity surface (Figure 34). Carbonate progradational deposits of this interval are the most important hydrocarbon-producing units in the Williston basin.

The general trend of the isopach contours is northeast in the western portion of the study area in Montana but changes to east-northeast and east near the state line in western North Dakota. The change in trend occurs across an anomalous feature, the Culbertson-Grenora feature, thought to be part of the Brockton-Froid-Fromberg fault zone. The northward tilting of the Williston basin during deposition of the lower Kaskaskia sequence was reversed during deposition of the upper Kaskaskia sequence. Thickness of the mapped interval increases from about 1640' in the north to about 2340' in the south at a gradient of 11 feet per mile in Montana portion of the study area, and about 13 feet per mile

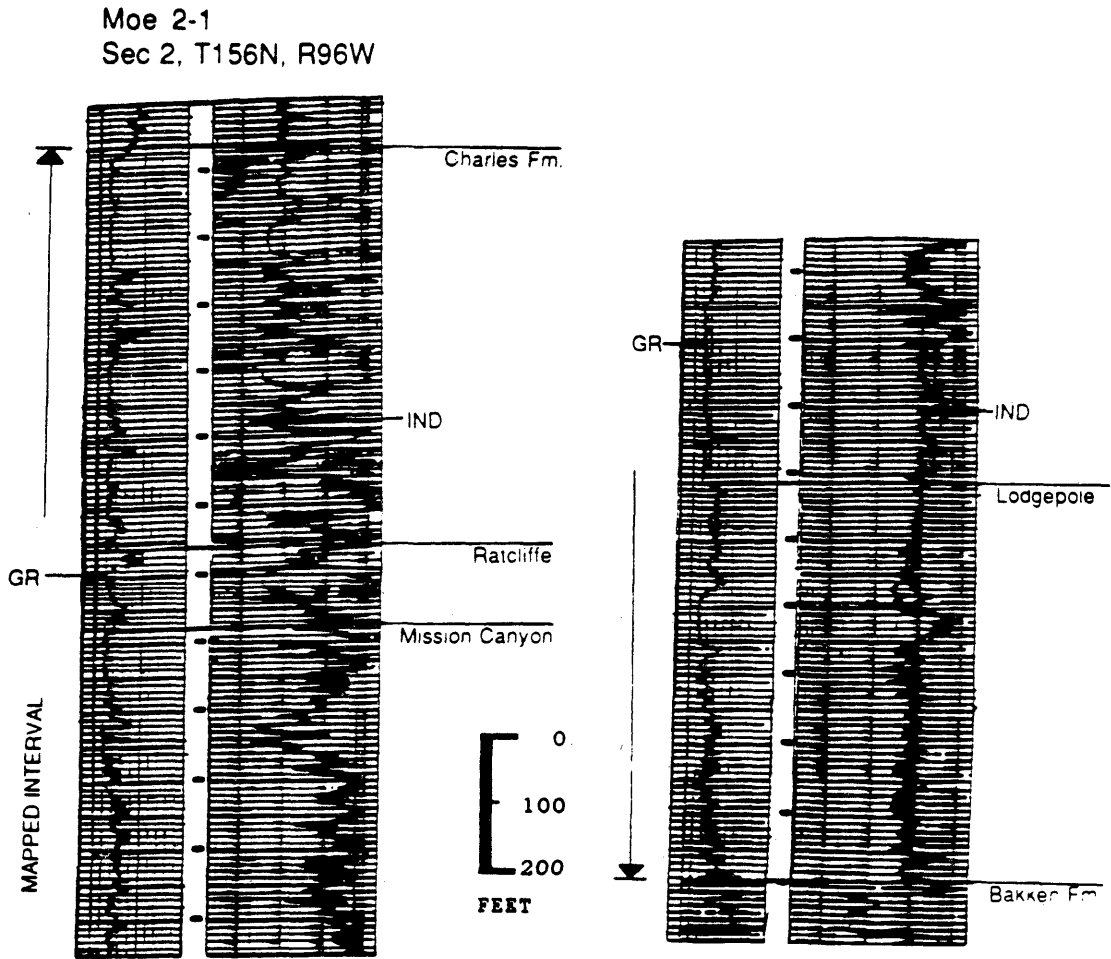


Fig. 34 Electric log of the isopached Charles - Bakken interval from well, Moe 2-1 (2-156N-96W), Williams County, North Dakota

in the North Dakota portion. Overall, the isopach shows relatively little relief over most parts of the area although the influence of the Nesson anticline is still being seen. Over most parts of Montana, northwest paleostructural lineations are again observed in Bainville area, Richland County and in Reserve, Dagma and Clear Lake field areas of Sheridan County (Plate 7). The most prominent linear is one trending northeast from the Culbertson area (T28N, R56-57E) through Shotgun Creek (T29-30N, R58E) to the Grenora area in North Dakota (T159N, R103W), coincident with the anomalous feature named Culbertson-Grenora feature (Plate 5), and here indicated by a tightening of contours along its trend. Regional cross section CC' drawn from north to south shows this feature as a seeming structural feature, possible fault, with a downthrown side to the east. All stratigraphic units within the mapped sequence seem to thin between the Hazel #5-1 well (5-30N-59E, NESW) and the Sinclair Brown No. 1 well (5-31N-59E, SENW) by approximately 10 to 20 feet, but a 50-foot salt section at the top of Charles Formation is missing in the Brown No. 1 well (Plate 8 (figure 31)). The general thickening of stratigraphic units in the downthrown block may indicate syndepositional structural movement.

The large thickness change of 50 feet at the top of the Charles Formation may indicate maximum structural movement during Charles deposition or simply erosional truncation of or scrapping of the 50-foot missing section in the western block or both. The east-west regional cross section BB' (Plate 4 (Figure 27)) shows a similar relationship in the southern portion of the feature around Culbertson but with an apparent throw in the opposite direction if the missing salt section was used as a criterion. In addition, the unconformity at the top of the Charles Formation is also recognized on the Nesson anticline as by regional cross section BB' which shows 55 feet of missing section at the top of Charles on the Sam Olson #4 well (10-155N-96W, NE) situated on the anticline, a pointer to the fact

that the erosional truncation was probably as a result of the topographic high created by structural movement.

### *Charles - Spearfish Interval*

The isopach of the interval between the top of Charles and the top of Spearfish formations represents most of the Absaroka sequence. The presence of the pre-Absaroka unconformity and mid-Tyler unconformity of Fanshawe (1978), in the Big Snowy Group of the mapped interval (Figure 35), may slightly affect the accuracy of structural interpretation deduced from the thickness map.

The depositional strike direction as revealed by the isopach map (Plate 10), is northeast in Montana portion of the study area but becomes more easterly in western North Dakota, and over the Nesson anticline to the east, it is essentially east. Linears of thick and thin rock areas like those observed in the south-southwest portion of the study area, trend northwest and are perpendicular to the depositional strike. On the Nesson anticline, the most prominent linear is the West Nesson fault indicated by sharp gradient and tightening of contours west of Beaver Lodge field. This fault also trends perpendicular to the depositional strike in this area. Thickness increase is generally from north to south from about 300 feet in the northwest portion in Montana and northeast area in Burke County, North Dakota to over 1400 feet in Montana area in the south and 1800 feet at the southern end of the Nesson anticline, at an average gradient of 22 feet per mile. The main salt dissolution feature in Montana (T29-30N, R58-59E), is associated with a conspicuously thick rock area as indicated on the isopach map, and it is located on a northwest-trending linear rimmed by a very high thinning gradient of 100 feet in per mile or more. The coincidence of this thick rock area with the main salt dissolution area is indicative of

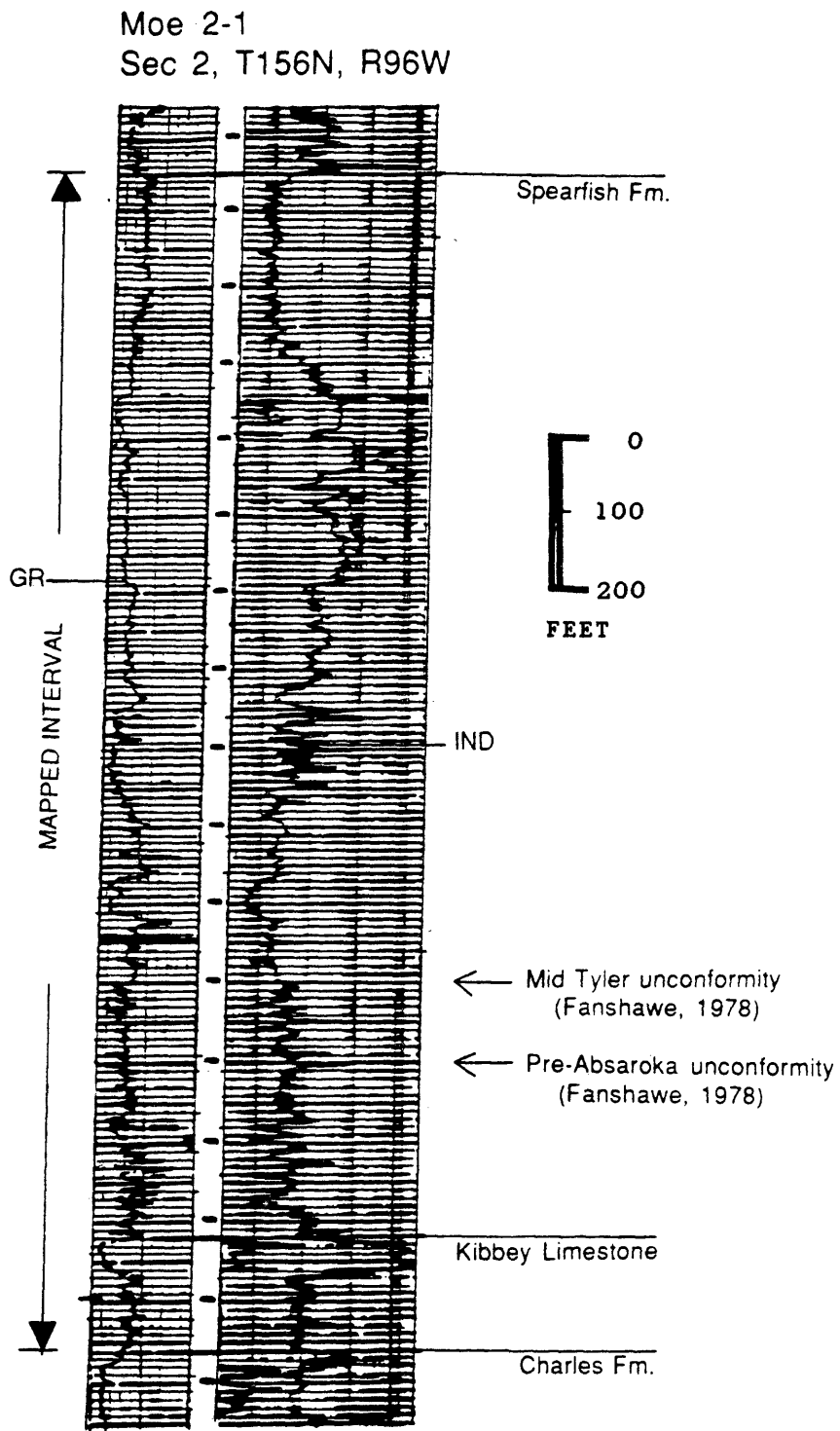


Fig. 35 Electric log of the isopached Charles-Spearfish interval from well, Moe 2-1(2-156N-96W), Williams County, North Dakota

thickness compensation in response to salt dissolution. The northeast-trending linear manifests itself by the closeness of contours north of the thickness compensation area along the Montana/North Dakota state line in a general northeast direction (Plate 10).

Over most parts of the Nesson anticline, the structural elements, including the active Beaver Lodge field area, seem to have been a little subdued, a situation presumed to have been caused by "filling of the basin by detrital dumping" by Gerhard et al (1987). However, the northeast paleostructural trend is still discernible. The now subtle thin along the Nesson anticline is offset at various places for example north of Beaver Lodge field around T156N R95W. Sharp contour gradient or tightening around West Temple, West Tioga and McGregor field areas might be indicative of structural activity, probable faults on the west side of Temple and McGregor fields as well.

### *Spearfish - Greenhorn Interval*

The isopach of the interval from the top of Spearfish Formation to the top of Greenhorn Formation (Figure 36), only represents the lower part of the Zuni sequence. The isopach map (Plate 11) exhibits a relatively uniform and persistent thickness throughout most of the study area. The thickness increases from north to south at a gradient of about 4 feet per mile in the west, and 7-10 feet per mile in the east in western North Dakota. Slight change is again observed across the state boundary. No strong linear elements are visible but local axes of thicks and thins trend in northeast and northwest directions throughout most of the study area. The northwest-trending paleostructural lineation in the southwest portion of the study area is strongly diminished if not completely obliterated at this time. The Beaver Lodge field area along the Nesson anticline, however, is represented by a northeast thin trend which is offset from West Tioga and Tioga fields to



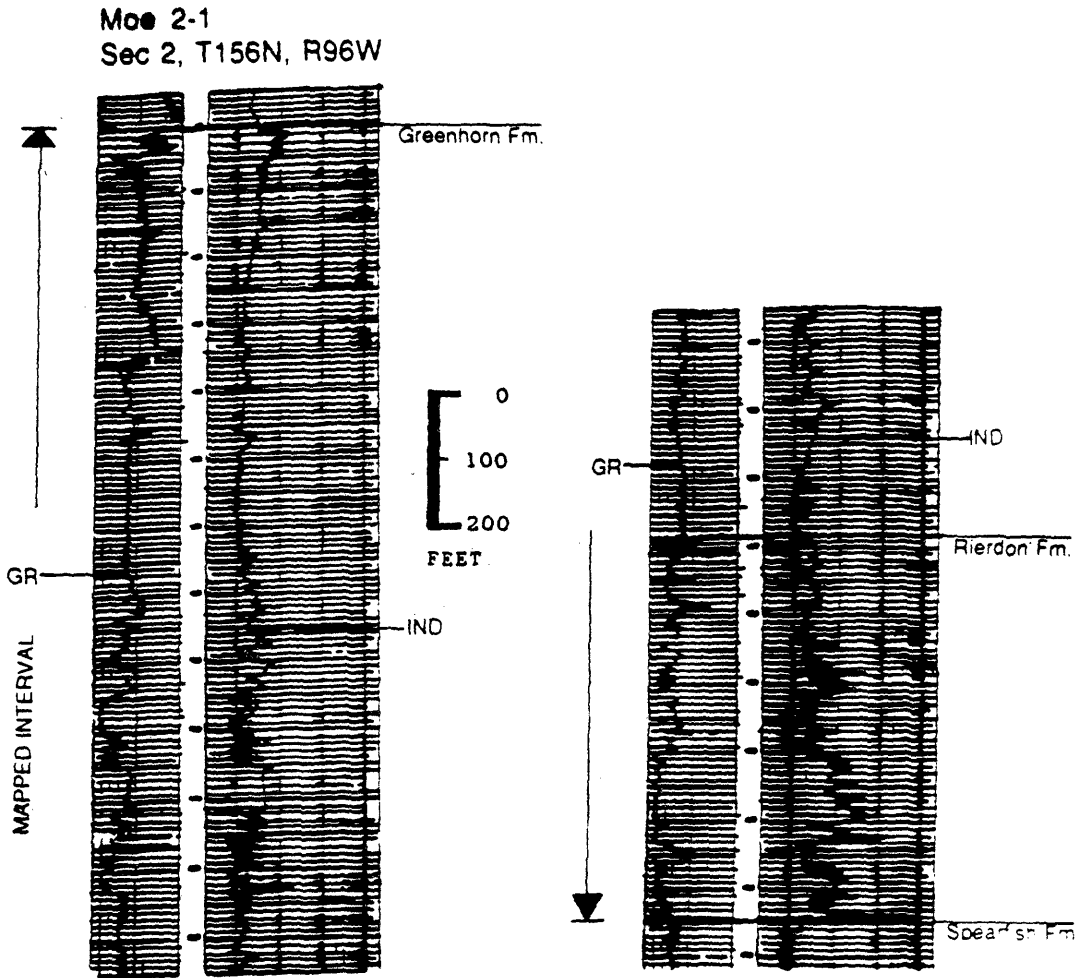


Fig. 36 Electric log of the isopached Spearfish-Greenhorn interval from well, Moe 2-1 (2-156N-96W), Williams County, North Dakota

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the north along the northeast-trending offset linear, and slightly offset from the northeast-trending thin rock area around T154N, R95W to the southeast (Plate 11). Of note is the north end of the Antelope anticline which had always shown up as a thin area and is now represented by a thick rock area with less defined orientation. This is evident of the cessation or reduced activity on this structure at this time.

Thinning in the Beaver Lodge field area suggests continued activity on the West Nesson fault and probably on the offset linear bounding the field to the north while uniform and persistent thickness distribution over the area indicates no significant deformational episode during deposition. Regional cross sections BB'(Plate 4 (Figure 27)) and DD' (Plate 9 (Figure 37)) constructed from east to west and north to south respectively support these observations. The southern portion of Hoffland and Capa fields in T154N, R95W which also has a northeast paleostructural trend seems to be offset from Charlson field where another area of thin rocks oriented in a northeast direction is mapped (Plate 11).

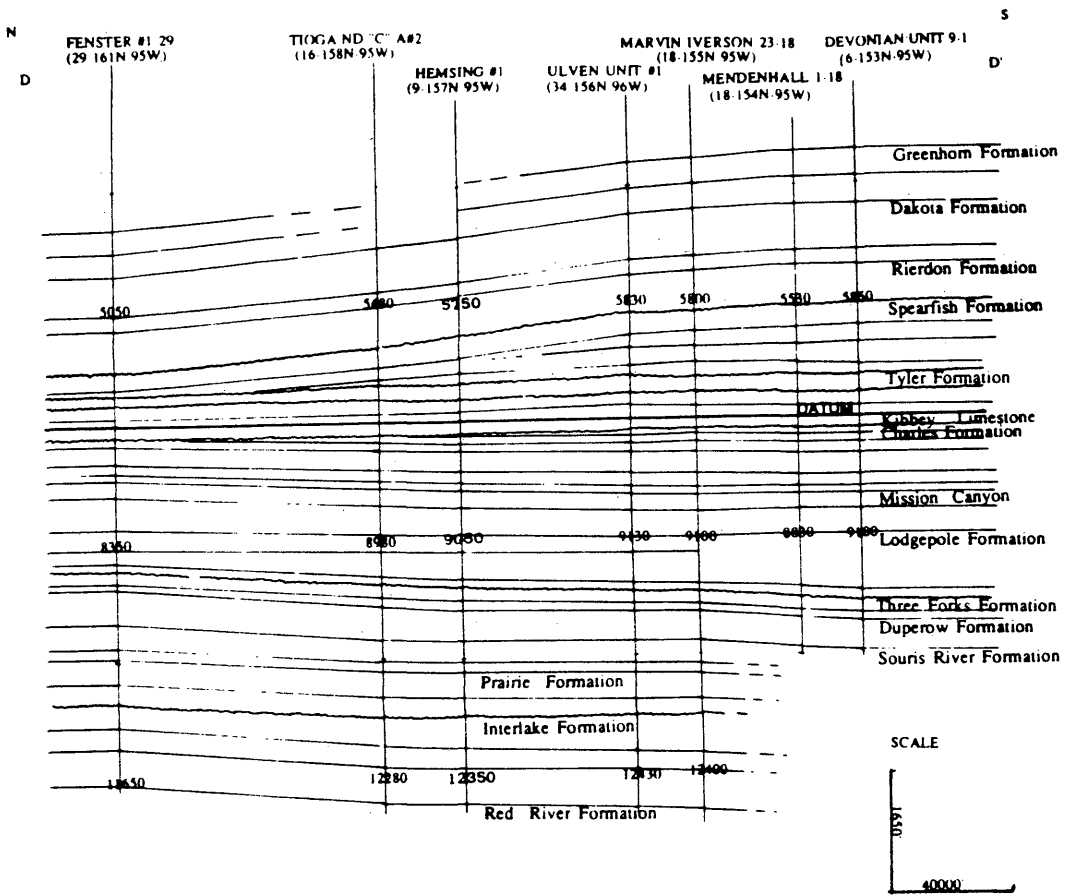


Fig. 37 N-S regional stratigraphic cross section DD'

## ISOPACH MAPS OF THE DEVONIAN UNITS

Isopach map of the Dawson Bay - Bakken interval (Plate 6) and the several stratigraphic cross sections prepared in the area suggest that this interval was a most tectonic-sensitive one, especially the Devonian strata. Consequently, an additional series of isopach maps of these tectonic-sensitive units was made to further aid in the paleostructural analysis. Five isopach maps of the Souris River, Duperow, Nisku, Three Forks and Bakken Formations were prepared.

### *Isopach of the Souris River*

Isopach map of the Devonian Souris River interval (Plate D1) shows a general east-west trend, thickening from about 210 feet in the southwest to over 310 feet in the north. This thickening trend reaffirms the new structural pattern that resulted from the northward tilting of the Williston basin in early Devonian time. To the east of the study area, the trend of the contours changes to northwest where a series of northeast-trending paleostructural lineations punctuate the map. On the Nesson anticline, Temple, McGregor, West Tioga and Beaver Lodge fields show up as areas of thin rocks while a structural low, about 2-3 miles wide and 12 miles long occurs to the west of Temple field. Similarly, a paleolow about 5 miles wide and 18 miles long trending approximately NNW, is present to the west of the paleohigh west of Beaver Lodge field. This structural attitude lends support to the interpretation of a fault trending northwest on the west side of Beaver Lodge field, and downthrown to the west. Another northwest-trending fault on the west side of Temple-McGregor field is similarly interpreted.

Slight tightening of contours on the east side of Beaver Lodge field is suggestive of an east bounding fault. The rate of stratigraphic thinning over most parts of the study area is about 1-2 feet per mile but changes anomalously to 8-10 feet per mile in the areas west of the paleohighs at Beaver Lodge and Temple fields, and also in the area of the interpreted eastern fault.

### *Isopach of the Duperow*

The isopach map of the Duperow (Plate D2) depicts essentially the same features as that of the Souris River. The general trend of the contours is east-west. Thickening is from about 450 feet in the south around Bainville to over 530 feet in the north at an average gradient of 1-2 feet per mile. Northwest and northeast paleostructural lineations are prominent. The northeast-trending paleohigh around Bainville is very much active as well as the northwest-trending paleohigh around Dwyer (T32N, R59E). Activity on the Nesson anticline is indicated by various areas of thin Duperow interval along the axis of the anticline as at Temple-McGregor and Beaver Lodge field areas and the Antelope anticline. A northwest-trending paleostructural low about 7 miles wide and 15 miles long occurs to the west of the paleohigh in the Beaver Lodge field area, further evidence of the West Nesson fault at this location. Similarly, Temple field area shows up as a north to northwest trending area of thin rocks adjacent to the axis of the paleolow which stretches north to near the Canadian border (Plate D2). Close contour spacing on the eastern flank of Beaver Lodge field attests to the presence of the East Nesson fault.

Of note is the trace of the axis of the paleostructural high along the Nesson anticline which displays numerous changes of direction from northwest to northeast as observed on previous maps. The most prominent of this change in direction occurs along the

northeast-trending offset linear, L3L4 north of Beaver Lodge field. Small isolated pockets of paleohighs are found trending northeast in the northwest North Dakota area.

### *Isopach of the Nisku*

The map shows a general but rather indistinct east-west trend, thickening from about 90 feet in the southwest corner to 110 feet in the north and northeast. A prominent structural nose trends northeast from Shotgun Creek area in Roosevelt County, Montana to the Northwest corner of North Dakota around the US/Canadian border. This trend direction is the same as that of the Culbertson-Grenora feature and the Brockton-Froid-Fromberg fault zone (Plate D3). To the east, the trend of the contours changes to a general north-south, northnorthwest and north orientation. Again, Temple, Mc Gregor, West Tioga, Beaver Lodge, Charlson and Antelope field areas show up as areas of thin Nisku strata as a result of recurrent structural movement. Isolated areas of thick rocks are found trending approximately northnorthwest.

### *Isopach of the Three Forks*

Isopach map of the Three Forks Formation shows a north-south paleostructural lineation with stratal thickness increasing from 120 feet in the west to about 240 feet in the east at an average gradient of 4 feet per mile in Montana area and 1-2 feet per mile in the western part of the Nesson anticline. On the Nesson, the Temple and Southwest Tioga blocks are indistinguishable but quite distinct from the Beaver Lodge block (Plate D4). In all, four fault blocks are identified on the Nesson anticline. The unconformity at the top of the Three Forks Formation might have in part, contributed to the difference in paleostructural trend between the older Devonian units and the Three Forks.

### *Isopach of the Bakken*

Like most of the Devonian units, the isopach map of the Bakken display a general east-west trend in the western portion of the study area, but becomes more northerly to the east because of the structural influence of the Nesson anticline (Plate D5). Also, the northeast-trending structural nose thought to coincide with the postulated trend of the Brockton-Froid-Fromberg fault zone is again prominent here, emphasizing possible recurrent structural movement in this zone as well as in the area surrounding the Nesson anticline. Thickness of strata increases from about 60 feet in the southwest to over 120 feet in the northeast and east.

Structural movement along the east flank set of faults is by far more prominent at this time than that on the set of west flanking faults. The Beaver Lodge fault block or block 2 is the most distinct of all the interpreted fault blocks at this time indicating that structural movement along West Nesson and East Nesson faults are more significant than that on the West Temple and East Temple or any other fault. Overall, three fault blocks could be interpreted at the Bakken level (Plate D5). A superposition of all the interpreted faults and linears is shown in the tectonic map, figure 38.

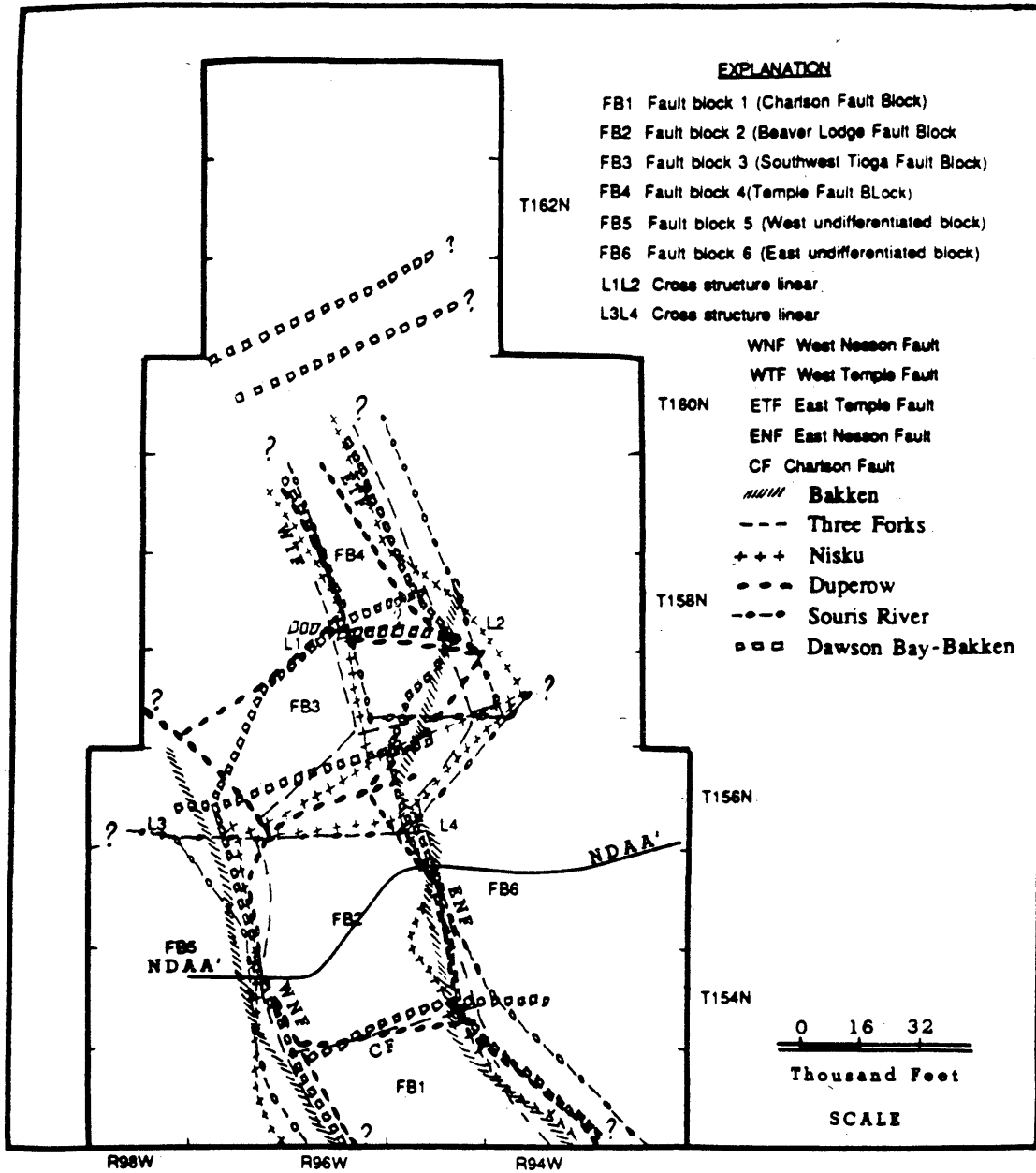


Fig. 38 Tectonic map of the Nesson anticline showing superposition of interpreted fault blocks at different geological times



## INTERPRETATION OF STRUCTURE MAPS

Four structure contour maps were prepared on tops of the Red River, Bakken, Charles and Greenhorn formations to study the effects of paleotectonic events in the study area.

### *Structure On Top Of Red River Formation*

The Red River structure contour map (Plate 12), reflects the present structural configuration of the study area at this level. Data on the Nesson anticline are limited and that in the northeastern portion of the study area in Burke County, North Dakota, is practically nil. Generally, the mapped surface dips from the northwest to the southeast while maintaining a general northeast strike. The structure becomes more complex to the east where the Nesson anticline expresses itself in the form of a south-plunging fold. Structural dips seem to be quite variable across the entire area. Gradients of 55 feet per mile characterize most parts of the Montana portion of the study area while gradients of 67 feet per mile are typical of western North Dakota. In the immediate vicinity of the Nesson anticline, where tightening of structure contours further supports the presence of the West Nesson fault, the gradient is as steep as 280 feet per mile. Another structural contour anomaly exists on the eastern side of the Nesson anticline with approximately the same trend as the West Nesson fault. This feature, the East Nesson fault is also inferred to be an east-bounding fault running parallel to the West Nesson fault, with the downthrown side to the east in Mountrail County, North Dakota (Plate 12). Structural throw on the West Nesson fault at the Red River level is about 500 feet west of Beaver Lodge field. On the East Nesson fault, the throw is slightly greater averaging about 550 feet. Several small anticlinal folds are found trending in a northwest direction to the west of the study area, where they become interspersed with narrow synclinal hinge lines that trend in the same

direction. The trend of the anticlinal and synclinal features is perpendicular to the direction of depositional strike.

The Nesson anticline follows a general north-south trend. However, the trace of the fold axis is offset at several places along the length of the structure. Prominent axial trace offsets along the fold can be observed in the areas around T157N R95W and T158N R95W coincident with the northeast-trending offset linear, L3L4 interpreted on the isopach maps (Plate 12). Lack of data at the southern end does not afford a proper analysis of the fold structure and its interaction with the southeast-trending Antelope anticline at this time. Structure and isopach maps of shallower intervals reveal that the Nesson fold splits at this junction to form the Antelope anticline. The structure becomes more diffuse to the north, although lack of deep data in this area may be partly responsible for the seemingly subtle positive structure. The West Temple fault which is downthrown to the west and the East Temple fault down thrown to the east, documented to the north, have relatively smaller throws than their southern counterparts. The northwest-trending fault near Bainville has a throw of about 100 feet and may be responsible for the strange borehole conditions of certain wells drilled in the area which could not hold packers (Gerhard, 1989, personal comm.).

### ***Structure On Top Of Bakken Formation***

The structure contour map of the top of the Bakken Formation (Plate 13) is similar in configuration to that of the Red River Formation with respect to strike and dip direction, orientation of narrow synclinal axes and anticlinal folds, and the axial trace of the Nesson anticline. The major difference in both structure maps lies in the magnitude of the dip gradient. Dips associated with various parts of the Bakken structure map are relatively less

than those of the Red River structure map. In Montana a dip of 55 feet per mile exists while the North Dakota portion has a dip of 67 feet per mile. In the vicinity of the West Nesson fault, the dip is 250 feet per mile, and around the East Nesson fault, it is 167 feet per mile. At the Bakken level the West Nesson fault has a throw of about 350 feet while the East Nesson fault has a structural throw of about 200 feet at the same horizon (Plate 27S)

The Culbertson-Grenora feature that trends from the Culbertson area in Roosevelt County to the Grenora area in western North Dakota, which is observed on the Bakken - Charles and shallower isopachs, does not have a distinct expression here as observed on the thickness map of the Prairie evaporite where it is highlighted by a northeast-trending salt thin linear and on the Bakken - Charles isopach map.

On the Nesson anticline, there is a gradual change in the axial trace orientation of the fold at Beaver Lodge field from a northeasterly direction in the north to a northwesterly direction in the south around Capa and Charlson field areas (T153-155N, R95-96W). This marks the trend of the interpreted northeast-trending linear, L3L4 that separates fault block 1 from fault block 2 on the isopach maps. The Antelope anticline is well defined as a southeast-trending appendage of the Nesson. Faulting at the northeast flank of the Antelope anticline is indicated by the close contour spacing. To the southwest, Bainville fault and East Bainville fault trending across the state line are manifest.

### ***Structure On Top Of Charles Formation***

Structural configuration at the top of Charles Formation (Plate 14) does not differ much from that at the top of Bakken in both Montana and North Dakota portions of the study area. The magnitude of the dip gradient does change though. In the west, the dip is

about 45 feet per mile and to the east, west of the Nesson anticline, it is 52 feet per mile. Across the West Nesson fault, the gradient is 110 feet per mile and across the East Nesson fault, it is 100 feet per mile. The Culbertson-Grenora feature does not have a distinct expression here. It is difficult to tell whether this feature actually represents a fault, part of the broad Brockton-Froid fault system, an erosional feature, salt dissolution phenomenon or other. On the Nesson anticline, the fold axis trace follows the same trend as in previous maps. The northeast-trending offset linear L3L4, north of Beaver Lodge field is noticeable. The change in direction from northeast to northwest at the southern end of Beaver Lodge field probably marks the location of another offset linear, that trends approximately ENE-WSW. The Antelope anticline is distinct as well. Structural throws on the West Nesson and East Nesson faults at the Charles level are about 300 feet and 200 feet respectively. The West Temple and East Temple faults bounding fault block 4 to the north are not well defined at this level.

### *Structure On Top of Greenhorn Formation*

Structure at the top of Greenhorn Formation (Plate 15) displays a gentle dip to the east. The strike direction is to the northeast. The northwest-trending linears seen on previous maps are subtle on the Greenhorn structure map. Dip gradients for most parts of the area is 25 feet per mile both in Montana and western North Dakota. However, around the West Nesson fault, the dip is 118 feet per mile. The 67 feet per mile dip of the contours on the eastern flank of the Nesson anticline supports the presence of the East Nesson fault here. Estimated throws on the West Nesson and East Nesson faults west of Beaver Lodge Field at the Greenhorn level are about 250 feet and 180 feet respectively (Plate 27). The

various fault blocks identified on the Nesson anticline at deeper horizons seem obscured here probably as a result of reduced structural activity during this time.

## STRUCTURAL INTERPRETATION

All the structure maps prepared display essentially the same features throughout. The general trend of the dominant linears is essentially the same (northwest and northeast) and they seem to be fairly repetitive from time to time. Similarly, the anticlinal fold axes, as well as the synclinal axes separating them, tend to be in close agreement through time. The major difference between the structure maps lies in the change of magnitude of the dip gradient through time. Table 1 shows the calculated dip gradients for four different parts of the study area at different stratigraphic horizons. The areas are (i) the western portion in Montana called area P, (ii) the eastern portion in western North Dakota called area Q, (iii) the area around the West Nesson fault called area R and (iv) the area around the East Nesson fault on the Nesson anticline, area S (Plate 1). The data, Table 1 indicates there is an increase in the eastward dip of the stratigraphic horizon from the top of Greenhorn to the top of Red River Formation. This increase in structural accentuation with depth might represent regional subsidence with time or subsidence and tectonics. Soeripto (1986) demonstrated an increase in structural closure (structural growth) from the top of Charles to top of Bakken and to top of Red River Formation at Lone Creek field (T25N, R57E) in Montana.

Relative displacements along the major faults were also measured using the closest wells on either side of the faults and calculating the structural offsets of correlated key stratigraphic horizons in each well. These data simply represent the offsets of the various horizons and not necessarily the throw on the fault planes, in which case, the stratal dips on both sides of the fault must be taken into account. The results showing the stratigraphic cross section used, the well location and the estimated vertical offsets are

	Red River	Bakken	Charles	Greenhorn
Montana	55.5	51.3	45.4	25
N. Dakota	66.7	62.5	52.6	25
W. Nessn Flt	250	166.7	117.6	111
E. Nessn Flt	166.7	111	100	66.7

(feet per mile)

Table 1 Calculated dips of different horizons at various sections of the study area. showing increasing dips with depth (structural growth)

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summarized in Table 2. The results indicate that structural offsets generally increase from the youngest to the oldest stratigraphic horizon. Average structural throw across the West Nesson and East Nesson faults, deduced from the structural cross section NDAA" (Plate 27S) and utilizing dip data from the structure contour maps shows a gradual increase in throw with depth.

The structural elements also demonstrate a good agreement with paleostructures interpreted from the isopach maps in terms of pattern, orientation and position. This observation lends support to the theory that recurrent movement of basement blocks along pre-existing zones of weakness might be the dominant style of deformation in the study area. This is the focus of the thesis, and in achieving this purpose, two main portions of the study area, suspected to be involved in recurrent movement of the basement through time, as inferred from the study area, are considered in greater detail to determine the history of structural development in those areas. The areas chosen are the Culbertson-Grenora feature in Montana which trends across the state line from Culbertson through Shotgun Creek to Dywer and Grenora in western North Dakota, and the Nesson anticline area.



FORMATION	WEST NESSON FAULT			EAST NESSON FAULT		
	TOP(DOWN THROWN BLK) FT SUBSEA	TOP(UP THROWN BLK) FT SUBSEA	STRUCTURAL OFFSET (FT)	TOP(UP THROWN BLK) FT SUBSEA	TOP(DOWN THROWN BLK) FT SUBSEA	STRUCTURAL OFFSET (FT)
RED RIVER	11841	10896	945	10361	11710	1349
INTERLAKE	10511	9576	935	9125	10241	1116
PRAIRIE	9885	9003	882	8544	9441	892
DAWSON BAY	9753	8867	886	8411	9300	889
SOURIS RIVER	9486	8625	861	8153	9017	864
DUPEROW	9012	8196	816	7697	8527	830
NTSKU	8906	8112	794	7608	8418	810
THREE FORKS	8687	7915	772	7417	8171	754
BAKKEN	8593	7841	752	7309	8021	712
LODGEPOLE	7886	7156	730	6704	7315	612
MISSION CANYON	7249	6537	712	6022	6646	624
CHARLES	6332	5664	668	5175	5795	620
GREENHORN	2316	1691	625	1534	1994	460

Data taken along Cross section NDAA' (Plates 29a, b & c)

Data Points: MAPCO NCGA#14-33 WELL (33-155-97.SESW) and SVEEN #1 ETLX WELL (31-155-96.SESE)  
(WEST NESSON FAULT)  
AMERADA PET (VERSON-NELSON #1 WELL (2-155-96.NE) AND GRONDALE 1-9 WELL (9-  
155-94.NENE) (EAST NESSON FAULT)

Table 2 Structural offsets along West Nesson and East Nesson faults

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## THE CULBERTSON-GRENORA FEATURE

The northeast-trending feature, the Culbertson-Grenora feature shown as a linear alignment of thin Prairie evaporite unit and also identified on the Bakken-Charles isopach map (Plate 7), as an anomaly trending from the southwest in Culbertson area, Roosevelt County, Montana (T27N, R57E) to the northeast area around Grenora in western North Dakota (T161N, R102-103W), was further investigated by constructing four detailed east-west stratigraphic cross sections along its length at different positions. This became necessary because the large salt dissolution feature at T30N, R58-58E, which lies along the trend of the northeast anomaly, obscures the attitude of the anomaly.

This study was supplemented by a separate study of the Cow Creek - Weldon field area in McCone County, Montana (T21-23N, R46-48E) where the structural expression of the Weldon-Brockton fault has been established (Hicks, 1985). Comparison of structural attitude of the Culbertson-Grenora feature at both places would aid in making appropriate judgement as to what the feature represents in the study area. For convenience, the discussion of the Culbertson-Grenora feature is considered at three main areas along the general trend of the feature. These are the Southern Non-Dissolution Area, the Central Dissolution Area and the Northern Non-Dissolution Area.

### *Southern Non-Dissolution Area*

The area referred to as the southern non-dissolution area is the southernmost segment of the northeast-trending feature in Culbertson area, Roosevelt County, Montana where Prairie salt dissolution or thinning is relatively minimal or nil. The best expression of this feature is shown by the Bakken to Charles isopach (Plate 7). The structure contour map of

the Charles Formation (Plate 14) shows it to a much lesser extent. Other isopach and structure maps do not give any indication of a structure in this location.

A detailed stratigraphic cross section, MT-D (Plates 16a,b & c (Figures 39a, b & c)), was constructed from west to east, approximately perpendicular to the strike of the northeast-trending feature, in order to view the thickening and thinning patterns, which might be indicative of structural activity on the feature. The Gunton-Red River interval generally thickens to the east being 108 feet thick in the Peerbom Estate 1 well (32-28N-56E, NWSW) and the Culbertson Unit #1 well (33-28N-56E, SWSW), 110 feet thick in Munz No. 1 well (1-27N-56E) and 112 feet in the Mc Cain No. 1-32 well (32-28N-57E, SWSE). The Terrapet Sundheim 1-35 well (35-28N-57E, SWNW) at the far eastern end of the cross section has no data deeper than the top of Souris River Formation.

In a similar fashion, all stratigraphic units thicken regionally to the east. The first noticeable counter regional thinning along this line of section is documented within the Stonewall Formation which decreases from 40 feet in the Peerbom Estate 1 well to 34 feet in the Culbertson Unit #1 well, a thickness change of 6 feet or 15% over a distance of about 1 mile. The thickness then increases to 39 feet in the Munz No. 1 well and 40 feet in the Mc Cain No. 1-32 well (Plate 16c (Figure 39c)). This counter regional thinning is the first indication of probable structural activity between the block containing the Peerbom Estate 1 well and that containing the Culbertson Unit 1 well. Upsection, the Devonian Prairie evaporite also thins counter regionally from 100 feet in the Peerbom Estate 1 well to 84 feet in the Culbertson Unit 1 well before thickening to 110 feet in the Munz No. 1 well and 140 feet in the Mc Cain No. 1-32 well. The counter regional thinning of 16 feet or 16% recorded between the first two wells again suggest positive structural movement at this time. The Devonian Duperow and Nisku Formations also show slight counter regional

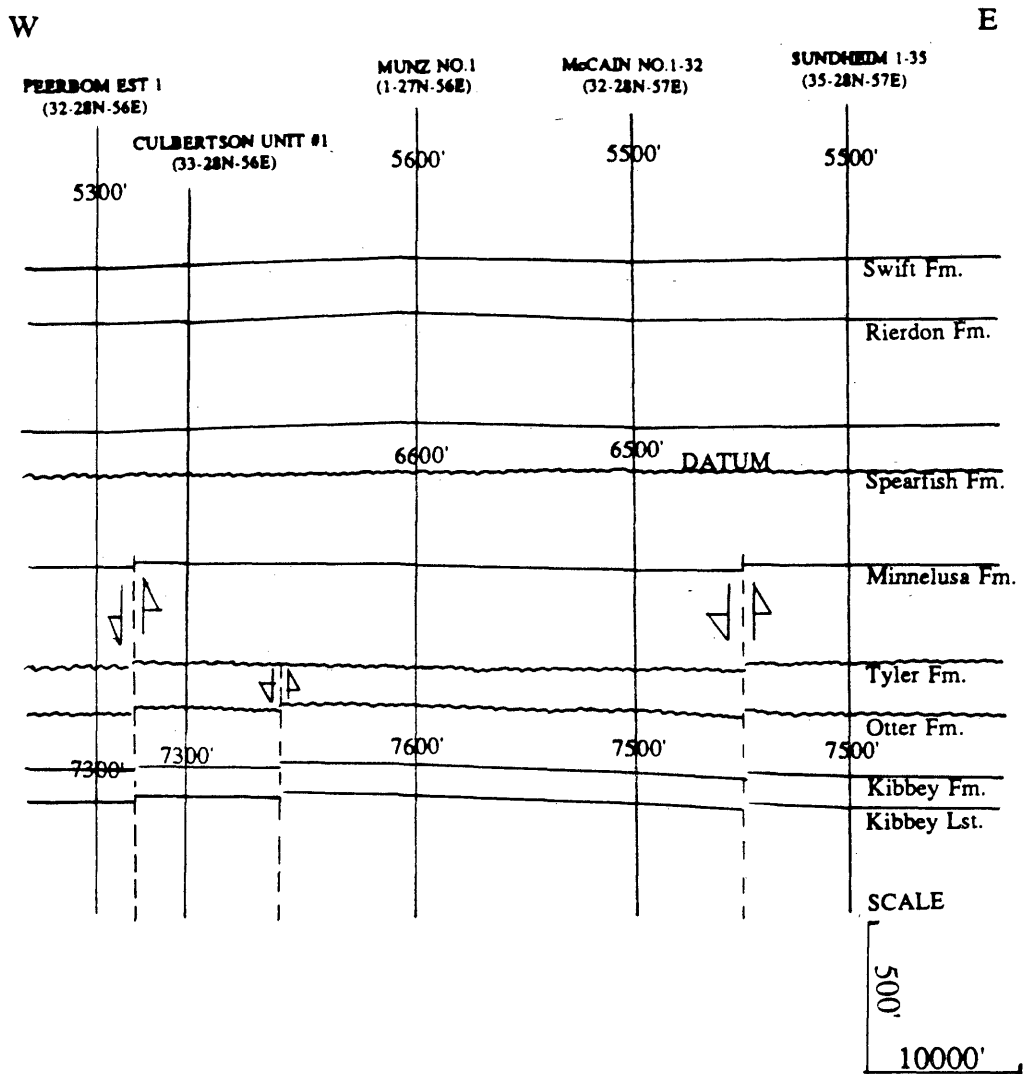


Fig 39a East-West stratigraphic cross section MT-D (Kibbey - Swift)

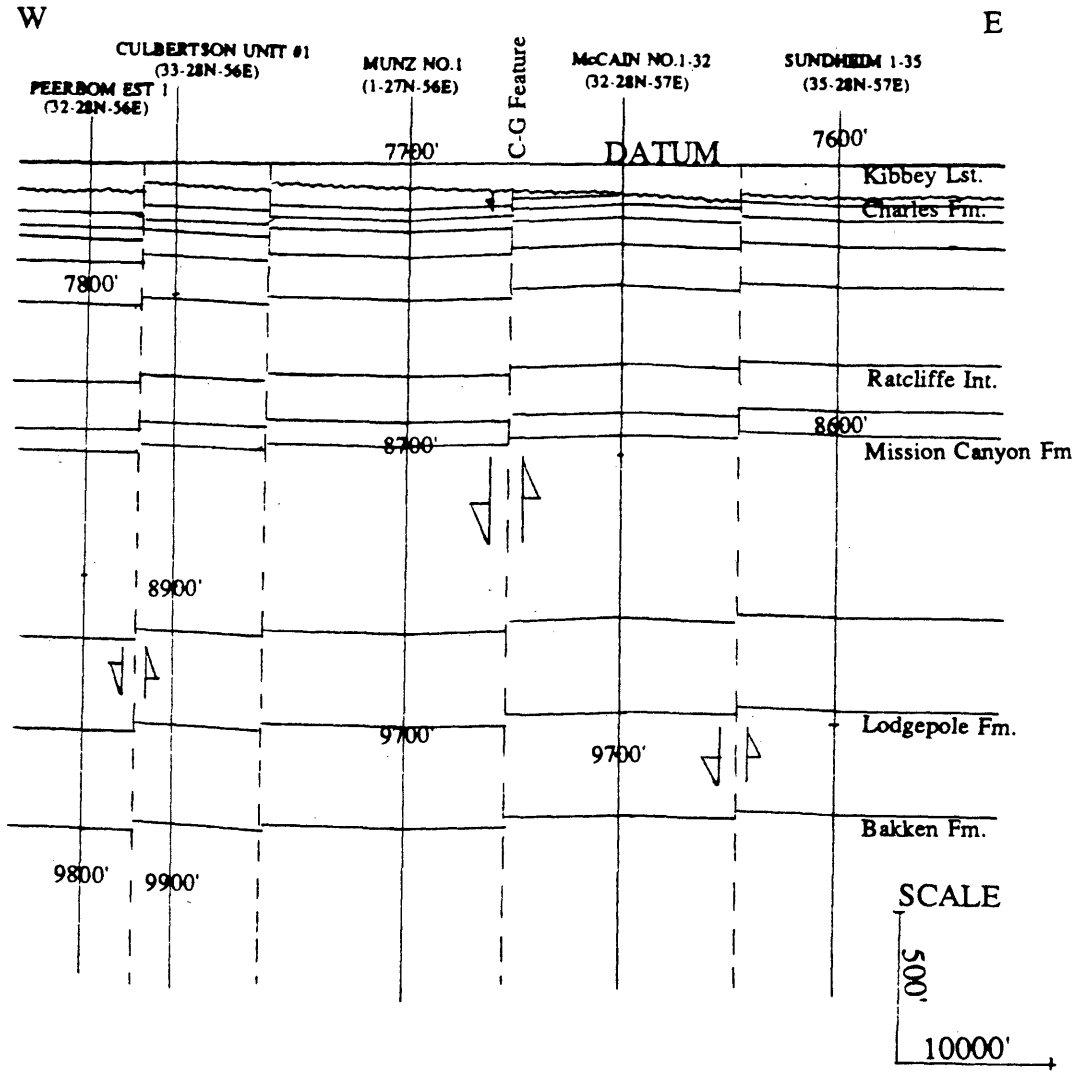


Fig. 39b East-West stratigraphic cross section MT-D (Bakken - Kibbey)

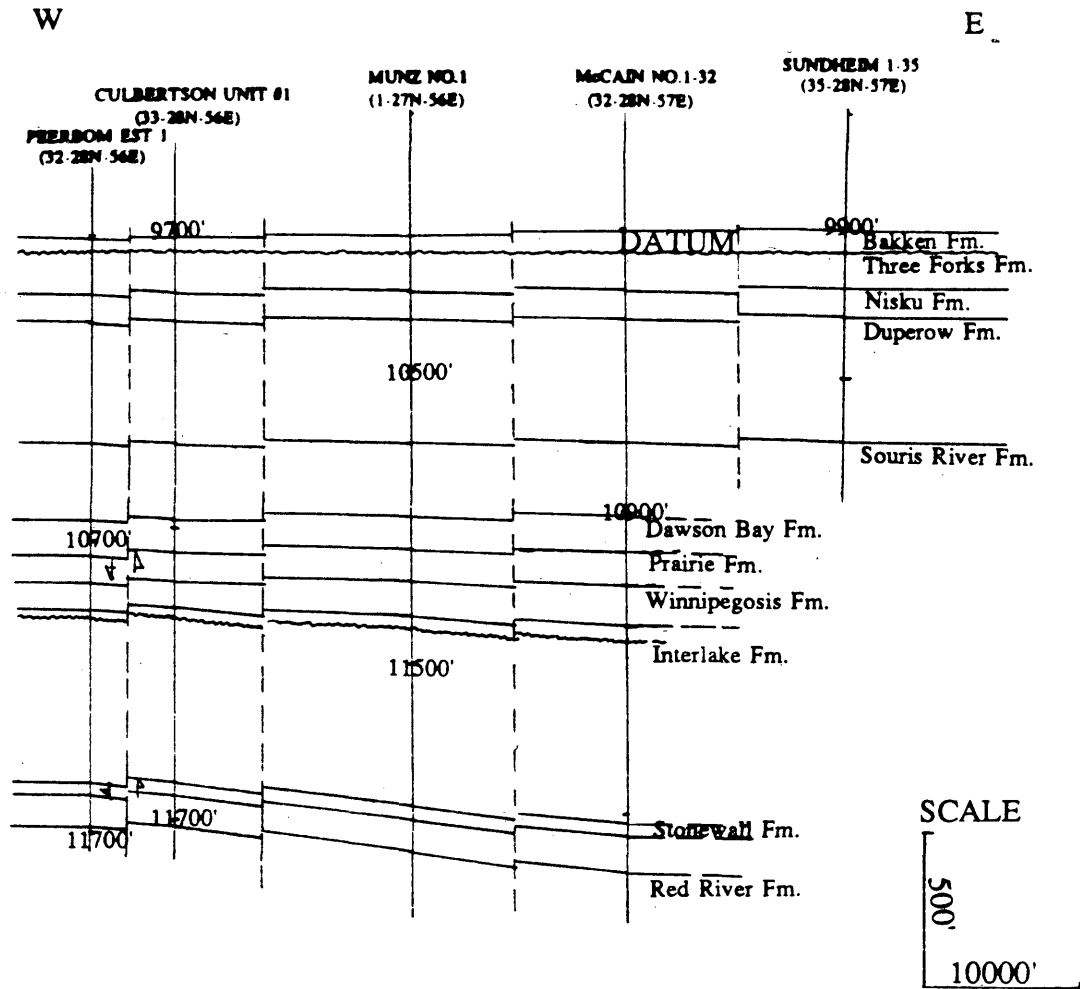


Figure 39c East-West stratigraphic cross section MT-D (Red River-Bakken)

thinning of 8 feet (2%) and 3 feet (3%) respectively between the Peerborn Estate 1 and Culbertson Unit 1 wells. However this change may be too small to interpret as active fault movement during the time of deposition of these two units (Plate 16c).

Of interest is the fairly uniform thickness distribution of the Second Red Bed member which caps the Prairie evaporite, an observation suggesting that the thinning recorded here might not be related to salt dissolution.

The Mississippian Lodgepole Formation also shows substantial thickness variation across the area especially in the upper half of the unit from the top of Lodgepole to the base of the prominent salt member (Plate 16b). This interval (Upper Lodgepole) thins from 325 feet in the Peerborn Estate 1 well to 294 feet in the Culbertson Unit 1 well by 31 feet or 10%. Between the Culbertson Unit 1 well and the Sundheim 1-35 well, thickness again increases steadily from 294 feet along the regional trend to 318 feet in the Munz No. 1 well and 330 feet in both the Mc Cain No. 1-32 and Sundheim 1-35 wells.

The overlying Mission Canyon thickens from 638 feet in the Peerborn Estate 1 well to 648 feet in the Culbertson Unit 1 well but thins by 2% to 632 feet in the Munz No. 1 well. A further thickness change of 22 feet or 3% is observed in the Mc Cain No. 1-32 well before the formation thickens back up to 630 feet in the Sundheim 1-35 well. The counter regional thinning of the Mission Canyon between the Culbertson Unit 1 well and the Munz No. 1 well and that between the Munz No. 1 and the Mc Cain No. 1-32 wells appear to be minimal but the implication of positive structural movement at these places, especially the latter, is further recorded in the overlying Charles Formation, where the top Charles units are drastically thinned between the Munz No. 1 well and the Mc Cain No. 1-32 well. Erosional truncation at the top of Charles might be responsible for most of the section lost between the two wells.

Detailed correlation of the individual thin beds within the Charles indicates that most of the carbonate and salt units thicken slightly to the east along the regional trend but the bulk of the thinning recorded is at the top of the formation. Top of Charles is a well known unconformity surface. The observed thinning may then be interpreted as due to structural movement during deposition of top Charles, erosional bevelling or dissolution. It is believed that structural upwarping of the Mc Cain 1-32 block made it topographically higher and hence more susceptible to erosion, thus the thinning might be due to a combination of factors, positive structural movement followed by erosional activity.

Upsection, the general trend is very much the same, with stratigraphic units generally thickening eastward. However, the Pennsylvanian Tyler Formation and the Permian Minnelusa show counter regional thinning along the line of section. The fault between the Peerbom Estate 1 well and the Culbertson Unit 1 well had recurrent movement in the Permian during the time of deposition of the Minnelusa as this unit thins from 350 feet in the Peerbom Estate 1 well to 330 feet in the Culbertson Unit 1 well, a thickness change of 20 feet or 6%. Minnelusa then thickens to 352 feet in the Munz No. 1 well and 348 feet in the Mc Cain No. 1-32 well but thins counter regionally by 4% to 333 feet in the Sundheim 1-35 well suggesting slight movement on this block. The Tyler Formation slightly thins from 152 feet in the Peerbom Estate 1 well to 150 feet in the Culbertson Unit 1 well but drastically thins by 27% to 110 feet in the Munz No. 1 well before thickening once again to the east. This major counter regional thinning is indicative of faulting between the Culbertson Unit 1 well and the Munz No. 1 well at the time of deposition of the Pennsylvanian Tyler Formation. At this point no significant effect of salt dissolution is recognised as there is no compensating stratigraphic thickening in the younger strata.



### *Central Dissolution Area*

The central dissolution area is the sub-circular salt dissolution area in the Shotgun area, Roosevelt County, Montana (T29-30N, R57-59E ) where Prairie salt is non-existent or anomalously thin. It is recognised as an isopach thin zone lying along the trend of the Culbertson-Grenora feature on the Prairie isopach map (Plate 5).

Stratigraphic cross section MT-A (Plates 17a, b & c (Figures 40a, b & c)) was constructed from west to east across this feature in order to study the effect of salt dissolution and its interaction with structural movement, if any, on the Culbertson-Grenora feature at this location. Stratigraphic units, again, thicken generally to the east. The Red River to Interlake interval increases in thickness from 725 feet in the True Oil Krogedal 31-5 well (5-30N-57E) to 745 feet in the Superior Oil Jacobsen State #1 well (13-30N-57E,SWNW) and steadily through the wells No.2 Jacobsen (17-30N-58E, SWNW), Picard A#1 (27-30N-58E, NENW), and Melum 1-30 (30-30N-59E) to 838 feet in the Sunmark Dome Giese Heirs No. 1 well (4-29N-59E, NENW). The overlying Ashern Formation as well as the Winnipegosis follow the same trend, increasing in thickness from west to east (Plate 17c). However, the Devonian Prairie Evaporite exhibits a drastic thickness change across the area. The Prairie Formation thins from 192 feet in the Krogedal 31-5 well to 45 feet in the Jacobsen State #1 well, 50 feet in the No. 2 Jacobsen Estate well, 32 feet in the Picard A# 1 well, 67 feet in the Melum 1-30 well and 52 feet in the Dome Giese Heirs No. 1 well. East of the Krogedal 31-5 well, the actual evaporite thickness is nil. The Second Red Bed capping the evaporite section has a thickness of 15 feet in the Krogedal 31-5 well and thickens generally eastward to an average of 50 feet. The counter regional thinning of the Prairie evaporite between the Krogedal 31-5 well and

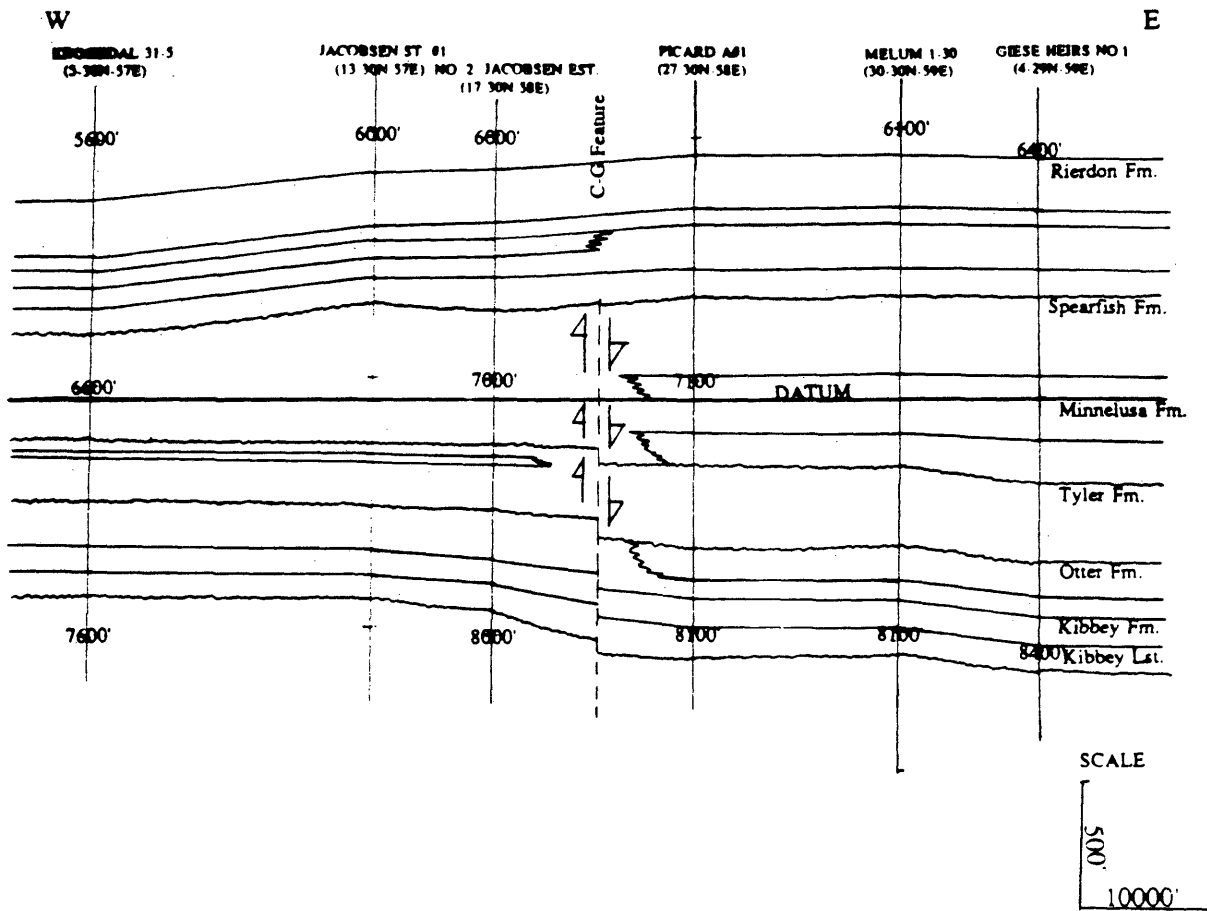


Fig. 40a East-West Stratigraphic cross section MT-A (Kibbey - Rierdon Interval)

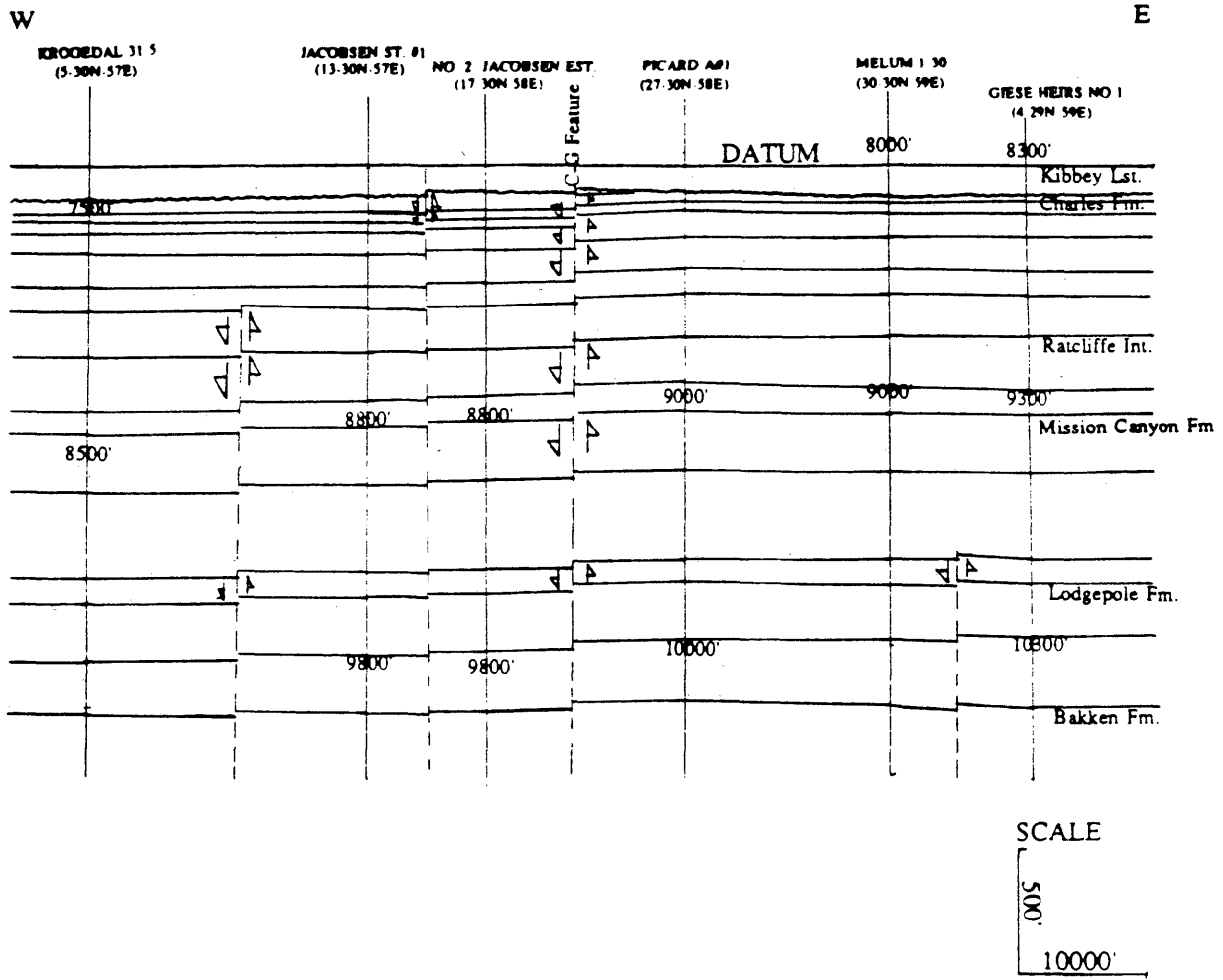


Fig. 40b East-West Stratigraphic cross section MT-A (Bakken - Kibbey Interval)

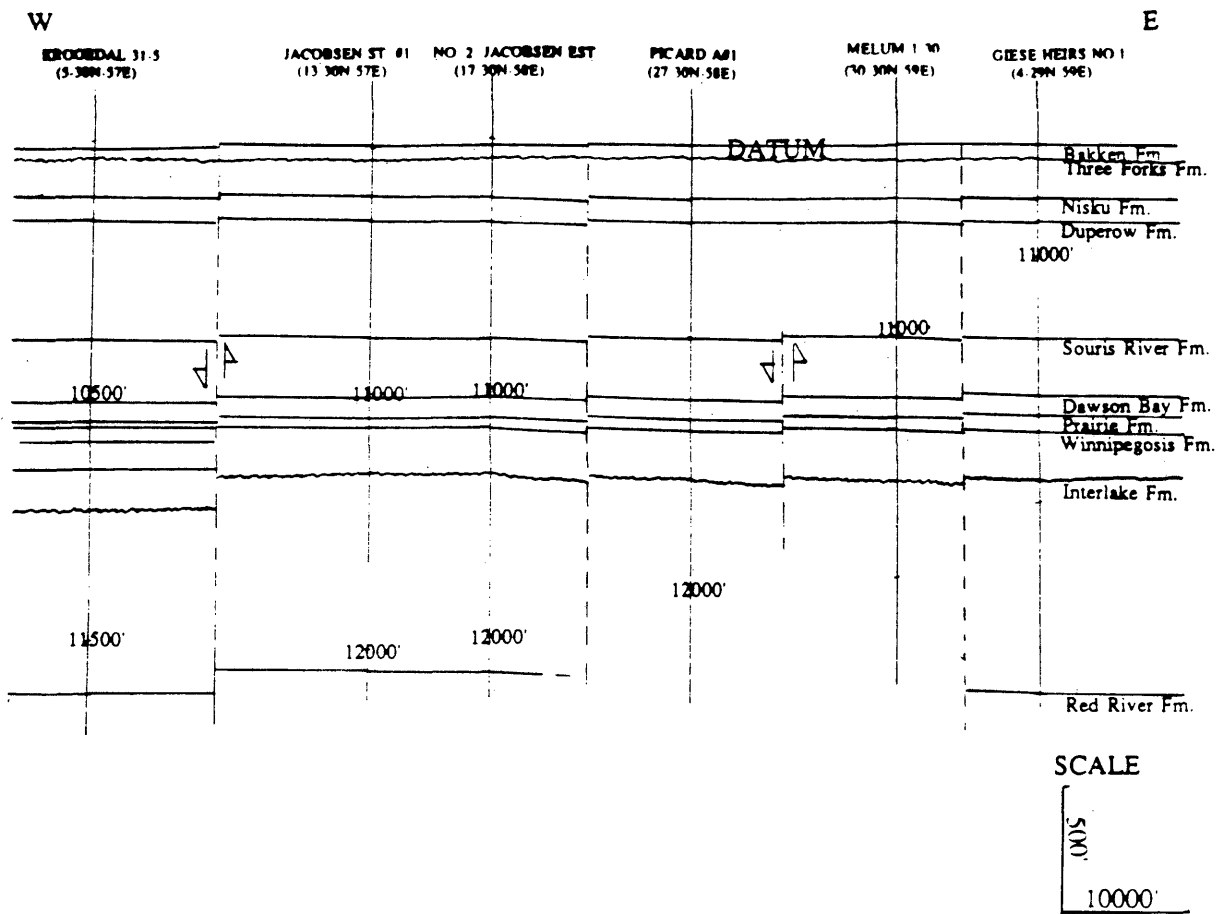


Fig. 40c East-West Stratigraphic cross section MT-A (Red River - Bakken Interval)

the Jacobsen State #1 well is of the order 177 feet or 100% over a distance of 4.5 miles. The absence of Prairie evaporite east of the Krogedal 31-5 well might be due to non deposition as a result of faulting or salt dissolution or both. Careful analysis of the overlying stratigraphic units is necessary in order to make any useful interpretation. Within the Lower Kaskaskia sequence, stratigraphic thickness anomaly is shown by Devonian Souris River Formation which thins from 236 feet in the Krogedal 31-5 well to 227 feet in the Jacobsen State #1 well and 222 feet in the No. 2 Jacobsen Estate well, a counter regional thinning of 9 - 14 feet or an average of 5%. Souris River then thickens to 245 feet in the Picard A# 1 well before thinning again counter regionally to 225 feet in both the Melum 1-30 and the Dome Giese Heirs No. 1 well, a thickness change of 20 feet or 8% resulting from probable movement on the fault between the two wells. Upsection, there is no significant immediate thickness compensation in the interval Dawson Bay to Bakken, as a result of the observed thinning in the Prairie. However, the Mississippian strata show a significant thickness variation across the area

Most of the Mississippian strata thicken eastward as usual along the regional thickening trend. The first strata to show any counter regional thinning are those of the Mission Canyon where the initial carbonate deposit which is 98 feet thick in the Krogedal 31-5 well thins by 9% to 89 feet in the Jacobsen State #1 well. This same unit then increases to 100 feet in the No. 2 Jacobsen Estate and Picard A# 1 wells. The stratigraphic unit once again thickens from 87 feet in the Picard A#1 well to 95 feet in the Melum 1-32 well. Upwarping of the block east of the Melum 1-32 well at this time caused the 28% thinning (27 feet) in the lower Mission Canyon section at Dome Giese Heirs No. 1 well where it is only 68 feet thick (Plate 17B).

The Ratcliffe Interval is 220 feet in the Krogedal 31-5 well but thins by 32 feet or 15% to 188 feet in the Jacobsen State #1 well suggesting recurrent movement on the fault separating the two blocks. Ratcliffe thickness increases to 215 feet in the No. 2 Jacobsen Estate well along the regional thickening trend but thins again across the trace of the Culbertson-Grenora feature by 7% to 200 feet in the Picard A# 1 well, 210 feet in the Melum 1-30 well and 208 feet in the Dome Giese Heirs No. 1 well. The structural activity along the trace of the Culbertson-Grenora feature which was reactivated between the Krogedal 31-5 and Jacobsen State #1 wells during the time of deposition of the lower Mission Canyon and Ratcliffe seems to have carried on to the time of deposition of Charles deposition. The Middle Charles section directly overlying the Ratcliffe thins from 190 feet in the Krogedal 31-5 well counter regionally to 172 feet in the Jacobsen State #1 well. Charles Formation units 4 & 5 (informal) show significant counter regional thinning of 15% and 6% respectively between the No. 2 Jacobsen Estate and the Picard A# 1 wells across the trace of the Culbertson-Grenora feature (Plate 17B). Perhaps the most significant thickness anomaly is recorded in the Charles units 1, 2 and 3 which thicken from 137 feet in the Krogedal 31- 5 well to 153 feet in the Jacobsen State #1 well but thins to 130 feet in the No. 2 Jacobsen Estate well. A major counter regional thinning of 54% is observed between the No. 2 Jacobsen Estate and the Picard A# 1 wells.

Upsection, significant thickness variation is observed in the Tyler, Minnelusa and Spearfish Formations between the No.2 Jacobsen Estate and the Picard A#1 wells at the exact location of the Culbertson-Grenora feature, but not the transition area between thick and thin deposition areas (the Krogedal 1-35 and Jacobsen State #1 wells). The Tyler Formation thickens from 259 feet in the No.2 Jacobsen Estate well to 330 feet in the Picard A#1 well, an increase of 71 feet across the feature. Similarly, the Minnelusa thickens from

195 feet in the No.2 Jacobsen Estate well to 270 feet in the Picard A#1 well and the Spearfish Formation thickens by 75 feet between the same wells. On the other hand, at the transition point between thick and thin salt deposition, that is, between the Krogedal 31-5 well (5-30N-57E) and the Jacobsen State #1 well, the only significant thickness changes recorded are in the Minnelusa (27 feet) and Spearfish (119 feet), giving a total of 146 feet. If the negative 17 feet in the Tyler is taken into consideration, we have a net thickness increase of 129 feet as against 177 feet of "dissolved" salt. These figures seem reasonable as compensation thickness between the Krogedal 31-5 well and Jacobsen State #1 well, since only the major stratigraphic units exhibiting significant thickness variations are considered. However, between the No.2 Jacobsen Estate well and the Picard A#1 well, where a total of 328 feet of thickness increase is documented as against only 177 feet of salt thickness differential between "normal" thick salt area in the Krogedal 31-5 well and thin salt area in the Picard A#1 well. The differential of 168 feet is not readily accounted for, other than considering additional subsidence as a result of structural movement in this area around the Montana dissolution hole. It should however be pointed that the location of the northeast-trending feature between the No.2 Jacobsen Estate well and the the Picard A#1 well is also coincident with the transition point between "thick" and "thin" Charles salt. But still, only 70 feet of Charles salt removal either by erosion or dissolution is not enough to account for the 168 foot differential. Assuming that both the Prairie and the Charles salt dissolved to warrant the compensation thickness effect in the younger strata, there is still a lot of extra thickness (98 feet) not accounted for by the dissolution-compensation phenomenon. The interpretation here thus becomes difficult to make. Structural movement in a reverse sense along the trend of the Culbertson-Grenora feature seems inevitable and should help in accounting for the extra stratral thicknesses in the Tyler, Minnelusa and

Spearfish. Accompanying the thickness variation is a great deal of facies changes in all the units affected by the structural movement as depicted on the cross section MT- A (Plate 17a).

Most of the observed thickening patterns is by onlap across the Culbertson-Grenora feature as shown by the 80 foot thick salt member characterized by rectangular gamma log motif and hole wash out at the base of Spearfish in the Picard A# 1, the Mc Cain 1-30 and the Dome Giese Heirs No. 1 wells but not present on the elevated block to the west. Similar facies changes are noticeable across the trace of the Culbertson-Grenora feature at the top of Tyler, bottom of the Minnelusa and within the Rierdon - Spearfish interval. It thus seems that the faulting between the Krogedal 31-5 well and the Jacobsen State #1 well that caused the thinning and subsequent dissolution of the Prairie in the latter well, reversed its direction of motion during the time of deposition of the Spearfish but changed back to normal (east side up) towards the end of Rierdon time because of the counter regional thinning of 25 feet or 10% recorded near the top of Rierdon Formation between the two wells.

#### ***Northern Non-Dissolution Area***

Eight to ten miles north of the the salt dissolution feature in Roosevelt County, Montana, another stratigraphic cross section MT-C (Plates 18a,b & c (Figures 41a, b & c)) was prepared across the northeast-trending feature in order to examine the continuity of the features observed in the central dissolution area. Again stratigraphic units systematically thicken from west to east. Of note is the thickness variation within the halite members of the Prairie. The oldest halite member is 89 feet thick in the Marshall No. 1 well (4-31N-58E, SWNW) and the Audrey Overby #1 well (2-31N-58E, CSW) but increases to 99 feet



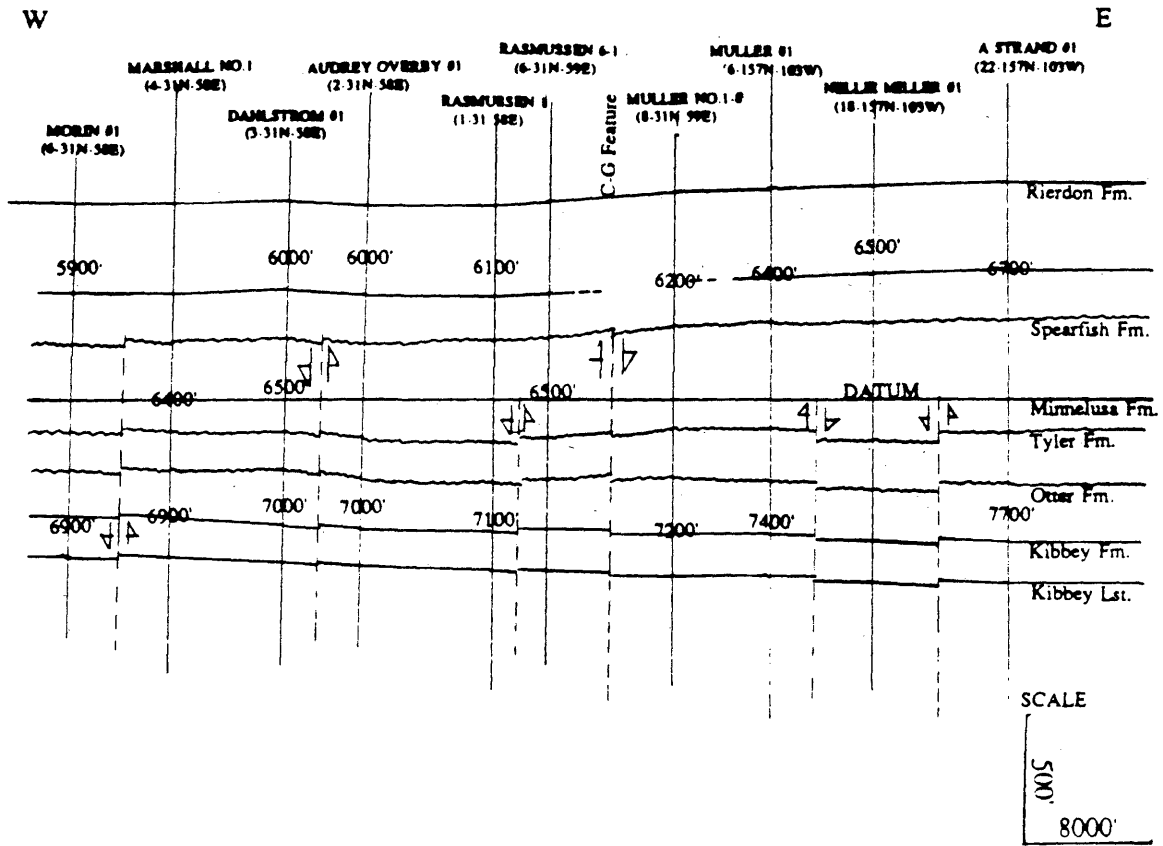


Fig. 41a East-West stratigraphic cross section MT-C (Kibbey-Rierdon)

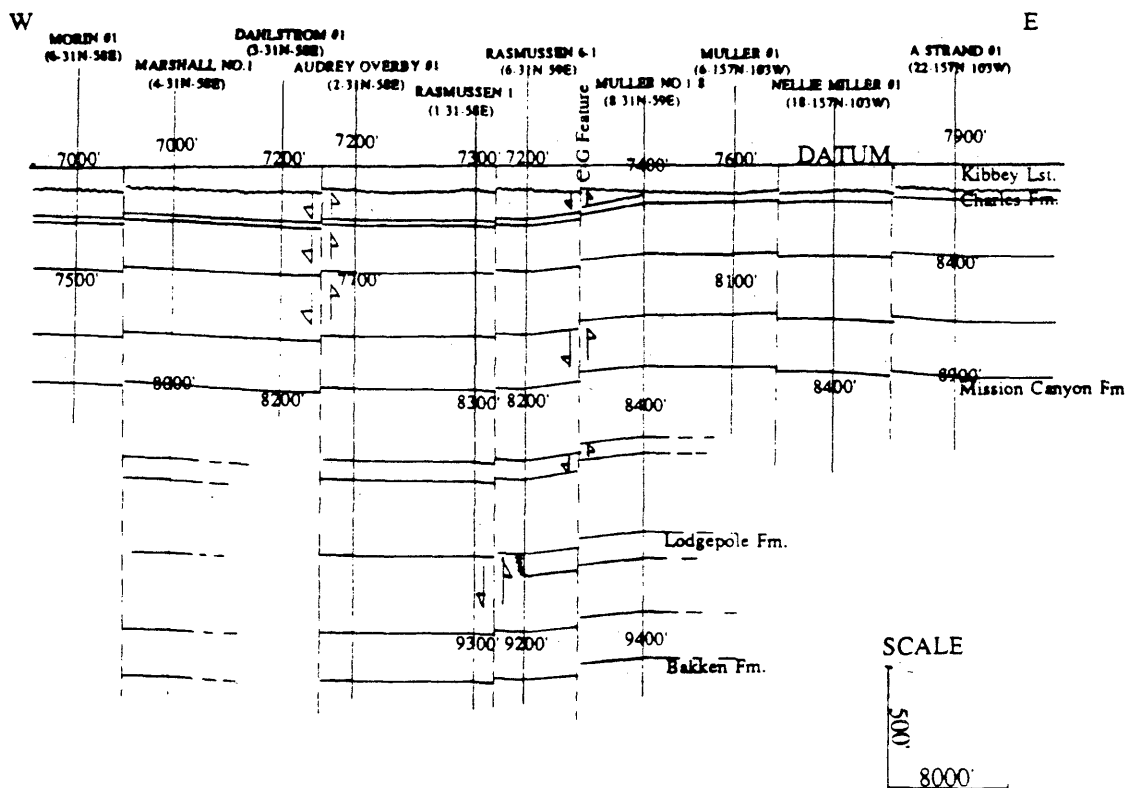


Fig. 41b East-West stratigraphic cross section MT-C (Bakken - Kibbey)

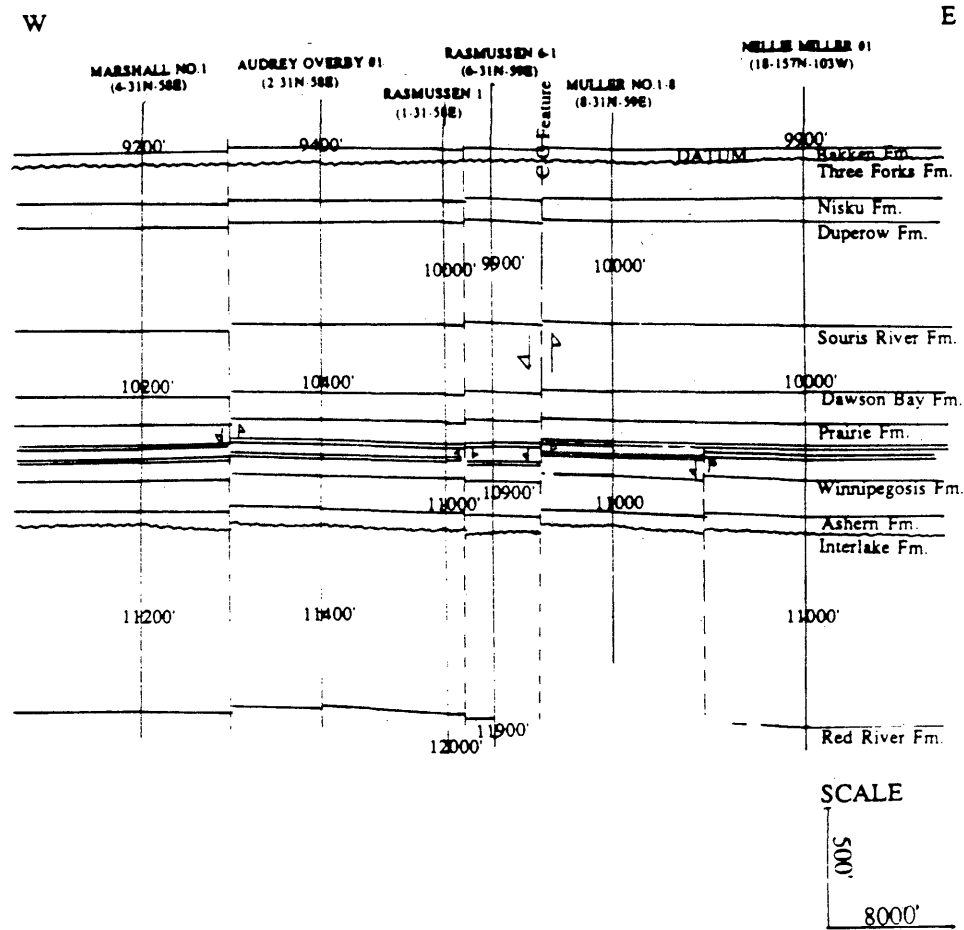


Fig. 41c East-West stratigraphic cross section MT-C (Red River - Bakken)

in the Rasmussen 1 well (1-31N-58E). The unit then thins counter regionally by 14% to 85 feet in the Rasmussen 6-1 well (6-31N-59E, SESW). This thickness change might be indicative of a slight structural movement at this location. Across the trend of the Culbertson-Grenora feature, the lower halite member of the Prairie thickens to 101 feet in the Muller No. 1-8 well (8-31N-59E, NWNE) but thins counter regionally to 88 feet in the Nellie Miller #1 well (18-157N-103W), a thickness change of 13 feet or 13%. This significant counter regional thinning is also interpreted as due to minor upwarping of the Nellie Miller #1 block.

The middle halite member is 42 feet thick in the Marshall No. 1 and the Audrey Overby #1 wells, and 46 feet in the Rasmussen 1 well. The unit then thickens anomalously to 74 feet (61% thickening) in the Rasmussen 6-1 well. However, across the trace of the Culbertson-Grenora feature the unit thins counter regionally to 40 feet (46%) in the Muller No. 1-8 well and Nellie Miller #1 wells. The stratal relationship suggests recurrent fault movement along the trend of the Culbertson-Grenora feature making the Rasmussen 6-1 well block depressed with respect to the Muller No. 1-8 well block. The sharp thickness increase (>60%) between the Rasmussen 1 and the Rasmussen 6-1 wells over a distance of less than a mile is indicative of a fault separating the two wells and downthrown to the east. The upper halite member of the Prairie, for the most part, shows a systematic thickness increase from west to east across the area.

Devonian Souris River Formation shows a similar thickness pattern as the Prairie. The Counter regional thinning of 14 feet or 5% between the Rasmussen 6-1 and the Muller No. 1-8 wells along the trend of the Culbertson-Grenora feature is significant.

Upsection, recurrent structural movement on the Culbertson-Grenora feature and the fault separating the Rasmussen 1 and Rasmussen 6-1 wells occurred during the Mississippian. Counter regional thinning within the Lodgepole is observed as the upper portion of the unit thickens from 312 feet in the Audrey Overby #1 well to 318 feet in the Rasmussen 1 well but thins by 18 feet or 6% to 300 feet in the Rasmussen 6-1 well. The thickness change is accompanied by a facies change at the top of the Lodgepole (Plate 18b). The facies changes from a carbonate unit apparently containing more grainstone/packstone facies to the mud dominated facies characterized by the relatively higher gamma count on the well log.

Recurrent structural movement is documented in the Mission Canyon Formation between the Rasmussen 6-1 well and Muller No. 1-8 well where the middle carbonate unit thins counter regionally from 75 feet in the Rasmussen 6-1 well to 60 feet in the Muller No. 1-8 well by 20%. The Ratcliffe interval is 207 feet thick in the Morin # 1 well (6-31N-58E) and the Marshall No. 1 well but thickens to 223 in the Dahlstrom #1 well (3-31N-58E) and thins counter regionally by 11 feet or 5% to 212 feet in the Audrey Overby #1 well. The interval thickness once again increases eastward to 229 feet in the Rasmussen 1 well and 253 feet in the Rasmussen 6-1 well. Across the trace of the Culbertson-Grenora feature however, the Ratcliffe thins by 33 feet to 220 feet in the Muller No. 1-8 and Muller #1 wells, 226 feet in the Nellie Miller #1 well and 223 feet in the A. Strand #1 well (22-157N-103W, SESE). This is a thinning of 13% and probably resulted from the movement on the eastern block at this time. Structural activity either ceased or progressed gently at the end of Ratcliffe deposition until the time of deposition of the top members of the Charles Formation which show a drastic thinning of about 90 feet between the Rasmussen 6-1 and the Muller No. 1-8 wells.

Upsection, the fault between the Dahlstrom #1 well and the Audrey Overby #1 well which is upthrown to the east became active during the time of deposition of the Otter and Spearfish. The fault along the trace of the Culbertson-Grenora feature also became active during the time of deposition of the Spearfish, but this time, in a reverse sense as 60 foot thickening (27%) is observed in this interval between the Rasmussen 6-1 well and the Muller No. 1-8 well. The younger stratigraphic units do not show much anomaly.

Further to the north another stratigraphic cross section MT-B (Plates 19a,b & c (Figures 42a, b & c)) was prepared. Not much interpretation can be drawn from the lower third of the section because of the shallowness of the Douglas Graupe #1 well (27-161N-102W, NESE). The Ratcliffe interval thickens from 173 feet in the Phillip Anderson #1 well (26-35N-58E, SWSE) to 197 feet in the Anderson No. 30-1 well (30-161N-102W, SWNW) but thins counter regionally by 15% to 167 feet in the Douglas Graupe #1 well suggesting movement on the Douglas Graupe #1 block. The Mississippian Charles top units thin from 126 feet in the Phillip Anderson #1 well to 118 feet in the Anderson No. 30-1 well and then increases to 124 feet in the Douglas Graupe #1 well and 120 feet in the Johnson 1 well. The counter regional thinning of 8 feet or 6% might indicate a down-to-the-west fault between the Phillip Anderson #1 well and the Anderson No. 30-1 well. Similarly, unit 2 thins by 7% from 70 feet in the Phillip Anderson #1 well to 65 feet in the Anderson No. 30-1 well and the Douglas Graupe #1 well, suggesting a reactivation of the fault between these two wells at this time. In addition, the salt facies in the top unit of the Charles at Anderson 30-1 is found to change into carbonate facies in the downthrown block (Plate 19b). The structural movement climaxed during the time of deposition of unit 1 as the 60 foot section in the Anderson No. 30-1 well is missing in the Douglas Graupe #1 well (Plate 19b).

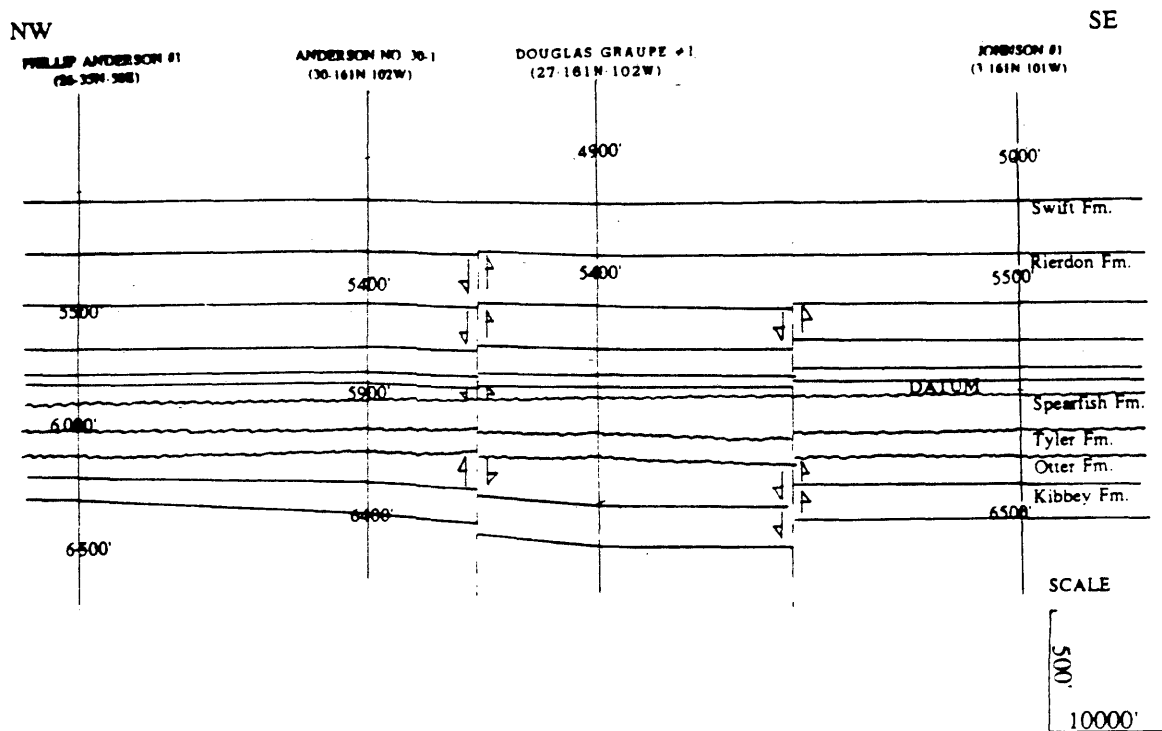


Fig 42a East-West Stratigraphic cross section MT-B (Kibbey - Rierdon Interval)

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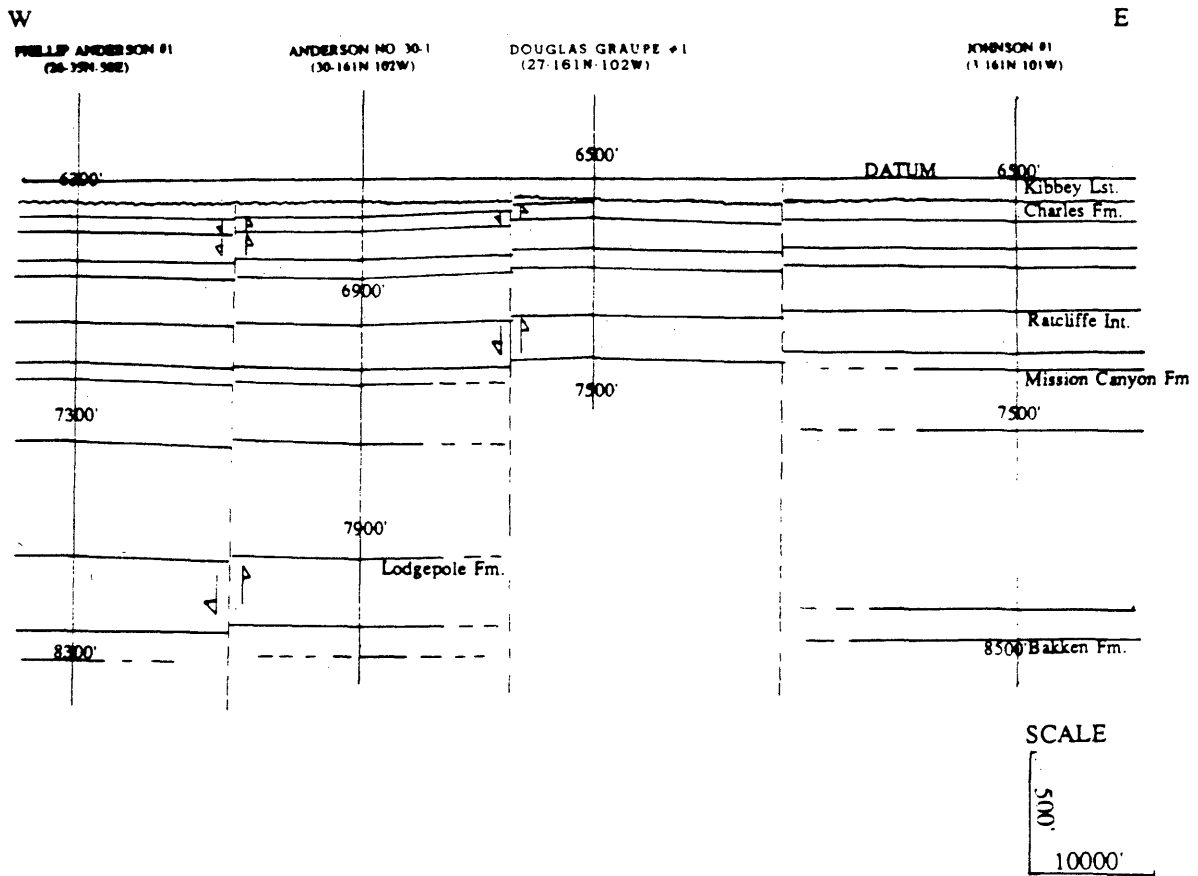


Fig 42b East-West Stratigraphic cross section MT-B (Bakken - Kibbey Interval)



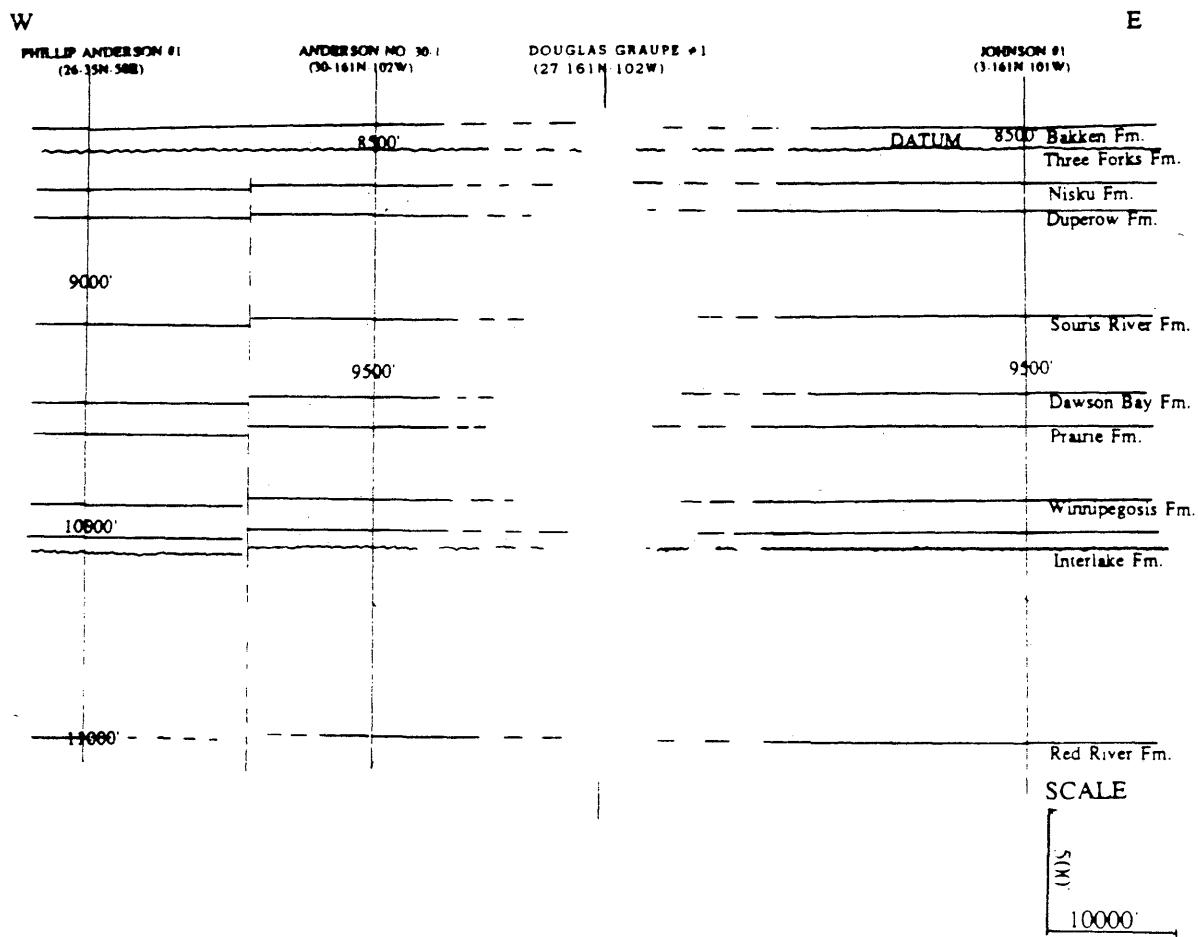


Fig. 42c East-West Stratigraphic cross section MT-B (Red River - Bakken Interval)

Upsection, structural reversal on the identified faults took place during the time of deposition of the Kibbey, Otter and Spearfish Formations. Excessive thickness increase of more than 50% in the Kibbey and the Otter from the Phillip Anderson #1 well to the Anderson No. 30-1 well suggests downwarping of the block containing the latter well. Similarly the fault separating the Anderson No. 30-1 and Douglas Graupe #1 wells became active again during the time of deposition of the Kibbey, Otter, Spearfish, Lower Piper and Rierdon.

The Kibbey Formation is 90 feet thick in the Phillip Anderson #1 well, thickens by 54% to 139 feet in the Anderson No. 30-1 well and 170 feet in the Douglas Graupe #1 well by 31 feet. It then thins counter regionally by 42 feet (24%) to 128 feet in the Johnson 1 well marking a down-to-the-west fault between the Douglas Graupe #1 and the Johnson 1 wells. The Otter thickens from 90 feet in the Phillip Anderson #1 well to 135 feet in the Anderson No. 30-1 well, but across the fault a further thickening of 90 feet or 66% is documented between the Anderson No. 30-1 and the Douglas Graupe #1 wells implying recurrent movement on the fault at this time. Similarly, the far eastern fault moved during the time of deposition of the Otter causing a 59% thinning in the Otter between the Douglas Graupe #1 well and the Johnson 1 well. The fault between the Anderson No. 30-1 well and the Douglas Graupe #1 well had recurrent movement during the time of deposition of the Spearfish as the interval thickens gently from 115 feet in the Phillip Anderson #1 well to 120 feet in the Anderson No. 30-1 well but anomalously across the fault to 150 feet in the Douglas Graupe #1 well. Reversed motion on this fault caused the counter regional thinning of the Rierdon Formation between the two wells (Plate 19a). The interpreted faults are high angle to vertical normal faults sub-parallel to the trend of the Culbertson-Grenora feature. Episodic recurrent movements occurred at various geological

times between Ordovician and late Triassic with structural reversals in the Absaroka along the trace of the Culbertson -Grenora feature. The Absaroka structural reversal caused the faults to be downthrown to the east, a similar pattern observed at Cow Creek/Weldon field area on the Weldon-Brockton fault.

### ***SURFACE DRAINAGE OF STUDY AREA***

It is interesting to note that the pattern of surface drainage of the rivers that flow across the study area. Not only do many of the rivers generally flow in northwest-southeast and northeast-southwest directions, but they also display remarkably straight stream courses such as those found at T28N, R58E; T28N, R59E and T29N, R52-53E of the study area (Plate 1). This rectilinear geometry suggests a strong structural control. Some of these patterns are continuous into the western side of North Dakota in Williams and Divide Counties, but with less frequency. It seems then that whatever is exercising this kind of control on the drainage may have had its energy concentrated to the southwest portion of the area and become attenuated to the northeast.

From the above considerations, there is very little doubt left to believe that the Culbertson-Grenora feature which trends northeast across the big dissolution area in Shotgun Creek, Roosevelt County, Montana, might in fact represent an old fault trace. Several fault blocks are identified on the detailed stratigraphic cross sections showing episodic structural movements at various geologic times. Faulting along the trace of the Culbertson-Grenora feature was constantly interpreted because of the counter regional thinning documented in the stratigraphic units especially those of the Mississippian Charles Formation, in which maximum structural movement seems to have occurred at the end of

Charles deposition. This phenomenon caused the severe erosional truncation at the top of Charles in the hanging wall.

At the central dissolution area, structural movement which led to the drastic thinning of the Devonian Prairie evaporite was complicated by salt dissolution. Assuming that the thinning resulted only from salt dissolution we should expect to find a compatible amount of sediment build up in the younger stratigraphic intervals. However, what we find is a lot of extra stratigraphic thicknesses not accountable for by dissolution alone. The extra thickness observed in the younger strata overlying the thin salt area between the Superior No. 2 Jacobsen Estate well and the Phillips Picard A#1 well suggests not only thickness compensation but also faulting which created additional accommodation potential. Assuming that thinning in the Charles salt too could be related to dissolution instead of structural movement, the expected compensation thickness in the younger strata when added on to that generated by the Prairie, still do not account for the thickness anomaly, hence structural movement is compelling.

In addition , the surface drainage pattern in the western part of the study area which shows a rectilinear arrangement of streams in northeast and northwest directions, coupled with the straightness of many of these streams, suggest a strong tectonic control. It is therefore be concluded that the Culbertson-Grenora feature may represent a fault zone, probably part of the broad Brockton -Froid-Fromberg fault system, which is postulated to be trending in a northeast direction. Structural activity on the feature however seems to be attenuated in a northeast direction and probably dies out somewhere in Divide County of North Dakota. The fault block tectonics pattern generated in the area is very much similar to that interpreted at Cow Creek-Weldon Field area, which is out of the limit of Prairie salt deposition, hence salt tectonics can at least be eliminated.

Weldon-Cow Creek field lies in McCone County, Montana between townships T21N and T23N and ranges R46E and R48E in the western flank of the Williston basin (Figure 43). This area lies approximately 60 miles southwest of the study area, and was selected for study to provide a better insight to the structural expression of the Weldon-Brockton fault, which is known to separate Weldon field from Cow Creek field (Hicks, 1985). Knowledge thus gained, was intended to be used in further evaluating the northeast-trending feature in the original study area. Similar expression of stratigraphic and structural attitude at both places would indicate and establish the northeast-trending feature as a fault, which is thought to be the northern limit of the Brockton-Froid-Fromberg fault zone. Otherwise, it may be likely that the Brockton-Froid-Fromberg fault has actually died out in this area. A total of 95 geophysical well logs from Weldon, Cow Creek, and East Cow Creek fields were studied, and structure contour maps on tops of the producing units, the Kibbey "B" sandstone (Plate 20) and the Charles Formation (Plates 22) and the isopach map of Kibbey "B" sand (Plate 21) were prepared so as to study the structural effect of the Weldon-Brockton fault. All the fields are relatively shallow fields. Discovered by the Sinclair Oil and Gas well, No. Federal Mc Cone 5012 #1 in 1964, Weldon field produces from the Mississippian Kibbey sandstone, from structural and stratigraphic traps. Cow Creek field is separated from Weldon field by a northeast-trending fault, the Weldon fault which is downthrown to the east. Cow Creek field was discovered in 1969 by Resources Capital Corporation and it produces from the Mississippian Charles A and B dolomitic limestone, from purely structural traps. East Cow Creek field, which lies to the northeast of Cow Creek field, produces from the Mississippian Kibbey sandstone. These reservoirs have an active water drive system.

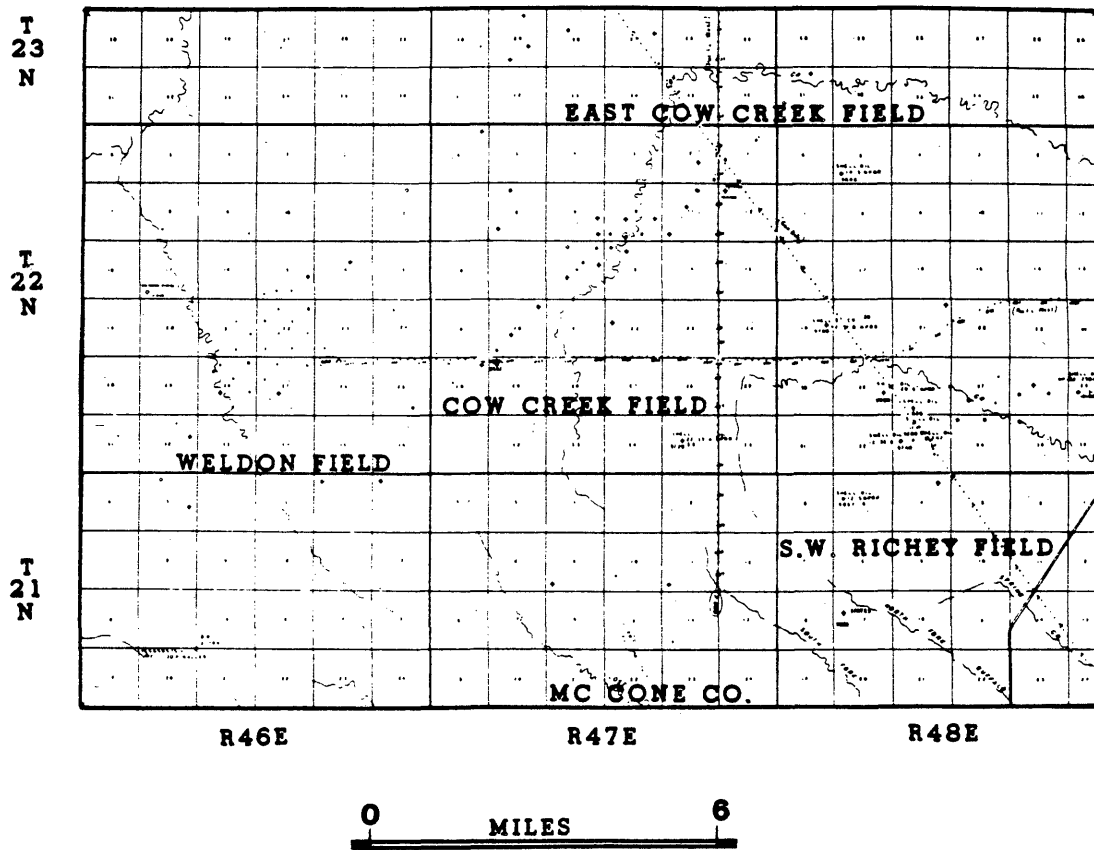


Fig. 43 Map of Weldon-Cow Creek field, Mc Cone County, Montana

### *Interpretation of Cow Creek Maps*

Structure contour map on top of the Kibbey B sand unit , the main producing unit in the Kibbey Formation (Plate 20), and the isopach map of the B sand unit (Plate 21), show the general depositional strike direction in this area to be northeast as was observed for the study area to the north. This area is dissected into two blocks by the northeast-trending fault known as the Weldon fault (Hicks, 1985) which is downthrown to the east. The western, upthrown block is the site of Weldon field and the eastern, downthrown block, contains Cow Creek and East Cow Creek fields. Apparent throw on the fault, estimated from the top Kibbey structure map, is about 400 feet.

In the hanging wall, the structure contours show a gentle dip of about 55 feet per mile into the fault, and in the footwall, closed anticlinal structures are oriented en echelon in a northeast direction and dip into the fault at a gradient of about 90 feet per mile. Cow Creek field is structurally low to East Cow Creek field, which has Kibbey production. East Cow Creek field on the downthrown side of the fault, has Kibbey production from an average depth of -3750 feet sub sea, while the production from an equivalent stratigraphic unit from Weldon field on the upthrown side, is from an average depth of -3400 feet sub-sea. This structural relationship suggests that activity on the Weldon fault probably took place after the accumulation of hydrocarbon in the Kibbey sandstone or that the reservoirs were filled by different migration path ways after structural activity.

### *Structural Interpretation*

Lack of deep subsurface data in the Cow Creek field area prevents the interpretation of its earliest structural history. It should be pointed out that this area is completely out of the limit of Prairie salt deposition, so that the problem of salt dissolution and compensation thickness that complicated structural interpretation in the study area can be eliminated.

Four detailed stratigraphic cross sections were constructed from northwest to southeast across the Weldon fault along its length at different locations in order to gain better understanding of the structural movement and times of movement on this structure.

Cross section CC<sub>1</sub>-CC<sub>2</sub> Plate 23 (Figure 44)) demonstrates anomalous thickening in three major stratigraphic units, the Heath, Tyler and Amsden Formations from the Lamar Hunt #1 Hall well (27-23N-47E, SENE) on the upthrown side of the fault to the 3-B Northern well 4 (1-22N-47E) on the downthrown side. The Heath Formation onlaps the Otter Formation from east to west. It is 84 feet thick in the 3-B Northern well but not present in the #1 Hall well. Documented structural movement on the Weldon fault probably occurred during the time of deposition of the Heath, Tyler and Amsden Formations. The overlying Tyler also thins from 92 feet in the 3-B Northern well to 64 feet in the #1 Hall well. Similarly, Amsden thins by 79% from 86 feet in the 3-B Northern well to 18 feet in the #1 Hall well. From this, it appears that major movement on the fault took place between the late Mississippian and late Pennsylvanian when the Heath, Tyler and Amsden were deposited. In the primary study area, these were the same times of major structural adjustment along basement weakness zones. Overlying and underlying this interval, thickness of stratigraphic units are very much uniform, showing only slight thinning toward the up-thrown block to the west. All the other stratigraphic cross sections



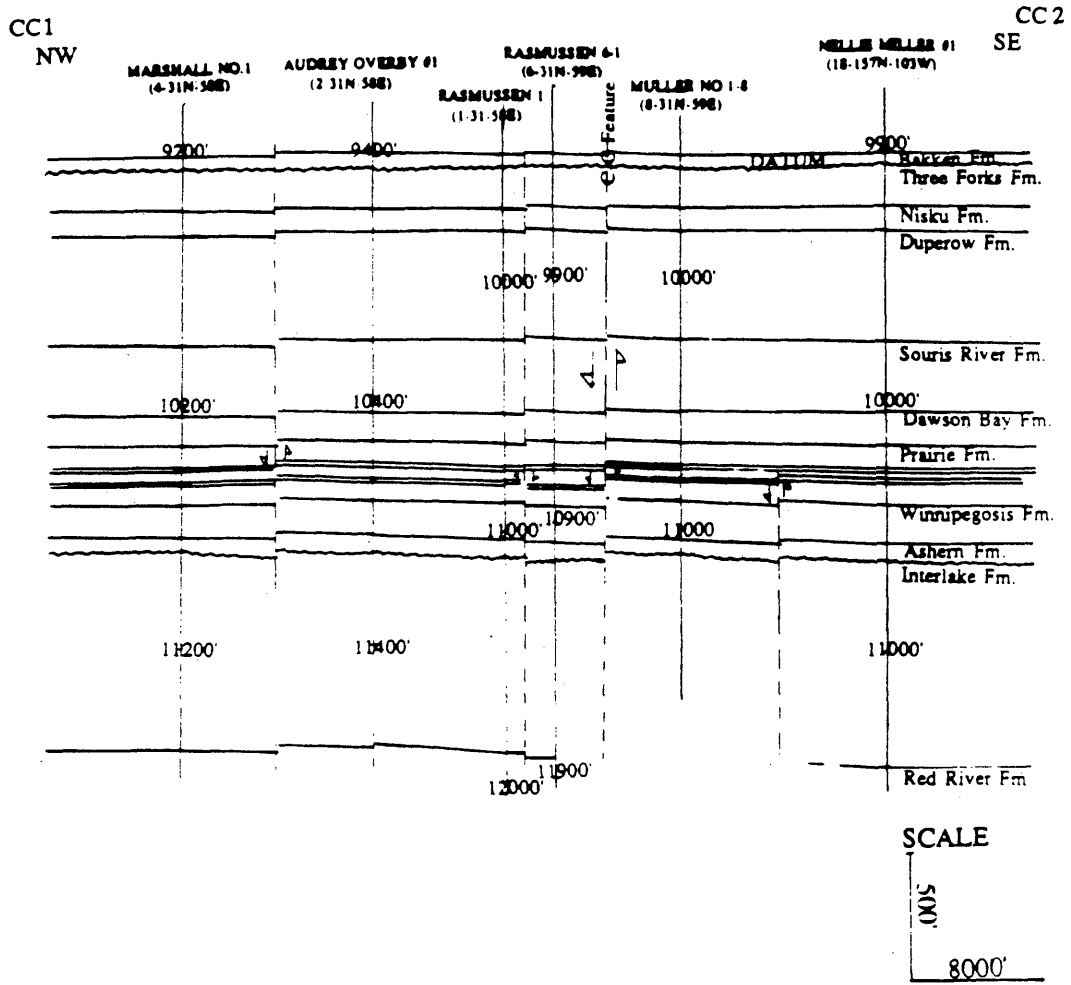


Fig. 44 NW-SE Stratigraphic cross section CC1-CC2 across Weldon fault

show similar pattern of thinning and thickening with only the Heath, Tyler and Amsden Formations basically affected (Figures 45, 46 & 47 (Plates 24, 25 & 26) ).

Lack of deep subsurface data in the Cow Creek-Weldon field area prevents any geologic interpretation deeper than the Mississippian Kibbey therefore only the structural attitude of stratigraphic intervals in both areas of study younger than the Kibbey, could be compared. Similar stratigraphic intervals, Tyler, Heath and Minnelusa (Amsden) amongst others, are structurally affected to a large extent in both areas. It may thus be concluded that the Culbertson-Grenora feature may indeed be part of the Brockton-Froid-Fromberg fault zone which trends northeast-southwest in the study area. However, it is apparent that the intensity of structural activity is much greater in the southwest especially in areas outside of the primary study area, as documented in Cow Creek-Weldon field, but becomes attenuated in a northeast direction. The exact point at which the structure terminates is hard to tell but geological and geomorphological evidence suggests that it is close to the Canadian/US in western Divide County of North Dakota.

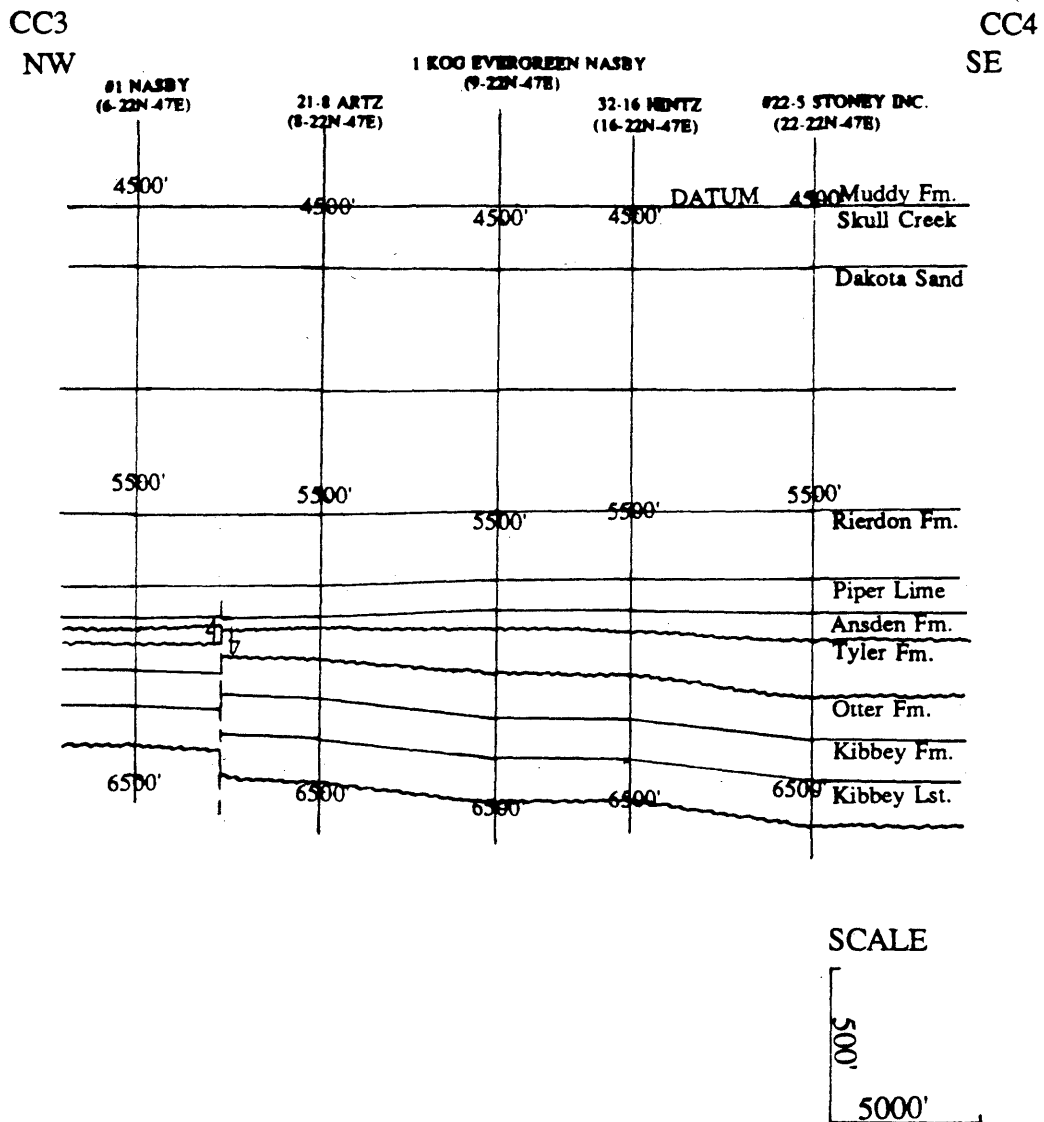


Fig. 45 NW-SE Stratigraphic cross section CC3-CC4 across Weldon fault

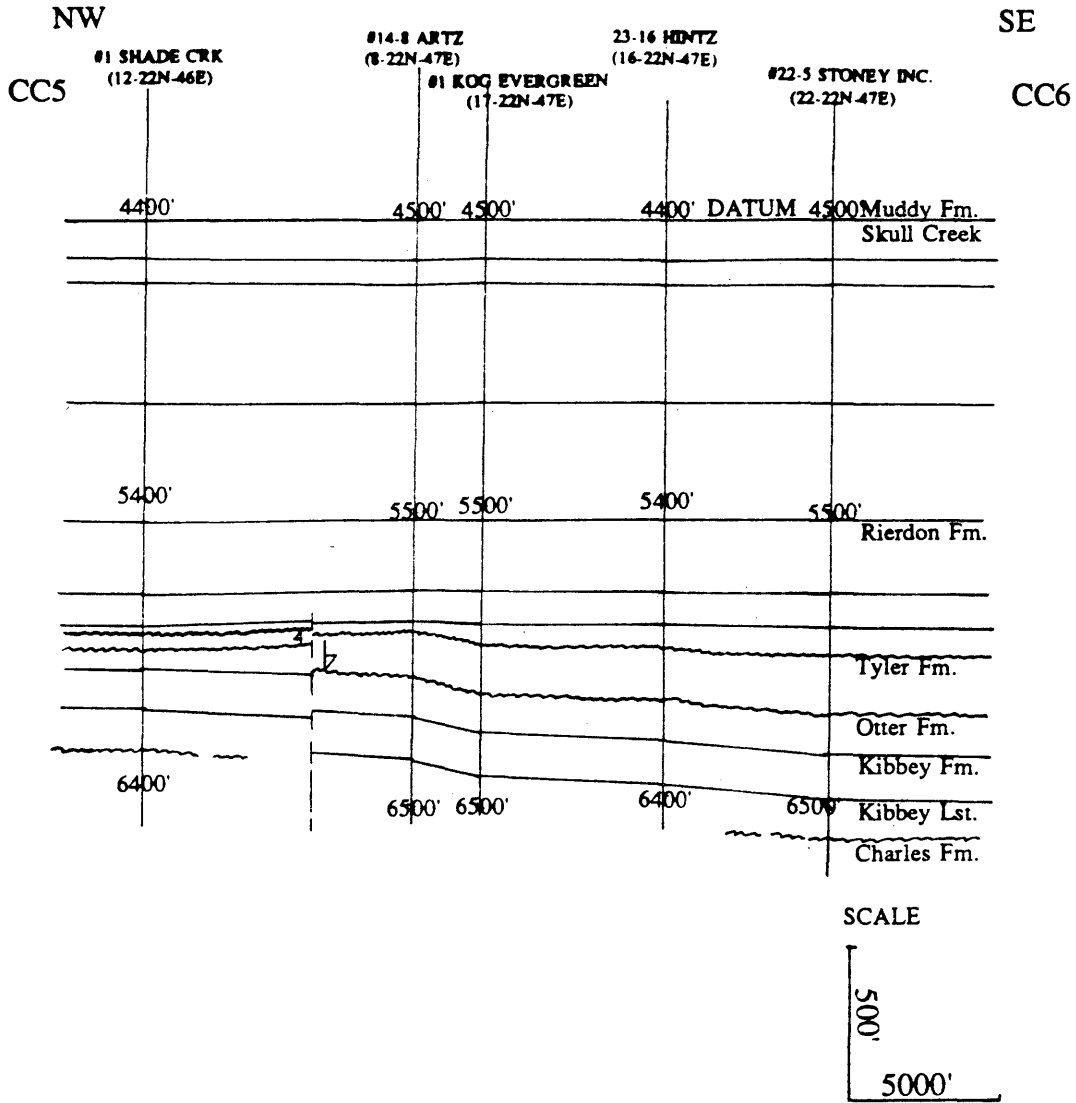


Fig. 46 NW-SE Stratigraphic cross section CC5-CC6 across Weldon fault

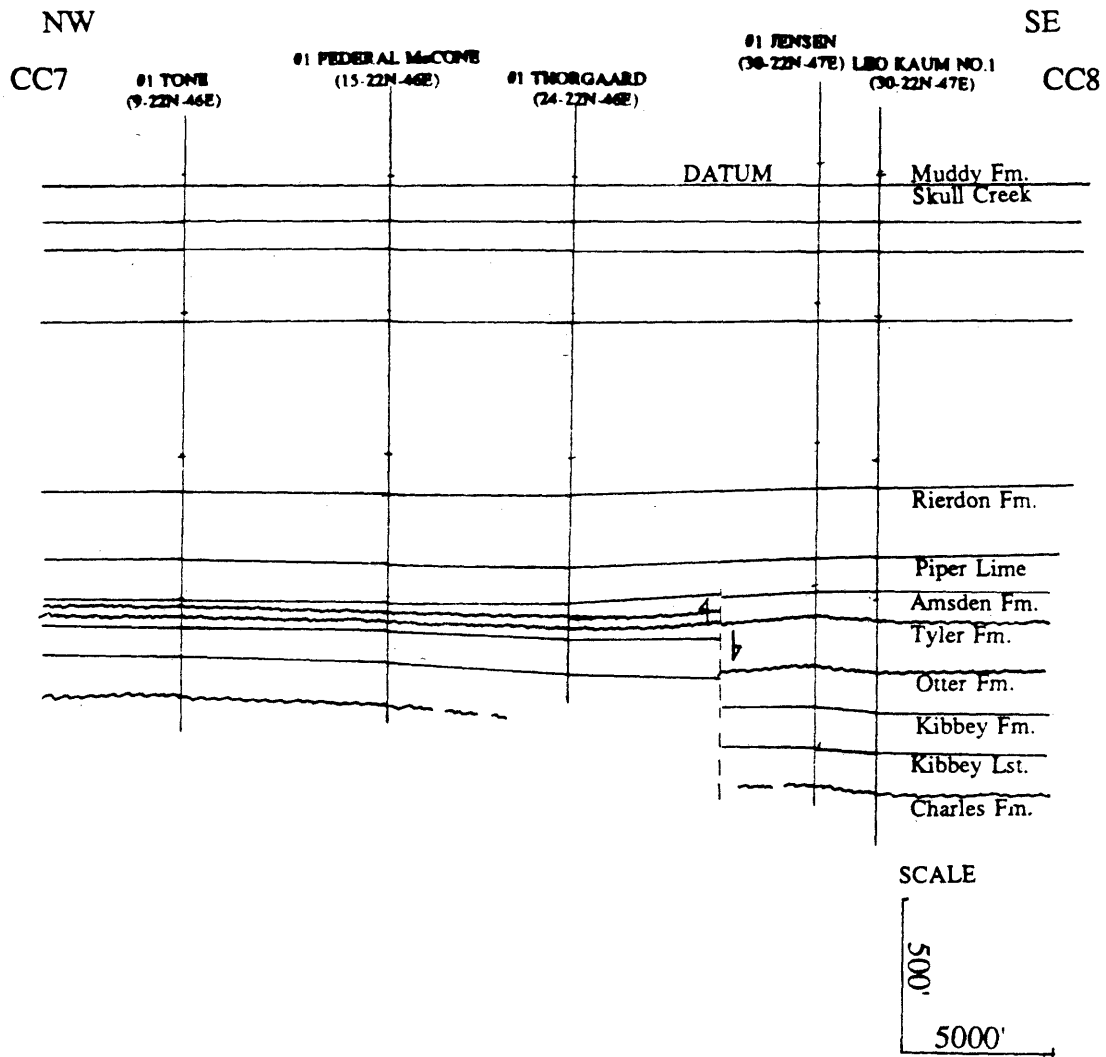


Fig. 47 NW-SE Stratigraphic cross section across CC7-CC8 Weldon fault

## STRUCTURAL DEVELOPMENT OF THE NORTHERN AND CENTRAL PORTIONS OF THE NESSON ANTICLINE.

### *Introduction*

The Williston basin contains several prominent structural features notably the Nesson anticline, Cedar Creek anticline, Billings anticline, Little Knife anticline, Antelope anticline and the Brockton-Froid-Fromberg fault zone. Structural trends of these features follow three major grain directions identified in the region. These are the northeast-southwest, northwest-southeast and north-south.

The Nesson anticline is a major north-south trending feature in the Williston basin. Centrally located within the basin, the anticlinal structure is the largest producing feature in the North Dakota portion of the basin. It stretches for approximately 110 miles along a generally north-south line just south of the Canadian border to the Killdeer mountains (Le Fever et al, 1987).

In the study area, the Nesson anticline is predominantly a south-plunging fold with slight irregularities along the hinge trace and the fold bifurcates or trifurcates just south of the Missouri River, giving rise to the Antelope anticline. Several structural offsets are also noticeable along the feature which may be related to lineaments or subtle faults. Recognition of these faults and linear elements is based on interpretation of a series of structure and isopach maps of stratigraphic intervals ranging from the Cretaceous Greenhorn Formation to the Ordovician Red River Formation, and the various stratigraphic cross sections prepared both across and along the anticline at key locations. The Nesson anticline is interpreted into a mosaic of fault blocks of varying sizes ranging from about 40 sq. miles to about 130 sq. miles. Isopach maps of stratigraphic intervals, especially those

of the tectonic-sensitive Devonian units were instrumental in defining the fault blocks. In all, six fault blocks are recognized based on isopach contour spacing, pattern and trend. The directional changes of the axial trace of the hinge line on the Nesson anticline, recognizable on the structure contour maps were also useful in identifying the cross-structure linears or faults.

The interpreted fault blocks are bounded on all sides by faults or fractures along which there has been recurrent structural movement through time. Five prominent faults bounding the fault blocks are recognized. These are the West Nesson fault which bounds Beaver Lodge fault block or block 2 to the west and trends northwest, the East Nesson fault which bounds Beaver Lodge fault block to the east and also trends northwest, the West Temple fault in the north which bounds the Temple fault block or block 4 to the west and trends northwest, the East Temple fault bounding block 4 to the east and also trends northwest and the Charlson fault which trends approximately east-west and separates the Beaver Lodge fault block from the Charlson fault block (block 1). Two additional faults or linears are strongly suspected. These are the northeast-trending linear L1L2 which appears to separate fault block 3 from fault block 4 and the linear L3L4 separating fault block 2 from fault block 3 (Figure 38).

Fault block 3 or the Southwest Tioga fault block is indistinct and may be subdivided into two or more blocks. The failure of the N-S stratigraphic cross sections constructed across these cross-structure linears L1L2 and L3L4 to record any significant stratigraphic thickness anomalies across the features might be due to the fact that the linears probably experienced a predominantly lateral movement during deformation. Lack of adequate data did not permit accurate investigation of the Southwest Tioga block or fault block 3, which is bounded by a possible fault or fracture on the west side that trends northeast and

connects the northwest-trending West Nesson fault. Similarly, a fault on the eastern flank linking the East Nesson fault and the East Temple fault is suggested. The semi-rectilinear fault geometry thus forms a mosaic of fault blocks in a pattern which is consistent with the regional structural configuration of the Rocky Mountain region.



## RESULTS AND INTERPRETATION

On the Nesson anticline in the study area 135 wells penetrate the Silurian Interlake Formation and deeper horizons. Data below the Red River Formation in this area is extremely limited. Thus the earliest structural history of the Nesson anticline in this area is at best speculative.

From the structure and isopach maps, and the various stratigraphic cross sections prepared, several fault zones along both flanks and across the Nesson anticline are inferred. These faults trend in varying directions and intersect one another in a semi-rectilinear manner to form a mosaic of fault blocks. The most prominent fault is the one located west of Beaver Lodge and extending southward to as far as Charlson field. This fault has been referred to as the Western Nesson fault or Master fault (Gerhard, 1987). The master fault has its origin in Sauk or earlier time (Gerhard, 1987). It has moved recurrently through time with a predominant movement downthrown to the west.

The second fault, the East Nesson fault occurs to the east of the Nesson anticline trending NNW from T154N, R95W for about 15 miles to about the northeast end of Beaver Lodge field. A third feature, a possible fault, the West Temple fault is documented to the north of the study area, west of Temple and West Tioga fields. It also borders Mc Gregor and NW Mc Gregor fields on the west side (Plate 1). This fault seems to be trending in a northwest-southeast direction and has a much less activity than its southern counterpart the West Nesson fault. A fourth fault, the East Temple fault which borders Temple field to the east and downthrown to the east, also trends northwest, parallel to the West Temple fault. The two sets of faults may be genetically related with possible offsets in the middle section between fault block 2 and fault block 4, but they appear to have

separate histories of movement. Farther north of Tioga and North Tioga fields, only very shallow wells exist which do not permit accurate interpretation of paleostructural history. However the alignment of the small and shallow fields like Kimberley, Noonan and Planeview fields in northwest direction might have a structural overtone.

The fifth fault identified in the area occurs to the south, just north of Charlson field. It can be noticed on the structure contour maps of the Charles and Bakken Formations where the fold axial trace seems to be laterally displaced with a change in orientation from north northeast to north. Structure contours that tighten around the northeast corner of Antelope anticline which is mostly outside the study area also suggest structural movement. In addition to these faults, two crestal faults on the Beaver Lodge field structures are recognized, the Beaver Lodge crestal faults 1 and 2. Cross faulting on the Nesson is suggested by the isopach trend, deflections in the trace of the paleostructural axis and general field alignment and offsets. Prominent among these possible cross faults are those labelled L1L2 and L3L4 on the index map (Plate 1) and tectonic map (Figure 38), that trend approximately northeast-southwest, and which were investigated by way of cross sectioning. To the far eastern portion of the area, there is some evidence of another paleostructure on the eastern side of the Nesson. Movement on a probable East East Nesson fault is suspected but there is not enough data to confirm this.

## HISTORY OF MOVEMENT ALONG THE NESSON ANTICLINE

The evolution of the Nesson anticline is best demonstrated by studying local documentable movements along the principal fault zones and then relating them to more regional geological conditions. Deep well data on both sides of the West Nesson fault from Beaver Lodge field area to the south around the northwest portion of Charlson field permit adequate analysis of structural activity. A series of stratigraphic cross sections were prepared normal to the general direction of the structural features inferred. Many of these faults appear to have separate histories of movement and development. Basic indication of structural activity is stratigraphic thinning/thickening patterns across inferred features. A basic premise in tectonic control on sedimentation is that fault block movement controls topography and bathymetry and hence thickness variations in stratigraphic intervals. In general, thick units will accumulate in depressed fault blocks and thin sedimentary units in elevated blocks. Thus the evaluation of thickness variations in depositional packages is key to determining paleostructural or paleotopographic trends. In most cases significant counter regional thinning will indicate positive structural movement in which the thin unit occupies the upthrown block while excessive or anomalous rapid thickening across a particular feature, may suggest downwarping of that fault block in which thick units accumulate. In each case, the approximate location and positioning of these faults have been determined primarily from the isopach maps prepared, and placed in the central portion of closely spaced contours. This then indicates the steepest gradient between control points and the place where anomalous rapid thickening can be explained by a fault.

The West Nesson and the East Nesson faults are further investigated by east-west trending stratigraphic cross sections NDAA' (Plates 29a, b & c) and NDBB' (Plates

30a, b & c) with a view to determining the timing and structural offsets. Possible northern extension of this fault is tested by several cross sections which will be discussed later while the southern limit is investigated by section ND-3 (Plates 31a, b & c), where the wells are not deep enough, but show indication of structural activity in all the stratigraphic units of the Madison Charles Formation.

For convenience of discussion the study area will be considered in three broad parts namely Beaver Lodge field area or fault block 2, Temple field area or fault block 4 and Charlson field area or fault block 1. Fault block 3 which is bounded to the north and south by the northeast-trending cross-structure linears L1L2 and L3L4, contains the southern tip of Tioga field and is relatively diffuse because of the poor data control here. Lateral movement along these features might have been dominant over vertical structural movement since the detailed stratigraphic cross sections JJ' (Plates 33a, b & c) and KK' (Plates 32a, b & c) prepared across the blocks did not show any stratigraphic thickness anomaly. The discussion of events and interpretation which follows is based on the maps and detailed stratigraphic cross sections prepared.

#### *Beaver Lodge Field Area (Fault Block 2)*

Movement on the West Nesson fault west of the Beaver Lodge field seems to have started as early as Ordovician time or earlier from the available data studied. Cross section NDAA' (Plate 29c) indicates significant thinning in the Ordovician Red River Formation from 635 feet in the Mapco NGCA #14-33 well (33-155N-97W, SESW) to 585 feet in the Boe Olson #1 well (15-155N-96W, SWNE), a thinning of 50 feet or 8%. The Sveen #1 Etux well (31-155N-96W, SESE) does not go deep enough to make accurate analysis. It appears that the Beaver Lodge fault block (block 2) may have been segmented into smaller

fractions at this time as intra block faulting is apparent. There is an additional thinning of 30 feet or 5% from the Boe Olson #1 well (15-155N-96W, SWNE) to the Amerada Iverson-Nelson Unit #1 well (2-155N-96W, CNE) which suggests a crestal fault, the Beaver Lodge Crestal fault 1 at this position on the Beaver Lodge structure. The Grondale 1-9 well does not penetrate the entire Red River interval so the East Nesson fault could not be accurately analysed here. Following the deposition of the Red River, fault block 2 became stable momentarily as activity on the West Nesson and East Nesson faults ceased or reduced considerably. Thicknesses of stratigraphic units across the feature do not change appreciably. The first major accurately documented indication of structural movement is noticed in the Middle Interlake Formation (Silurian) as this section thins by 20 feet or 5% from 443 feet in the NCGA #14-33 well to 413 feet in the Sveen Etux #1 and 422 feet in the Boe Olson #1 well. Thinning of 67 feet (19%) in the Middle Interlake also exists between the Boe Olson #1 and Iverson-Nelson Unit #1 wells, indicating renewed structural activity on the Beaver Lodge crestal fault 1 during the Silurian. The East Nesson fault is manifest by the rapid thickening of this unit from 355 feet in the Iverson-Nelson Unit #1 well to 445 feet in the Grondale 1-5 well (9-155N- 94W, NENE) and 420 feet in the Ross-36-33 well (36-156N-93W, NWSE), a thickness change of over 90 feet or 25%. No data is available for the Texel 21-35 well.

Silurian Upper Interlake rocks show gradual thickening from west to east across the fault. Sediment thickness changes from 430 feet in the NCGA #14-33 well to 450 feet in the Sveen #1 Etux well, 448 feet in the Boe Olson #1 well and 452 feet in the Iverson-Nelson Unit #1 well. However, across the East Nesson fault, renewed activity on this feature alters the regional thickening gradient appreciably as the Upper Interlake rocks thicken by 108 feet or 24% to 560 feet in the Grondale 1-9 well on the downthrown side

of the fault. Most of the thinning in the Upper Interlake may be attributed to erosional truncation of the Interlake Formation in late Silurian time. This late Silurian activity on the East Nesson fault suggests tilting of fault block 2 to the west at this time.

The Devonian seems to be a very active period tectonically in this area. Significant thinning of the Devonian stratigraphic units across the feature is indicative of syndepositional uplift on the Nesson anticline. The Devonian Ashern Formation shows no apparent counter-regional thinning across the West Nesson fault as the formation thickness slightly increases from 162 feet in the NCGA #14-33 well (33-155N-97W, SESW) to 163 feet in the Sveen #1 Etux well (31-155N-96W, SESE). Abrupt counter regional thinning of the Ashern from 163 feet in the Sveen #1 Etux well to 129 feet in the Boe Olson #1 well (15-155N-96W, SWNE) on the Beaver Lodge fault block suggests another intra block fault, the Beaver Lodge Crestal fault 2, which is downthrown to the west at Beaver Lodge field. Easily correlated thin units within the Ashern show that most of the difference in thickness within the Ashern occur at the lower 30-foot section, a relationship suggesting that thinning was by onlap onto the unconformity surface of the Silurian Interlake Formation (Plate 29c). Across the East Nesson fault, anomalous thickening of the Ashern Formation is recorded as stratal thickness increases by 54% from 120 feet in the Amerada Iverson-Nelson Unit #1 well (2-155N-96W) on the upthrown side to 185 feet in the Grondale 1-9 well (9-155N-94W), 285 feet in the Texel 21-35 well (35-156N-93W) and 250 feet in the Ross 36-33 well (36-156N-93W) on the downthrown side. Accompanying the stratigraphic thickness variation is a remarkable facies change across the fault especially near the top of the Ashern interval where the 60-foot carbonate section in the upthrown fault block 2, changes facies to a basically salt-dominated unit in the downthrown fault block 6 which was then a deeper and probably restricted fault block.

The stratal relationship is illustrated schematically in Figure 48. To the east of the Grondale 1-9 well, the Ashern thins counter regionally by 20 feet (11%) to 165 feet in the Texel 21-35 well (35-156N-93W, SESW) and 145 feet in the Ross 36-33 well (36-156N-93W, NWSE). This thickness change is also accompanied by facies changes which suggests a localized fault movement between the Grondale 1-9 and the Texel 21-35 well. This probable fault which is downthrown to the west is referred to as East East Nesson fault. It appears that a 10 foot thick salt section present in the Grondale 1-9 well can still be found at Texel 21-35 but is completely gone in the Ross 36-33 well (Plate 29c). The salt unit is characterized by blocky (rectangular) gamma ray log motif, high resistivity and offscale readings on the caliper indicating washed out hole.

Structural activity on the Beaver Lodge fault block was renewed in middle Devonian as both the West Nesson and East Nesson faults became active again during the time of deposition of the Prairie evaporite. The Prairie salt thins by 63 feet or 22% from 291 feet in the Mapco NCGA #14-33 well to 228 feet in the Sveen #1 Etux well across the West Nesson fault. Easily correlatable, time-stratigraphic halite members of the Prairie, also show the same pattern of counter regional thinning. The lower halite member thins by 24 feet or 29% from 84 feet in the NCGA #14-33 well to 60 feet in the Sveen #1 Etux well on the upthrown side of the fault. The middle member thins by 5 feet (11%) and the top member by 42 feet or 74% indicating maximum structural movement during the time of deposition of the top Prairie member. On the Beaver Lodge fault block, the Prairie thickens eastward from 228 feet in the Sveen #1 Etux well to 260 feet in the Boe Olson #1

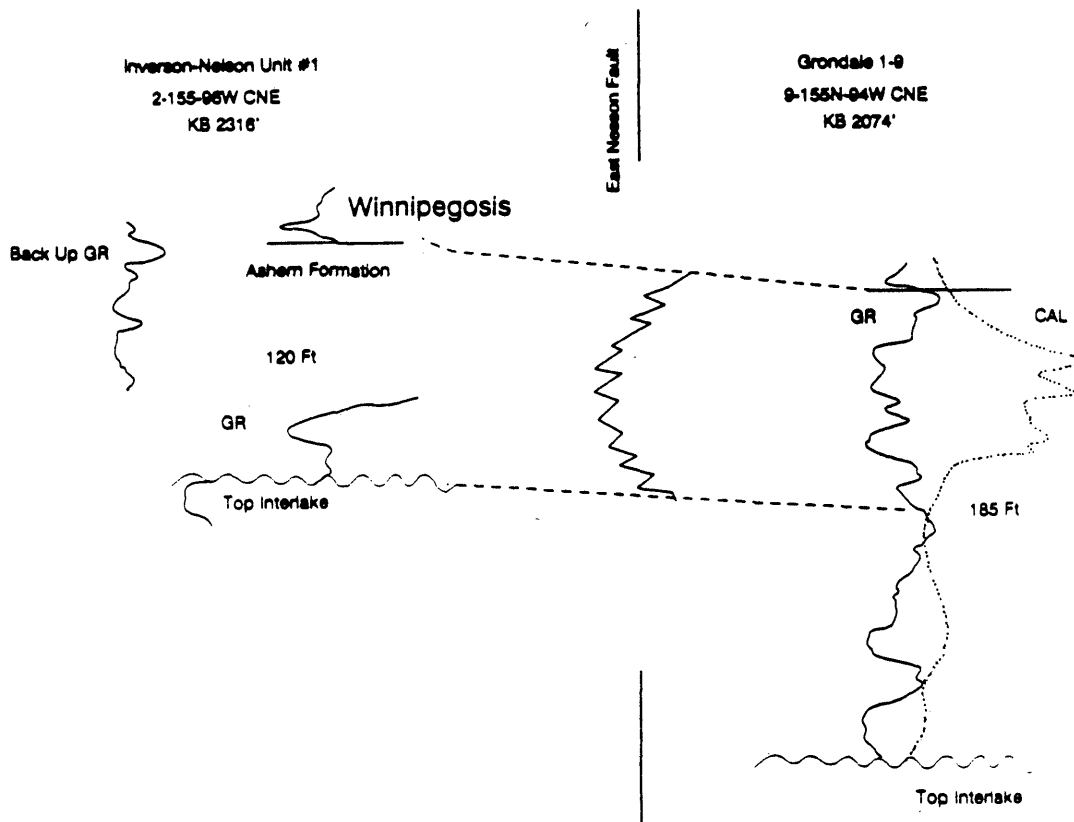


Fig. 48 Facies changes within the Ashern Formation due to faulting



well and 268 feet in the Iverson-Nelson Unit #1 well. Across the East Nesson fault, thickening of the Prairie evaporite is abrupt, reaching 386 feet in the Grondale 1-9 well, 405 feet in the Texel 21-35 well and 419 feet in the Ross 36-33 well, a thickness change of at least 118 feet or 44%. The halite members of the Prairie evaporite again show the same pattern of thickening across the East Nesson fault into fault block 6. As observed for the West Nesson fault, individual halite bed thickening across the East Nesson fault ranges from 5% to over 200%, with maximum movement occurring during the time of deposition of the top halite member, which thickens anomalously from 30 feet in the Iverson-Nelson Unit #1 well to 92 feet in the Grondale 1-9 well on the downthrown side of the fault. The lower halite member thickens by 48% from 81 feet to 120 feet and the top middle member by 33% from 72 feet to 96 feet. Within the Beaver Lodge fault block, stratigraphic units generally thicken eastward along the regional thickening trend.

The Second Red Bed, a red to green non-fossiliferous dolomite and shale unit capping the Prairie salt maintains a constant thickness across the entire area, averaging 12 feet in thickness. The near constancy of the Second Red Bed is a significant factor in determining whether the thickness variation observed within the Prairie is related to structural movement or salt dissolution.

It was demonstrated by Oglesby (1988) that in the Williston basin the Second Red Bed always thickens when top-to-bottom salt dissolution is involved, whereas the thickness remains fairly constant when thinning in the Prairie is depositional. In Roosevelt County, Montana, across the big dissolution feature at T29-30N, R57-59E, great amount of thickening is recorded in the Second Red Bed (Plate 17c). Another factor to be considered in the case of salt dissolution is the presence of overthickened younger strata overlying the area from which salt has been removed by dissolution. This phenomenon known as

thickness compensation is not documented in this area. Stratigraphic thinning of the Prairie evaporite across the Nesson anticline in the Beaver Lodge field area thus seems to be structurally controlled.

The Devonian Dawson Bay Formation overlying the Winnipegosis shows no counter-regional thinning across the West Nesson fault in this area as the formation thickens from 133 feet in the NCGA #14-33 well to 135 feet in the Sveen #1 Etux well. Slight thinning (6 feet) in the Dawson Bay between the Sveen #1 Etux well and the Boe Olson #1 well might suggest minor reactivation of the Beaver Lodge crestal fault 2, much in the same way that the thinning observed between the Boe Olson #1 and the Iverson-Nelson Unit #1 wells seems to indicate for the Beaver Lodge Crestal fault 1. Across the East Nesson fault, the Dawson Bay thickens gradually to the east.

Recurrent movement on the major faults was renewed during the time of deposition of the middle to upper Devonian Souris River Formation as correlated small-scale units within the formation thin across the West Nesson fault and thicken across the East Nesson fault. The Souris River interval thins by 25 feet from 267 feet in the NCGA #14-33 well to 242 feet in the Sveen #1 Etux well. Within the Beaver Lodge fault block, stratigraphic thickness generally increases eastward between the Sveen #1 Etux well and Iverson-Nelson Unit #1 well. However, across the East Nesson fault, Souris River thickens abruptly by 25 feet or 10% from 258 feet in the Iverson-Nelson Unit #1 well to 283 feet in the Grondale 1-9 well in fault block 6. The Duperow Formation shows significant stratigraphic thinning across the West Nesson fault and thickening across the East Nesson fault. Detailed correlation of internal small units within the formation shows the same pattern of stratigraphic thickness changes across the area. Individual thin but easily correlated units within the formation thin from the NCGA #14-33 well to the Sveen #1

Etux well across the West Nesson fault. Stratigraphic thickness change of 45 feet (9%) is documented within the Duperow across the West Nesson fault as the formation thins from 474 feet in the NCGA #14-33 well to 429 feet in the Sveen #1 Etux well (Plate 29c). Eastward of the Sveen #1 Etux well (31-155N-96W, SESE), the Duperow gradually thickens to 439 feet in the Boe Olson #1 well (15-155N-96W, SWNE) and 456 feet in the Iverson -Nelson Unit #1 well (2-155-96W, CNE). Across the East Nesson fault, stratal thickness of the Duperow increases anomalously by 34 feet to 490 feet in the Grondale 1-9 well (9-155N-94W, NENE), 502 feet in the Texel 21-35 well (35-156N-93W, SESW) and 493 feet in the Ross 36-33 well (36-156N-93W, NWSE).

The Devonian recurrent movement on the principal faults along the Nesson anticline is expressed in virtually all the Devonian stratigraphic units. The Nisku Formation (Birdbear) shows counter-regional thinning across the West Nesson fault as the unit thins from 106 feet in the NCGA #14-33 well in fault block 5 to 84 feet in the Sveen #1 Etux well in fault block 2, a thickness change of 22 feet or 21% across the West Nesson fault. Eastward of the Sveen #1 Etux well in the upthrown Beaver Lodge fault block, the Nisku thickens slightly to 89 feet in the Amerada Iverson-Nelson Unit #1 well. However, across the East Nesson fault into block 6, formation thickness increases anomalously by 20 feet or 22% to 109 feet in the Grondale 1-9 well indicating renewed movement on the East Nesson fault. Eastward of the Grondale 1-9 well there is gradual regional thickening of the Nisku (Plate 29c). In a similar manner the Three Forks and the Bakken Formations are affected by the Devonian deformation as counter-regional thinning across the West Nesson fault and over thickening across the East Nesson fault are observed on the stratigraphic cross section NDAA' (Plate 29c).

The Three Forks and the Bakken formations , each thins by 23 feet or 10% across the West Nesson fault. Across the East Nesson fault, thickness change of 56 feet (29%) is recorded in the Three Forks Formation while the Bakken shows excess thickness of 38 feet or 34% in the downthrown fault block 6. The effect of post-depositional structural activity in the Bakken may be very significant in terms of hydrocarbon migration path ways because of the fracturing that is likely to be generated as a result of such movement.

For the most part, the Mississippian period was characterised by tectonic stability and relatively continuous deposition over the Nesson anticline in this area. The stratigraphic thinning of the lower Mississippian Lodgepole strata from 707 feet in the NCGA #14-33 well to 685 feet in the Sveen #1 Etux well across the West Nesson fault and the thickening from 605 feet in the Iverson-Nelson Unit #1 well to 706 feet in the Grondale 1-9 well across the East Nesson fault is indicative of recurrent movement on the Beaver Lodge fault block. Renewed structural activity on the Beaver Lodge crestal fault 2 whose initial documentable movement was in the Devonian (Ashern time), took place in lower Mississippian time as the Lodgepole thins by 39 feet or 6% across the fault from the Sveen #1 Etux well and the Boe Olson #1 well. Beaver Lodge crestal fault 1 was equally active during this time as Lodgepole strata thin from 646 feet in the Boe Olson #1 well to 605 feet in the Iverson-Nelson Unit #1 well (Plate 29b).

To the far east, the suspected East East Nesson fault first documented in early Devonian time during the time of deposition of the Ashern, seems to be active again during the time of deposition of the Lodgepole as the interval thins from 706 feet in the Grondale 1-9 well (9-155N-94W, NENE) to 672 feet in the Ross 36-33 well (36-156N-93W, NWSE). Uplift of this area may have caused the erosional truncation of the upper portion

of the Mississippian Charles Formation noticed in the Texel 21-35 (35-156N-93W, SESW) and the Ross 36-33 wells.

Deposition of the Charles Formation was mostly uniform as indicated by fairly constant thickness of easily correlated thin halite, anhydrite and shale units within the formation across the entire area. However, significant stratigraphic thickness variation exists in the uppermost section of the Charles Formation which may be mostly attributed to erosional removal. The greatest salt removal is in the far eastern part of the study area which seems to have started being positive back in the Devonian and was reactivated in early Mississippian time as evidenced by the 34 foot thinning in the Lodgepole between the Grondale 1-9 and the Texel 21-35 wells. This counter regional thinning is accompanied by facies changes near the top of Lodgepole where a 60 foot carbonate unit characterized by offscale caliper reading and low gamma count in the Grondale 1-9 well, changes facies across the feature (Plate 29b)

The West Nesson fault was again active during the time of deposition of the Permian Opeche Shale as the stratigraphic unit thins from 388 feet in the NCGA #14-33 well (33-155N 97W, SESW) to 343 feet in the Sveen #1 Etux well (31-155N-96W, SESE). Counter regional thinning of 83 feet or 34 % is also recorded in this interval between the Sveen #1 Etux well (31-155N-96W) and the Boe Olson #1 well (15-155N-96W, SWNE) indicating renewed structural movement on the Beaver Lodge Crestal fault 2 (Plate 29a). Further thinning of 52 feet between the Boe Olson #1 well and the Iverson-Nelson Unit #1 well suggests renewed structural activity on the Beaver Lodge crestal fault 2 at this time. This structural movement probably began during the time of deposition of the Minnelusa as the formation thins from 124 feet in the Sveen #1 Etux well to 85 feet in the Boe Olson #1 well and continued throughout the time of deposition of the Opeche and Pine Salt-

Minnekhata intervals, as significant counter-regional thinning is observed on the detailed stratigraphic cross section (Plate 29a). Detailed well log correlation of units within the thinning intervals indicate thinning in the individual small units and facies changes, especially in the Pine Salt-Minnekhata interval which suggests syndepositional faulting. The Beaver Lodge crestal fault 1 was also active during the time of deposition of the Opeche as thinning of 26 feet or 9% is recorded between the Boe Olson #1 well and the Iverson-Nelson Unit #1 well.

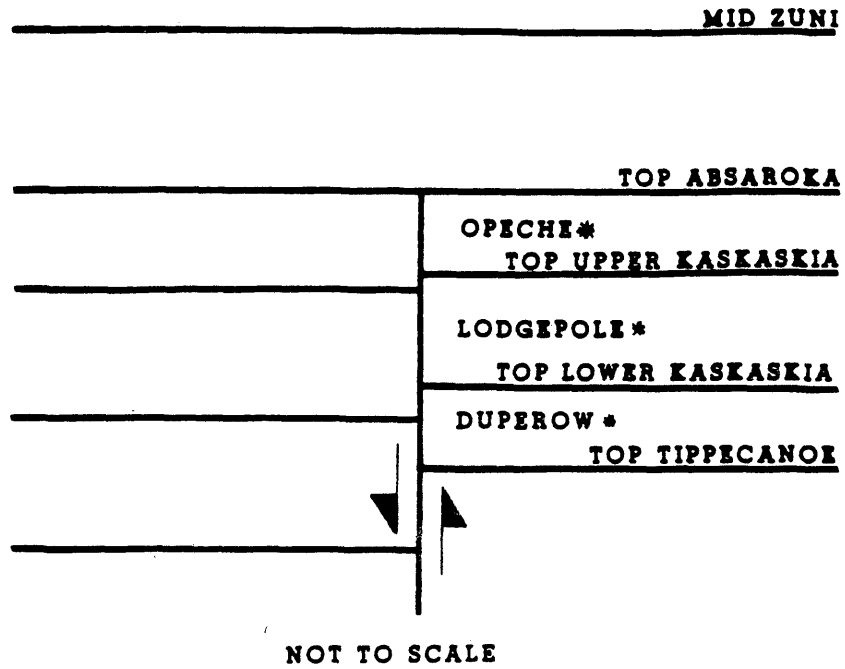
The Pennsylvanian Tyler Formation is 219 feet thick in the NCGA #14-33 well, 236 feet in the Sveen #1 Etux well, 240 feet in the Boe Olson #1 well and 248 feet in the Iverson-Nelson Unit #1 well. However, across the East Nesson fault, the formation thins counter regionally by 29 feet or 12% to 219 feet in the Grondale 1-9 well and 214 feet in both the Texel 21-35 and Ross 36-33 wells indicating reversed structural movement on the fault. The East Nesson fault was equally active during the time of deposition of the Opeche Shale which thickens by 22% from 265 feet in the Iverson-Nelson Unit #1 well to 323 feet in the Grondale 1-9 well. Renewed uplift in the far eastern section of the study area occurred during the time of deposition of the late Mississippian Otter Formation and continued through the Pennsylvanian when Tyler Formation was deposited as counter regional thinning of 20 feet (10%) is recorded between the Grondale 1-9 well and the Texel 21-35 well. The uplift on the East East Nesson fault between the Grondale 1-9 well and the Texel 21-35 well reached its maximum activity during the time of deposition of the Opeche Shale as this unit thins by 168 feet or 52% from 323 feet in the Grondale 1-9 well to 155 feet in the Texel 21-35 well and 151 feet in the Ross 33-36 well (Plate 29a).

The structural reversal on the East Nesson fault which occurred during the Pennsylvanian at the time of Tyler deposition reverted to its original sense of motion in Permian time as the Opeche Shale thickens across the fault.

It appears that the greatest amount of movement on the East East Nesson fault is from late Mississippian to Permian. All the stratigraphic units within this interval (Otter, Tyler, Minnelusa, Opeche and Pine salt -Minnehata) thin appreciably between the Grondale 1-9well (9-155N-94W, NENE) and the Texel 21-35well (35-156N-93W, SESW), the greatest amount of thinning occurring in the Opeche (Plate 29a).

From the Spearfish to Greenhorn, there was little movement on the structures although local thins and thicks occur randomly which might be related more to the clastic sedimentation patterns at this time than structural activities. Ceasation of positive structural movement on the Beaver Lodge crestal fault 1 in post-Spearfish time is indicated by the extra stratal thickness and additional sedimentary facies characterized by blocky gamma ray log motif, relatively high resistivity and slight hole wash-out on electric logs which is observed overlying the Spearfish Formation on the Beaver Lodge fault block from the Iverson-Nelson Unit #1 well (2-155N-96W, CNE) eastwards (Plate 29a). Generalized fault block movement along the West Nesson fault is illustrated in the structural diagram in figure 49 while that in the East Nesson fault is depicted in figures 50a & b. Similar patterns of stratigraphic thickness changes across from the west in fault block 5 through the Beaver Lodge fault block into fault block 6 on the east side, are recorded by cross section NDBB' (Plates 30a, 30b & 30c) which was constructed about 5 miles north of NDAA'.

Recurrent structural movement along the West Nesson fault on the west side of the Beaver Lodge field north of the stratigraphic cross section NDAA' (Plate 29) occurred basically at the same time as that observed six miles to the south on the west side of Beaver



\* MAJOR STRATIGRAPHIC INDICATORS

Fig. 49 Generalized fault block movement through time along West Nesson fault



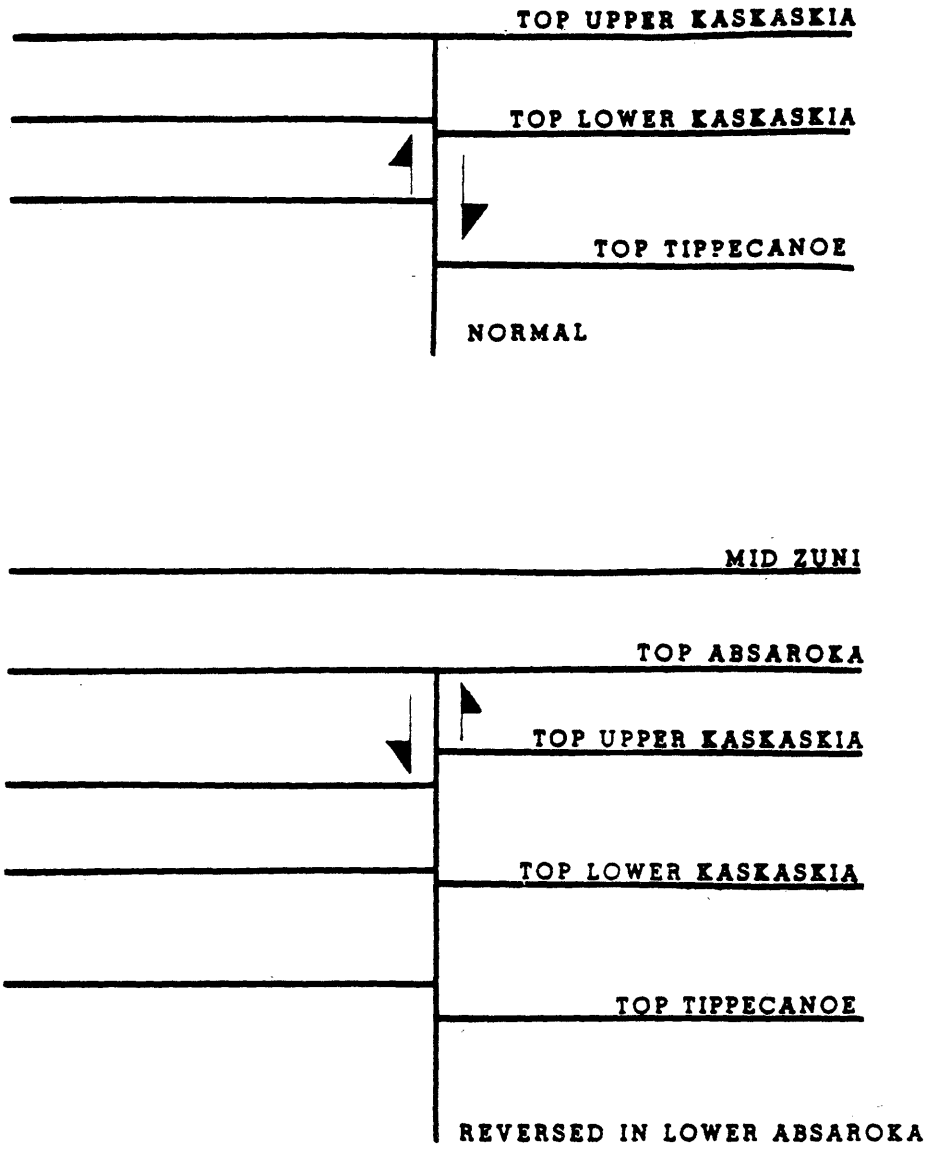
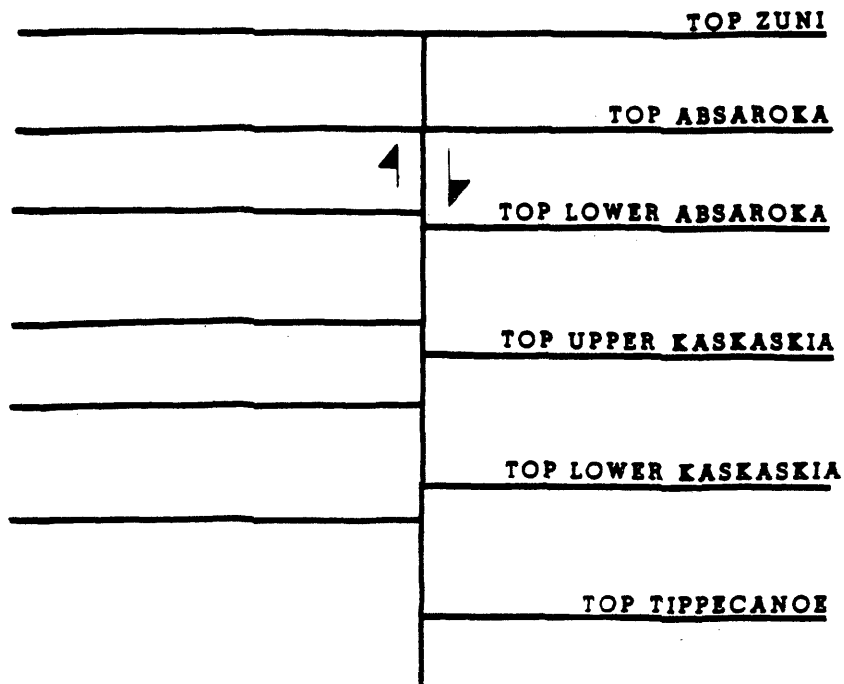


Fig. 50 Generalized fault block movement through time along East Nesson fault (cont. on next page)



**RETURN TO NORMAL IN OPECHE (MID UPPER ABSAROKA) TIME**

**Fig 50b** Generalized fault block movement along East Nesson fault (Cont from previous page)

Lodge field. The major difference in structural activity between the two locations is in the magnitude of stratigraphic thickness variation documented across the fault between the area tested by cross section NDAA' and that tested by cross section NDBB'. Generally, this factor seems to be decreasing from south to north. Table 3 is a summary of the structural movement in a general northward direction documenting the trend of the magnitude of thickness changes across fault at varying locations. This table as well as Table 4 (for the eastern arm of the Nesson anticline) are very helpful in analysing and differentiating between the various faults and fault blocks tested by the series of cross sections.

The earliest documentable history of fault movement is in the Silurian during the time of deposition of the Middle Interlake strata. Middle Interlake stratigraphic thickness is fairly uniform between the Shell Oil Kirkpatrick #14-21 well (21-155N-98W, SWSW) and the Exxon Isoberg State #1 well (13-155N-98W, NWNE) but decreases by 21 feet or 5% across the West Nesson fault from 436 feet in the Isoberg State #1 well to 415 feet in the Universal Res. 1-32 Kerdaugh State well (32-156N-96W, SWSW). Lack of deep well data to the east prevents the analysis of the East Nesson fault here. Stratigraphic thinning across the West Nesson fault noticed in the Devonian are also substantial in this area but not as intense as in the area west of Beaver Lodge field tested by cross section NDAA'.

The lower Devonian Ashern Formation thickens slightly from 151 feet in the Kirkpatrick #14-21 well to 168 feet in the Isoberg State #1 well but thins counter-regionally by 21 feet across the West Nesson fault to 147 feet in the 1-32 Kerdaugh State well in the Beaver Lodge fault block. Further thinning of 27 feet (18%) between the 1-32 Kerdaugh State well and the Sam Olson #1 well (10-155N-96W, NE) confirms the northern extension of the Beaver Lodge Crestal fault 2 (Plate 30c). The Ashern thickens from 120 feet in the Sam Olson #1 well to 134 feet in the Iverson-Nelson Unit #1 well (6-155N-

Time of major struct. movement	Index strat. unit	Fault active	Fault type/sense of motion	Index strat. cross section	Thickness change
PERMIAN	Minnehata	West Temple	Normal/West side down	TT	43
"	Opeche	West Temple	"	MM'	22'
"	"	West Nesson	"	NDAA'	45'
"	Minnelusa	West Temple	"	MM'	50'
MISSISSIPPIAN	Lodgepole	West Nesson	"	NDAA'/ NDBB'	22'/ 22'
DEVONIAN	Bakken	West Temple	"	MM'	5'
"	"	West Nesson	"	NDAA'/ NDBB'	23' 5'
"	Three Forks	West Temple	"	TT'/MM'	6'/13'
"	"	West Nesson	"	NDAA'/ NDBB'	23'/ 15'
"	Nisku	West Temple	"	TT'/MM'	15'/2'
"	"	West Nesson	"	NDAA'	22'
"	"	"	"	NDBB'	23'
"	Duperow	West Temple	"	TT'/MM'	19'/26'
"	"	West Nesson	"	NDAA'	25'
"	"	"	"	NDBB'	5'
"	Souris R.	West Temple	"	TT'/MM'	3'/19'
"	"	West Nesson	"	NDAA'	25'
"	"	"	"	NDBB'	5'
"	Prairie	West Temple	"	TT'/MM'	25'/40'
"	"	West Nesson	"	NDAA'	63'
"	"	"	"	NDBB'	60'
"	Ashern	West Temple	"	TT'	23'
"	"	West Nesson	"	NDBB'	21'
SILURIAN	U. Intlk.	West Temple	"	TT'	23'
"	M. Intlk.	West Nesson	"	NDAA'	30'
"	"	"	"	NDBB'	21'
ORDOVICIAN	Red River	West Nesson	"	NDAA'	50'

Table 3 Summary of structural movement along West Nesson and West temple faults

Time of major struct. movement	Index strat. unit	Fault active	Fault type/sense of motion	Index strat. cross section	Thickness change
PERMIAN	Opeche	East Temple	Reverse/West side down	MM'	54'
"	"	East Nesson	Normal/East side down	NDAA'	58'
PENNSYLVANIAN	Tyler	East Temple	Reverse/West side down	MM'	28'
"	"	East Nesson	"	NDAA'	29'
"	"	"	"	NDBB'	35'
MISSISSIPPIAN	Oter M. Canyon	East Temple	"	MM'	92'
"	"	"	"	MM'	33'
"	Lodgepole	East Temple	Normal/East side down	TT/MM'	51/21'
"	"	East Nesson	"	NDAA'	101'
"	"	"	"	NDBB'	53'
"	Bakken	East Temple	"	TT/MM'	39/11'
"	"	East Nesson	"	NDAA'	38'
"	"	"	"	NDBB'	21'
"	Three Forks	East Temple	"	TT/MM'	32/18'
"	"	East Nesson	"	NDAA'	56'
"	"	"	"	NDBB'	45'
"	Nisku	East Temple	"	MM'	7'
"	"	East Nesson	"	NDAA'	20'
"	"	"	"	NDBB'	24'
"	Duperow	East Temple	"	TT/MM'	24/35'
"	"	East Nesson	"	NDAA'	34/35'
"	Souris R.	East Temple	"	MM'	15'
"	"	East Nesson	"	NDAA'	25'
"	"	"	"	NDBB'	19'
"	Prairie	East Temple	"	TT'	68'
"	"	East Nesson	"	NDAA'	115'
"	"	"	"	NDBB'	56'
"	Ashern	East Temple	"	TT'	120'
"	"	East Nesson	"	NDAA'	65'
"	"	"	"	NDBB'	26'
SILURIAN	U.Intlk.	East Temple	"	TT/MM'	75-50'
"	"	East Nesson	"	NDAA'	105'
"	"	"	"	NDBB'	155'
"	M.Intlk.	East Temple	"	MM'	29'
"	"	East Nesson	"	NDAA'	90'

Table 4 Summary of structural movement along East Nesson and East Temple faults

95W, NE). Across the East Nesson fault, excess thickness of 26 feet is present in the downthrown fault block 6 at the Kissinger Ortloff 13-28 well (28-156-94W, SWSW). This thickening is accompanied by facies changes similar to that recorded on cross section NDAA' in the southern portion of the fault block. The East East Nesson fault was again active at this time as 28% thinning in the Ashern is observed between the Ortloff 13-28 well and Ross 36-33 well. Again the characteristic facies relationship documented in NDAA' where salt facies change to carbonate and mud facies is present here. The structural movement during the time of deposition of the Ashern probably continued into the time of deposition of the Winnipegosis where the effect is basically expressed in the facies changes recorded in this unit (Plate 30c). The middle Devonian Prairie evaporite thickens from 321 feet in the Kirkpatrick #14-21 well to 349 feet in the Isoberg State #1 well. The individual halite members of the Prairie also thickens in a similar manner from west to east. However, across the West Nesson fault, there is counter-regional thinning both in the units as well as in the Prairie interval as the Prairie thins by 17% from 349 feet in the Isoberg State 1 well to 289 feet in the 1-32 Kerdaugh State well. To the east, across the East Nesson fault, the Prairie thickens by 22% from 299 feet in the Iverson-Haugen 1 well to 385 feet in the Ortloff 13-28 well and 418 feet in the Ross 36-33A well. The Second Red Bed overlying the Prairie also maintains a constant thickness of about 11 feet across the entire area (Plate 30c).

Other Devonian stratigraphic units that show counter-regional thinning as a result of recurrent structural movement on the West Nesson fault are Souris River (5' or 2%), Duperow (28' or 6%), Nisku (23' or 21%), Three Forks (15' or 7%) and the Bakken (5' or 5%). Across the East Nesson fault, these formations also show excess thickening between the Iverson-Haugen 1 well and the Ortloff 13-28 well thus making the Beaver Lodge fault

block a positive block for most of the Devonian period. The history of structural movement along the West Nesson fault and West Temple fault is summarized in Table 3.

A similar documentation is prepared for the eastern side of the Nesson anticline where the East Nesson and East Temple faults are identified and are presented in Table 4.

Anomalous thickening of the Devonian Prairie occurs between the Iverson-Haugen 1 well and the Ortloff 13-28 well as the evaporite unit thickens by 86 feet or 29% from 299 feet to 385 feet. Similarly the Duperow thickens from 457 feet to 492 feet by 8%, Nisku from 93 feet to 117 feet by 26%, Three Forks by 45 feet or 22% from 207 feet to 252 feet and Bakken by 18% or 21 feet across the East Nesson fault. Relative tectonic stability in the Beaver Lodge fault block during most part of the Mississippian can be seen in the stratigraphic thickness patterns across the area. Apart from the lower Mississippian Lodgepole strata that show thinning of 22 feet across the West Nesson fault and excess thickening of 53 feet across the East Nesson fault, the rest of the Mississippian stratigraphic units either gradually thicken from west to east or show no appreciable thickness variation as in the Charles Formation, where once again most of the movement on the East East Nesson fault has contributed to severe erosional truncation here.

Recurrent movement on the West Nesson fault, as shown by Table 3, seems to be dying out to the north in a general sense because of the smaller magnitude of thickness change documented across the fault between the area tested by stratigraphic cross section NDAA' and that tested by section NDBB'. Upsection the Pennsylvanian structural reversal on the East Nesson fault is indicated by counter regional thinning in the Tyler Formation from 242 feet in the Iverson-Haugen 2 well (6-155N-99W, NE) to 207 feet in the Ortloff 13-28 well (28-156N-94W, SWSW). The Beaver Lodge Crestal fault 2 had recurrent movement from the time of deposition of the Minnelusa to the time of deposition of the

Pine Salt as thinning is observed in the Minnelusa, Opeche and Pine Salt-Minnekhata intervals between the 1-32 Kerdaugh well (32-156N-96W) and the Sam Olson 1 well (10-155N-96W). To the east, the East East Nesson fault was active again during the time of deposition of the Otter and Opeche. The thinning here led to the non-deposition of the Minnekhata in the Ross 36-33 well. Intensity of recurrent movement on the West Nesson and East Nesson faults as shown in Tables 3 & 4 seems to be decreasing to the north in a general sense because of the relatively smaller magnitude of thickness change across the faults between the area tested by stratigraphic cross section NDAA' and that tested by the cross section NDBB'.

Isopach and contour maps prepared suggest faulting or offset linear L3L4 along a northeast-southwest trend north of Beaver Lodge field as indicated on the Index map (Plate 1). A similar offset linear or fault may be inferred at the southern portion of Beaver Lodge field separating the field from Capa field to the south. The third questionable fault inferred from the paleostructural trend of the axial trace along the Nesson anticline can be placed in a roughly east-west direction north of Charlson field. These probable faults which are potential block boundaries, are further investigated by detailed stratigraphic cross section KK' (Plates 32a,b &c(Figures 51a, b &c )), JJ'(Plates 33a, b, c (Figures 52a, b & c)). Much stratigraphic anomaly could not be documented along the sections that test the cross faults L1L2 and L3L4 on the Nesson as a result of inadequate well spacing, lack of appreciable deep data and others, except the Charlson fault which was investigated by cross section XX' (Plates 37a, b & c). It is suspected that the dominant movement on the northeast-trending corss-structure faults or linears was mostly lateral rather than vertical, a situation which made stratal thickness anomaly detection difficult.



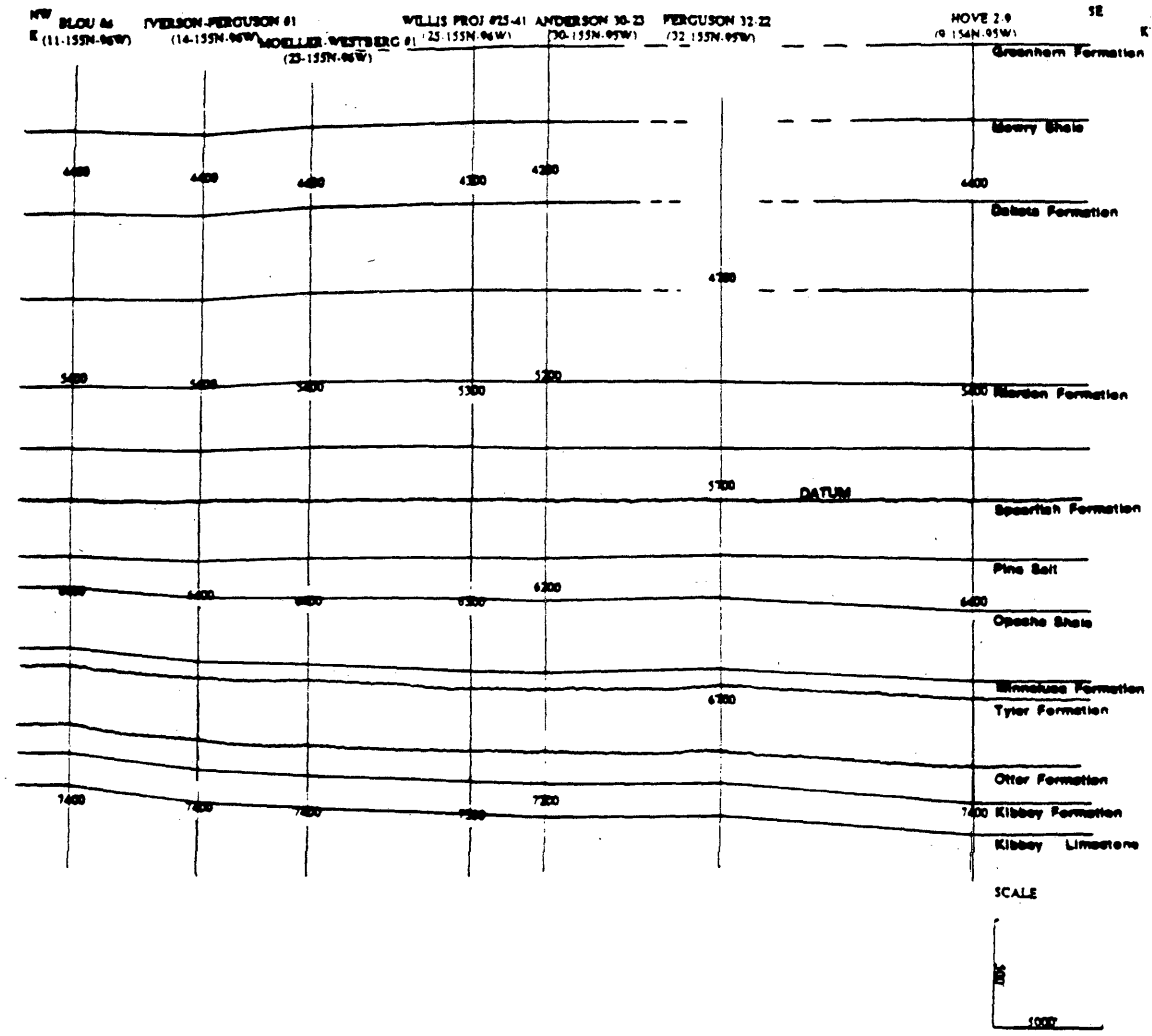


Fig. 51a NW-SE detailed stratigraphic cross section KK'(Kibbey - Greenhorn)

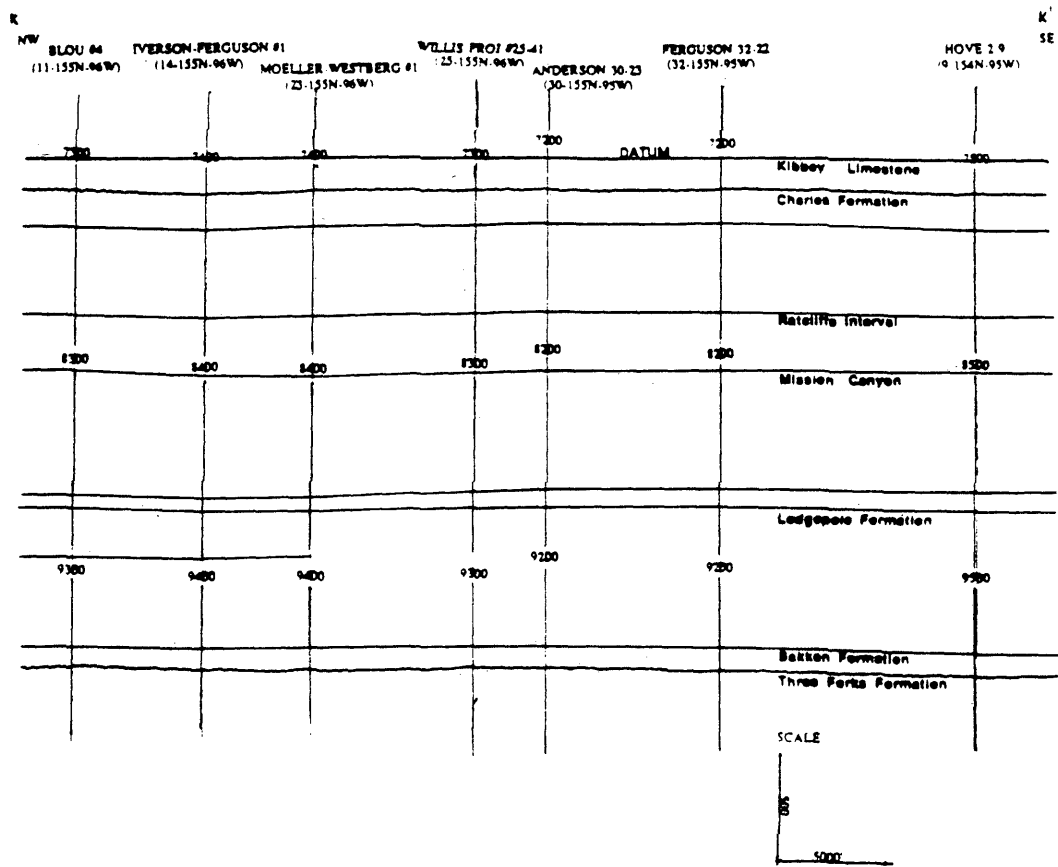


Fig. 51b NW-SE detailed stratigraphic cross section KK' (Bakken - Kibbey)

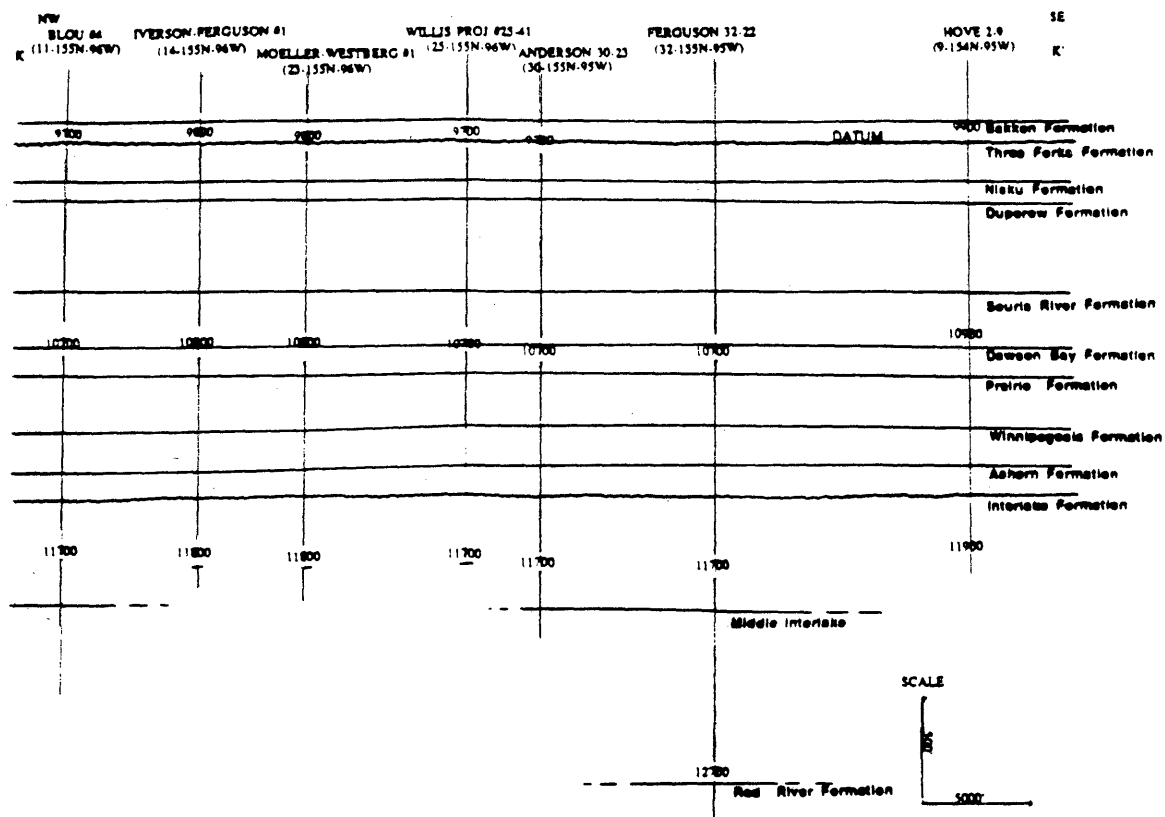


Fig. 51c NW-SE detailed stratigraphic cross section KK' (Red River - Bakken)

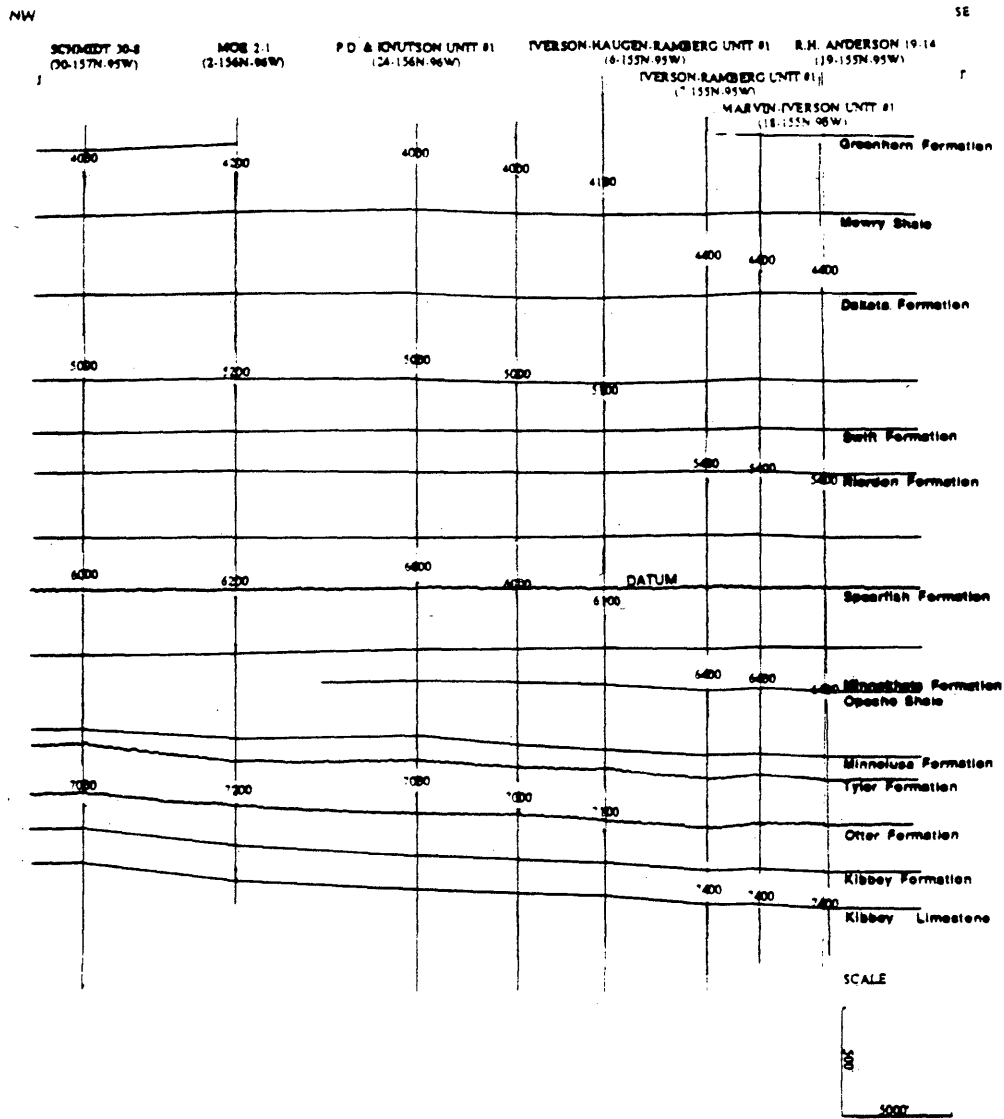


Fig. 52a NW-SE detailed stratigraphic cross section JJ' (Kibbey - Greenhorn)

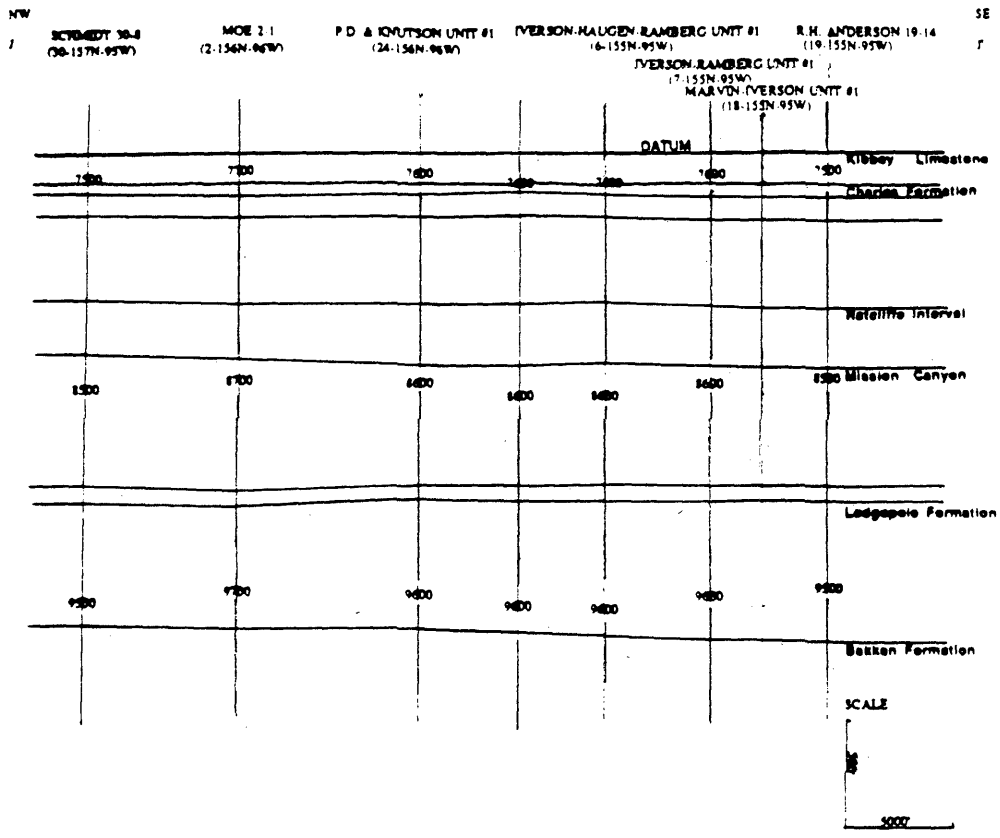


Fig. 52b NW-SE detailed cross section JJ' (Bakken - Kibbey )

*West Temple Field Area (Fault Block 4)*

The area west of Tioga, Temple and NW McGregor fields constitute what is referred to as Temple fault block or block 4 and was investigated through the analysis of three detailed stratigraphic cross sections drawn across in an east-west direction to test the far northern extension of the West Nesson fault. The Temple fault block is bounded to the west by the northwest-trending West Temple fault and to the east by the East Temple fault. The northeast-trending linear L1L2 forms the southern boundary while to the north, the block becomes diffuse for lack of deep well data. Cross section TT' (Plate 34a, b & c) illustrates the major stratigraphic changes occurring in this area. The earliest evidence of structural movement on the fault blocks is revealed in the Silurian Interlake Formation which shows a 5% counter regional thinning of 23 feet across the West Temple fault near the top of the formation. Upper Interlake strata gradually thicken from 418 feet in the Arco Simpson No. 1 well (27-158N-97W, NWSE) to 445 feet in the Ranger Herfindahl 11-22 well (22-158N-96W, NESW) and 454 feet in the Northwest Normark No. 1 well (26-158N-96W, SWNE). Across West Temple fault, the thickness decreases by 5% to 431 feet in the Rodahl No. 1 well (30-158N-95W, NWNE). There is no deep well data for the Calvert #1 Carter well (28-158N-95W, NWNW). Silurian Upper Interlake strata thicken slightly from 429 feet in the Amerada Lester Agre #2 well (27-158N-95W, SENE) to 430 feet in the Amerada Ives Unit #1 well (26-158N-95W, NENE). Across the East Nesson fault, Upper Interlake strata thicken abruptly by 15% to 505 feet in the Amerada Hess Erickson #2X well (22-158N-94W, NENE). It should be noted that part of the thinning in the Upper Interlake may be due to erosional removal. As in the Beaver Lodge fault block to the south, the Temple fault block was also affected by the Devonian deformation.

The early Devonian Ashern Formation gradually thickens from 127 feet in the Simpson No. 1 well (27-158N-97W) to 134 feet in the Ranger Oil Herfindahl 11-22 well (22-158N-96W, NESW) and 131 feet in the Normark No. 1 well (26-158N-96W, SWNE) but thins counter regionally by 21% across the West Temple fault to 104 feet in the Rodahl No. 1 well. The Ashern then uniformly thickens to 108 feet in the Lester Agre #2 well (27-158N-95W, SENE), 110 feet in the Ives Unit #1 well (26-158N-95W, SENE) and 118 feet in the Erickson 2X well (22-158N-94W, NENE). No clear evidence of structural movement on the East Nesson fault is seen here.

Most of the other Devonian units show some counter-regional thinning across the West Temple fault on the west side of West Tioga field. However the magnitude of thickness changes is not as great as those observed on the West Nesson fault in the Beaver Lodge fault block. The Devonian Prairie evaporite shows minor thickness variation in the west, slightly thickening from 382 feet in the Simpson No. 1 well (27-158N-97W, NWSE) to 385 feet in the Herfindahl 11-22 well (22-158N-96W, NESW) and 380 feet in the Normark No. 1 well (26-158N-96W, SWNE). Across the West Temple fault, the Prairie Evaporite thins by 25 feet or 7% in the Rodahl No. 1 well. No deep data is available for the #1 Carter well but the Prairie thickens again to 366 feet in the Lester Agre #2 well (27-158N-95W) and 392 feet in the Ives Unit #1 well (26-158N095W). Excess thickness of 68 feet (17%) is recorded across the East Nesson fault between the Ives Unit #1 well and the Erickson 2X well. The overlying Second Red Bed member, as in the Beaver Lodge fault block, shows fairly constant stratigraphic thickness across the entire area. In addition, detailed correlation of individual small halite units of the Prairie indicates thinning across the inferred fault. This suggests that the thinning in the Prairie was

structurally controlled rather than a dissolution feature. The overlying Dawson Bay Formation does not show appreciable stratigraphic anomaly across the area.

Reduced structural activity in the area at the time of deposition of the Souris River is indicated by the persistent thickness of thin stratigraphic units within the Souris River Formation across the fault block. Souris River interval thickens by 7% from 274 feet in the Simpson No. 1 well to 280 feet in the Herfindahl 11-22 well and 275 feet in the Ives Unit #1 well. Across the East Nesson fault, the Souris River thickens by 18 feet to 293 feet in the Erickson #2x well indicating renewed movement on the fault at this time. The Duperow Formation thins slightly from the west to the east along the line of section from 492 feet in the Simpson No. 1 well to 489 feet in the Herfindahl 11-22 well and 483 feet in the Normark No. 1 well. However, across the West Temple fault the formation thins counter regionally by 19 feet or 4% between the Normark No.1 and Rodahl No. 1 wells. Farther east, the formation thickness remains fairly constant at 464 feet between the Rodahl No. 1 well and the #1 Carter well but thickens to 476 feet in the Ives Unit #1 well. Across the East Nesson fault, the Duperow thickens abruptly to 500 feet in the Erickson #2X well. In a similar manner the overlying Nisku Formation thins abruptly by 15 feet (14%) across the West Temple fault and the Three Forks by 6 feet or 3%. No stratigraphic anomaly within the Bakken is present here.

Structural activity on the East Nesson fault was subdued during the time of deposition of the Nisku as little or no thickness changes occur within the Nisku across the structure. However movement on the East Temple fault was renewed in late Devonian time as the Three Forks formation abruptly thickens from 200 feet in the Ives Unit #1 well to 232 feet in the Erickson #2X well (Plate 34c). Also 39 feet of thickness change or 39% thickening is recorded in the Bakken across the East Nesson fault.



The low magnitude of stratigraphic thinning here, coupled with the place of occurrence, presents at least two possibilities. One is that the fault on the west side of West Tioga and Temple fields, the West Temple fault is a different fault from the West Nesson fault. The other is that they may be the same fault and that the lower order of magnitude of stratigraphic thickness change is due to the fact that the West Nesson fault generally dies out northward. It is very difficult to say which is more likely because of sparsity of data in the area around T157N R96W referred to as fault block 3 to test the system.

From the Mississippian Mission Canyon time to the time of deposition of the Kibbey, there seems to be little activity as the only major counter regional thinning observed is 10 feet at the top of Mission Canyon between the Normark No.1 well and the Rodahl No.1 well. Stratal thickness of the Mission Canyon increases again from the Ives Unit #1 well to the Amerada Erickson #2X well (22-158N-94W, NENE).

There was a major recurrent movement during the time of deposition of the Minnehata as this unit shows substantial counter regional thinning across the West Temple fault from 60 feet in the Normak No. 1 well (26-158N-96W) to 17 feet in the Rodahl No. 1 well (30-158N-95W), a thickness change of about 72%. The thinning recorded in the Opeche and Minnelusa on the crest of the structure between the Carter #1 well (28-158N-95W) and the Lester Agre #2 well (27-158N-95W) may be related to a crestal fault between the two wells. From the time of deposition of the Spearfish to the time of deposition of Greenhorn, there was again relatively quiescent and continuous deposition over the area. Local thins and thicks however occur.

Stratigraphic cross section MM' (Plates 35a, 35b & 35c) located just 4 miles north of section TT' runs east-west across the Temple fault block, and is intended to test the northern extension of the West Temple fault. The earliest structural history of this fault as

revealed by the cross section is not clear as two key wells, the Cenergy 43-12 Biwer well (12-158N-96W, NESE) and the Burnette Keith Blikre No.1 well (2-158N-95W, NWSW) did not go deeper than the top of the Winnipegosis Formation. There are indications however that the beginning is much earlier than that revealed by the available data. As in previous cross sections, the Devonian was very eventful. The middle Devonian Prairie evaporite shows a 10% counter regional thinning of 40 feet across the West Temple fault between the Northwest Grimsrud No. 1 well (3-158N-96W, NWSE) and the Cenergy 43-12 well (12-158N-96W, NESE). The Second Red Bed again shows constant thickness. The most significant thinning is observed in the Devonian Duperow Formation which increases slightly from 496 feet in the 24-31 Smith well (31-159N-96W, SESW) to 498 feet in the Grimsrud No.1 well but thins by 5% across the West Temple fault to 472 feet in the 43-12 Biwer well and 465 feet in the McGinnity #11-8 well. To the east of the McGinnity well and the East Temple fault, stratigraphic thickness of the Duperow is back up to 500 feet in the Keith Blikre No.1 well and 494 feet in the Williams #12-13 well ( Plate 35c ), an anomalous thickening of at least 8%. Similar thickness variation exists in the other Devonian units at slightly lower magnitude. The Nisku Formation barely changes in thickness, while the Souris River and Three Forks formations change by 19 feet (7%) and 13 feet (6%) respectively across the West Temple fault. The Bakken Formation does not show much stratigraphic anomaly across the West Temple fault.

Across the East Temple fault, excess stratigraphic thickness of 15 feet was recorded in the Souris River Formation, 35 feet in the Duperow, 7 feet in the Nisku, 8 feet in Three Forks and 11 feet in the Bakken.

A careful study of the thickness variations in the different stratigraphic units from cross sections MM' and TT' weakens the argument of a West Nesson fault that extends and dies

to the north, since in that case, one would expect the relative throw on the fault to decrease consistently from south to north. That is not exactly what is seen. Relative throws, deduced from magnitude of stratigraphic thickness variations on the West Nesson fault, decreases from south to north until the area around T158N R96W where cross section TT' is located. However, in section MM' the magnitude of thinning increases instead of decreasing (Table 2). This leads to the possibility that the West Temple fault is a different fault of its own which might be genetically related to the West Nesson fault, but seems to have a separate history of movement of its own.

Gradual thinning, and in some cases, terminations of the Upper Mississippian Charles salt may suggest continued uplift even though part of this may be due to post depositional salt solution or erosion.

On the East Temple fault, it appears there is significant movement, this time in a reversed sense as the Mission Canyon Formation thins by 33 feet from 805 feet in the McGinnity #11-8 well across the fault to 772 feet in the Keith Blikre No.1 well and further by 11% or 86 feet to 686 feet in the Amerada Williams #12-13 well, implying recurrent movement on the suspected East East Nesson fault. Uplift in this area is shown by the thickened Nesson anhydrite which increases from 109 feet in the Depco McGinnity 11-8 well to an average of 160 feet in the Burnett Oil Keith Blikre No.1 well and the Amerada Hess Williams #12-13 well, and the facies changes within the middle portion of Mission Canyon. This small local fault might be the boundary between the Temple and McGregor fields. Structural activity on the West Temple fault continued throughout the time of deposition of Minnelusa and Opeche as the stratigraphic units thin across the feature. Minnelusa has a 63% thickness reduction as the unit thins counter regionally from 80 feet in the Grimsrud No. 1 well to 30 feet in the 43-12 Biwer well. Similarly, the overlying

Opeche Shale thins by 20% from 108 feet to 86 feet in the same wells. The reversed structural movement on the East Temple fault seems to reach its greatest magnitude during the time of deposition of the Otter Formation as it thins by over 90 feet or 36% in the Keith Blikre No. 1 well and by 80 feet in the Williams #12-13 well. The structural reversal continued throughout the time of deposition of the Pennsylvanian Tyler Formation and Permian Opeche Shale as these units show severe counter-regional thinning across the fault. The period between the time of deposition of Spearfish to Greenhorn was relatively stable.

Farther to the north, about 4 miles north of section MM' (Plates 35a, b & c), an east-west stratigraphic cross section NN' (Plates 36a, b & c) was prepared across the fault block to test the northern extension of both the West Temple and the East Temple faults. Data in this area do not permit interpretation deeper than the Devonian Duperow Formation, which only shows slight stratigraphic variation across the feature. Only 10 feet of thinning is recorded in the Duperow across the West Temple fault. While the Nisku Formation shows practically no change in stratigraphic thickness, the Three Forks Formation thins by only 7 feet. The West Temple fault may thus have its center of activity concentrated to the west of Temple field as indicated by cross section MM' and be tailing off in both directions to the north and south.

As in previous cases, the Mississippian Period was relatively stable. Only slight thinning of strata is noticed. On the crest of the feature where the thinning occurs, the Nesson anhydrite thickens by 5 to 15 feet. The East Temple fault is also evident here as the Mission Canyon thins from 808 feet in the Ranger Oil Toftness 9-8 well (8-159N-95W) to 750 feet (7%) in the Hunt Carl Overlee #3 well (30-160N-94W). The Nesson anhydrite at the top of the sequence is thickened by 20 feet. The West Temple fault was again active

during the time of deposition of the Minnelusa and Minnehata Formations. Stratigraphic thinning of the order 25 feet or 45% across the feature exists in the Minnelusa. The Opeche is extremely thin in this area. The Minnehata, characterized by blocky gamma ray log motif and offscale readings on the caliper ( washout) thickens from 94 feet in the 1 Olaf Sevre well to 110 feet in the Total State No. 1-16 well, but across the West Temple fault, it is completely absent in all the wells drilled on the upthrown side to the east (Plate 36a). Similarly, the Spearfish shows significant counter regional thinning of 27 feet or 8% across the same feature. A minor localized fault west of the interpreted West Temple fault seems evident by the counter regional thinning in the Devonian Duperow and Permian Opeche especially.

The East Temple fault continues to be active at this time as the Kibbey, Otter, Tyler and Minnelusa Formations thin by various amounts ranging from 7 feet in the Kibbey to 46 feet in the Tyler. The structural reversal on the East Temple fault that started in Mississippian time did not return to its original sense until the time of deposition of the Spearfish.

#### *Charlson Field Area (Fault Block 1)*

The area around Charlson and Antelope fields is referred to as Charlson fault block or block 1, and was investigated through a north-south stratigraphic cross section XX' (Plates 37a,b & c) drawn from south of Hofflund field ( T154N R95W ) to south of Charlson field (T153N R95W). An east -west trending fault is the northern boundary of the Charlson fault block and appears to separate Charlson field area from the area to the north. Significant stratigraphic thickness changes are observed from north to south. Available data in this area do not permit interpretation of structural history earlier than

middle Devonian as most of the wells quit near the top of the Interlake Formation. The middle Devonian Ashern Formation increases in thickness steadily from north to south between the Amerada Hess E.H. Herfindahl No.1 well (9-154N-95W, SWSE) and the Amerada Hess Yttredahl 12-34 well (33-154N-95W, NESE) but thins by 5% from 165 feet in the Yttredahl 12-34 well to 157 feet in the 1 Silurian Unit #7 well (14-153N-95W) and 159 feet in the Amerada Hess Federal No.17-12 well (17-153N-95W, SWNW) across the inferred structural feature. Similarly, the other Devonian units show significant thinning across the structural boundary. The Winnipegosis Formation thins by 32 feet (15%), the Prairie evaporite thins by 23 feet (9%), the Dawson Bay by 10 feet (7%), Souris River by 17 feet (6%), and Duperow by 36 feet (8%). The Nisku Formation barely changes in thickness while 26 feet of stratigraphic thinning is observed in the Three Forks Formation.

The Mississippian Period was a tectonically active time in the area making it quite different from the other interpreted fault blocks where the Mississippian was relatively mild. Significant stratigraphic thickness changes are documented in all the Madison units. The Lodgepole interval shows thinning of 85 feet or 11% across the feature. The Mission Canyon Formation thins by 47 feet or 17% the Charles salt by 34 feet or 7% and the Ratcliffe Interval by 20 feet or 9%. Following the deposition of Tyler, there was tectonic stability or slight subsidence of the Charlson fault block as the overlying stratigraphic units slightly increase in thickness. Another indication of little or no structural differentiation in fault block 1 are the uniformly deposited Opeche Formation and Pine Salt intervals. This state of quiescence or slight subsidence persisted throughout the time of deposition of Greenhorn and probably later.

The Antelope field produces from the Bakken/Sanish interval which is drape-folded over a series of basement fault blocks. Hayden, 1984 analyzed near and far trace stacks

from the Antelope field and characterized the wave response of fractured Bakken zones with offsets. Fracturing, she concluded, is essential to the creation of the Bakken reservoirs, since the matrix system of the Bakken completely lacks permeability. Extensive fracturing may be caused by various factors including fluid overpressuring and recurrent structural movement caused by differential stress resulting from tectonic activities.

The Bakken has been characterized by two distinct seismic responses in the Antelope field; a high amplitude trough-peak-trough and an elongated low amplitude waveform. The high amplitude trough-peak-trough response is typical of matured, hydrocarbon-saturated Bakken interval while the elongated low amplitude waveform is characteristic of a fractured zone.

The new technology of horizontal drilling in the Bakken Formation, a traditional source rock-turned reservoir rock, is an important development in the oil and gas industry and may very well be the hottest play in the Rocky Mountain region today. This technique more than doubles the chances of hitting a fractured reservoir as opposed to vertical drilling. Cost of a horizontal Bakken well is high, but the payoff comes in reserves and initial test.

## RECURRENT MOVEMENT AND HYDROCARBON OCCURRENCE

The profound influence recurrent structural movement on basement may have on overlying sedimentary patterns and hydrocarbon accumulation can not be overstated. Recurrent movement may be transmitted through the entire sedimentary sequence to be expressed as surface lineaments. Drape folds often form in response to basement movement with their shapes dictated by the amount of relief across the basement block. These folds may affect a portion of or the entire sedimentary column. Where reservoir-quality sands are found draping such paleo-topographic highs, conditions favorable to hydrocarbon accumulation are set up.

Recurrent movement may juxtapose an impermeable unit against a permeable one within the sedimentary sequence and thus create traps favorable hydrocarbon accumulation.

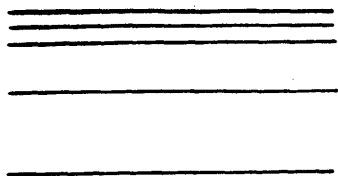
Secondary dolomitization is often associated with basement movement. This movement may be vertical or horizontal, and both usually set up fractures in the overlying strata, producing conduits along which magnesium-rich fluids, necessary for dolomitization, can migrate. The dolomitization locally enhances the porosity of original limestone units creating potential hydrocarbon reservoirs. In addition to allowing migration of magnesium-rich fluids, the conduits formed by recurrent movement on basement also allow the flow of hydrocarbon into previously "tight" rocks. Figure 53 illustrates the formation of a dolomitized oil reservoir as a result of recurrent movement on basement.

Leaching of sediments resulting from recurrent movement could also, in addition to, or independent of dolomitization, enhance the porosity of overlying sediments.

The fracturing induced by recurrent structural movement increases porosity only to a slight extent but enhances the permeability considerably and thus increasing hydrocarbon

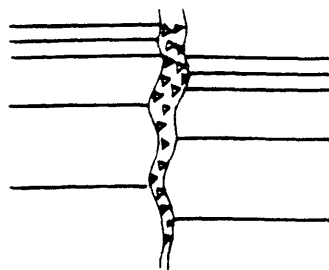


**1. DEPOSITIONAL STAGE**

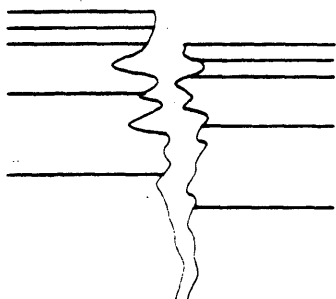


**2. FAULTING STAGE**

Breccias fill fracture

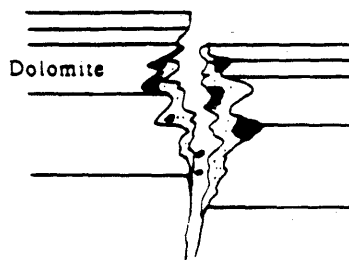


**3. LEACHING AND SOLUTION**



**4. DOLOMITIZATION STAGE**

Porosity of lst. enhanced



**5. BLOCK TILTING AND OIL MIGRATION**

Dolomitized rock more prospective than surrounding lst.

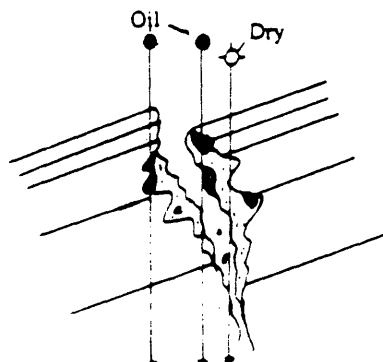


Fig. 53 Generation of hydrocarbon reservoir as a result of recurrent structural movement and subsequent dolomitization

potential of the sedimentary column. Several fields along the trend of the Nesson in the study area such as Beaver Lodge, Mc Gregor, Tioga, Charlson and Antelope fields all produce hydrocarbon from fractured reservoirs at the Madison level. The intersection of faults or fractures often form a more attractive site for hydrocarbon accumulation because of the intensity of fracturing in these areas. The fault/fracture intersection areas, as interpreted from the isopach maps of the tectonic-sensitive Devonian units, are found to shift from time to time. This observation may suggest that the fault blocks rotated through geologic time, a phenomenon which will further enhance the fracturing potential in these areas. The interpreted fault block model for the Nesson anticline in the study area also shows that the oil fields are situated within short distances from the interpreted block boundaries on the east flank (Plate 38), and not exactly on the crests of the fault blocks. This observation is testimony to the influence of fracturing along zones of recurrent movement on hydrocarbon occurrence. Part of the reason why most of the fields are closer to the East flank fault system than the west flank fault system may be the fact that recurrent structural movement on the former was more severe and frequent than on the latter. The structural reversal on the eastern faults, the East Nesson and East Temple faults supports this assertion. The model can thus be used to predict favorable areas for hydrocarbon accumulation in an unknown area where the structural blocks have been analyzed.

## SUMMARY AND CONCLUSIONS

Extensive subsurface mapping of the central Williston basin utilizing over 3000 geophysical well logs document several fault/fracture patterns and periods of major tectonic activities between the Paleozoic and late Triassic. Major tectonic movements are documented in the Devonian (early, middle and late), Silurian, Mississippian, and late Triassic, and the dominant style of deformation was recurrent structural movement on basement. Three major paleostructural trends, northwest, northeast and north are recognized in the study area and are believed to have been influenced by two major structural features - the Culbertson-Grenora feature, thought to be a major part of the Brockton-Froid-Fromberg fault system and the Nesson anticline, which appears to consist of a mosaic of fault-bounded structural blocks.

The study identified and correlated 25 formation tops between the Cretaceous Greenhorn Formation and Ordovician Red River Formation from over 3000 wells in the central portion of the Williston basin. Additional suite of 95 geophysical well logs was incorporated into a special study of the structural characteristics the Weldon-Brockton fault in Cow Creek/Weldon field area, Mc Cone County, Montana, where it has been established past work including Hicks (1985).

The Red River to Interlake isopach map (Plate 2) records upper Tippecanoe paleostructure which was dominated by northwest and northeast lineations. The general north-south trend of isopach contours changes to north-northeast near the Montana/North Dakota state line, and may have been influenced by the northeast-trending Culbertson-Grenora feature, thought to be part of the Brockton-Froid-Fromberg fault zone. Regional thickening of stratigraphic units within the Tippecanoe sequence is from west to east as

shown by the E-W regional stratigraphic cross sections AA' (Plate 3 (Figure 26)) and BB' (Plate 4 (Figure 27)). Counter regional thinning or rapid anomalous thickening of stratigraphic units, often marked by closely spaced contours, was the primary basis for identifying possible areas of structural movement and faulting. The thickness distribution of the interval was most influenced by the Nesson anticline where several areas of thin rocks including Beaver Lodge and Tioga are found trending mainly in northwest and northeast directions. The areas where changes occur are marked by northeast-trending offset linears. This isopach as well as those of the other intervals, especially the tectonic-sensitive Dawson Bay - Bakken (Plate 6) and the Devonian strata (Plates D1, D2, D3, D4 & D5) were useful in the interpretation of the Nesson anticline into a mosaic of at least six fault blocks.

Detailed E-W stratigraphic cross sections NDAA' (Plates 29a, b & c) and NDBB' (Plates 30a, b & c) constructed across the Nesson anticline, identified the West Nesson fault, Beaver Lodge fault block or block 2, and the East Nesson fault block (Plate 1). Syndepositional structural movement on the Beaver Lodge fault block in the Ordovician caused the counter regional thinning of the Red River from 635 feet in the Mapco NCGA #14-33 well to 585 feet in the Boe Olson #1 well (Plates 29c). Intrablock structural movement was also documented on the Beaver Lodge fault block and identified at least 2 crestal faults, the Beaver Lodge crestal fault 1 and Beaver Lodge crestal fault 2. Structural movement during the Silurian may have been syndepositional and post-depositional as both the Middle Interlake and Upper Interlake units were affected. Erosional truncation was responsible for most of the thinning in the Upper Interlake, which may suggest post-depositional movement.

The East Nesson fault is manifest by the rapid thickening of the Middle Interlake member from 355 feet in the Iverson-Nelson unit #1 well to 445 feet in the Grondale 1-9 well (Plate 29c), a thickness change of 90 feet or 25%. Temple fault block or block 4 also showed recurrent movement in the Silurian as documented by E-W cross sections TT' (Plate 34c) and MM' (Plate 35c). In Montana area, the only documented structural movement was in the southern part of the Culbertson-Grenora feature, where detailed stratigraphic cross section MT-D (Plate 16c (Figure 42c)) records 15% counter regional thinning in the Stonewall Formation over a distance of only 1 mile. Structural movement and faulting at this time was probably related to the various tectonic activities going on around the North American plate. The Paleozoic cycle of orogeny at the western side of the North American plate, caused by underthrusting of the Pacific plate along an east-west dipping subduction zone, probably interacted with similar events on the eastern side of the continent, where the proto-Atlantic ocean of Iapetus was closing up as a result of subduction along the Appalachian edge in a series of events called the Taconic orogeny. The Taconic orogeny continued through Ordovician and Silurian periods. Also, the early Devonian structural activities along the Transcontinental arch to the east of the basin, may have played a significant role. Proximity of the Nesson anticline to the sources of orogenic events may be responsible for the effects being more felt in North Dakota than in Montana.

Northwest and northeast paleostructural trends continued to be active throughout the Devonian when the Prairie evaporite was deposited, as alignment of narrow thin Prairie intervals occurred along northeast and northwest directions. The most prominent thin salt linear is the one referred to as Culbertson-Grenora feature in this thesis. It trends northeast from Culbertson area, Roosevelt County, Montana, through a semi-circular salt dissolution area in Shotgun Creek to Grenora in western North Dakota (Plate 1 (Figure 2)). Several

fault blocks were identified from detailed E-W stratigraphic cross sections MT-A (Plates 17a,b & c (Figures 40a, b & c)), MT-B (Plates 19a, b & c (Figures 42a, b & c)), MT-C (Plates 18a, b & c (Figures 41a, b & c)) and MT-D (Plates 16a, b & c (Figures 39a, b & c)) prepared across the Culbertson-Grenora feature at various locations along its trend. Episodic recurrent structural movement was the style of deformation. Counter regional thinning of 16 feet or 16% recorded in the Prairie from 100 feet in the Peerbom Estate 1 well to 84 feet in the Culbertson Unit #1 well, is evidence of structural movement (Plate 17c). Correlated individual halite members of the Prairie show similar pattern of thinning across inferred structures along the cross sections constructed along the trend of the feature.

Apparent structural movement was however complicated by Prairie salt dissolution and compensation thickness in overlying strata in the semi-circular dissolution area. Careful analysis of the thickness anomaly observed in the younger stratigraphic intervals of the Tyler, Minnelusa and Spearfish, indicates that the cause of the overthickened younger strata was just not dissolution alone. Rather, it was a combination of salt dissolution and recurrent structural movement. Stratal thickness computation along E-W detailed stratigraphic cross section MT-A (Plate 17c), indicates compensation thickening of 27 feet in the Minnelusa and 119 feet in the Spearfish between the Krogedal 31-5 well and the Jacobsen 1 well, giving a total of 146 feet of overthickened strata as against 177 feet of dissolved salt between the two wells. These figures seem reasonable as compensation thickness. However, between the "Prairie-normal" area in the Krogedal 31-5 well and the Picard A#1 well, across the trace of the Culbertson-Grenora feature, the story is different. Stratal thickening of 69 feet in the Tyler, 110 feet in the Minnelusa and 149 feet in the Spearfish add up to a total of 328 feet of overthickened younger strata as against 177 feet of

dissolved Prairie evaporite. This relationship across the trace of the Culbertson-Grenora feature can not be explained by salt dissolution and compensation alone.

Assuming even a one to one relationship between how much salt was dissolved and how much extra thickness was picked up in the younger strata, there is still 151 feet of rocks not accounted for. When the Charles salt is factored in, the 70-foot loss of Charles salt across the Culbertson-Grenora feature still does not fully account for the extra thickness. Faulting along the trace of the Culbertson-Grenora feature may thus have facilitated salt dissolution and created additional accommodation potential for the extra thickness. In addition, the rectilinear surface drainage pattern in the area, coupled with the straightness of some of the streams imply strong tectonic control and lends support to a structural interpretation.

The Cow Creek/Weldon field study demonstrates structural movements on the northeast-trending Weldon-Brockton fault in the Pennsylvanian and Permian during the time of deposition of the Heath, Tyler and Amsden (Minnelusa). No deep wells are available for documenting earlier structural history. Similar stratigraphic intervals are affected in the study area but with reduced intensity. It thus seems that the Culbertson-Grenora feature may be part of the Brockton-Froid-Fromberg fault zone and that structural activities on it are concentrated to the southwest with a general attenuation to the northeast.

Structural thinning of the Prairie evaporite along the Nesson anticline is shown by the areas of thin salt intervals that trend northwest and northeast in a similar fashion displayed by the Tippecanoe paleostructure. The narrowness of salt isopach thins, their spatial arrangement and orientation in northwest and northeast directions and sub-linear patterns, suggest a strong tectonic control. All the interpreted fault blocks on the Nesson moved recurrently during the time of deposition of the Prairie as demonstrated on detailed

stratigraphic cross sections NDAA' (Plate 29c), NDbb" (Plate 30c), TT' (Plates 34a, b &c) and MM' (Plates 35a, b & c). Additional evidence for the structural interpretation as opposed to salt dissolution in the area is the constant thickness of the Second Red Bed member that caps the Prairie evaporite across the entire area except in the dissolution hole in Montana, where it thickens from 15 feet in the Krogedal 31-5 well to an average of 50 feet in the dissolution area, section MT-A (Plate 17c). Oglesby (1988) concluded that the Second Red Bed member thickens where there is Prairie salt thinning due to dissolution.

Lower Kaskaskia paleostructure is represented by Dawson Bay to Bakken isopach (Plate 6) and shows a completely different structural pattern in the area, a pointer to the severity of the Devonian deformation. Early Devonian structural activity on the Transcontinental arch caused the northward tilting of the Williston basin causing stratigraphic units to thicken from southwest to northeast. Subtle recurrent structural movements are documented in the Souris River Formation to the northern and central portions of the Culbertson-Grenora feature (Plates 18c (Figure 41c) & 17c (Figure 40)). The Nesson anticline area was by far more affected by the Devonian deformation, probably as a result of its proximity to the focus of tectonic activities at this time. The Acadian orogeny, whose main deformation was in middle Devonian but spanned the entire Devonian period, was going on in the northeastern corner of the North American plate at this time. Rocks of the Appalachian geosyncline were being thrust northward and westward and crumpled against the craton from Newfoundland to Pennsylvania. Structural movement on the Nesson anticline is indicated by the rapid change of stratigraphic thinning rate from 7 feet per mile in the vicinity of the anticline to 33 feet per mile just west of the Beaver Lodge field around T155N, R97W (Plate 6). The Dawson Bay - Bakken isopach as well as those of the Devonian units of Souris River (Plate D1), Duperow (Plate D2),



Nisku (Plate D3), Three Forks (Plate D4) and Bakken (Plate D5) were used to better define the fault block geometry along the Nesson anticline. The northwest-trending West Nesson and East Nesson faults bound Beaver Lodge fault block to the west and east respectively, and the northwest-trending West Temple and East Temple faults to the north, bound Temple block to the west and east respectively. Both fault blocks are offset in the middle section along a pair of northeast-trending linears L1L2 and L3L4 which define the northern and southern boundaries of the Southwest Tioga fault block or block 3. The Charlson fault block or block 1 is limited to the north by east-trending Charlson fault, to the west by the West Nesson fault and to the east by the east Nesson fault. Fault blocks 5 and 6 are undifferentiated fault blocks to the west and east of the Nesson anticline respectively (Figure 38).

Recurrent structural movement on each of the fault blocks during the Devonian caused counter regional thinning of the Souris River, Duperow, Nisku, Three Forks and Bakken formations. Thinning within the Duperow was the most profound. Structural reactivation of the fault blocks was often accompanied by facies changes such as that recorded in the Ashern Formation across the Beaver Lodge fault block on cross section NDAA' (Plate 29c). Thinning was by onlap onto the Interlake unconformity surface. The carbonate unit on the upthrown Beaver Lodge fault block is represented by a predominantly salt unit in the downthrown, deeper and probably restricted, fault block 6 to the east (Figure 48). The distinction between faults was based in part, on the magnitude of apparent throw on the faults as deduced from the amount of stratigraphic thickness changes documented across faults (Tables 3 & 4). Fault block 3 has no adequate data to document its paleostructural history.

Northeast paleostructural lineations became more dominant during Upper Kaskaskia deposition when basin configuration returned to normal. Upper Kaskaskia sequence is represented by Bakken to Charles isopach map (Plate 7) which shows a general northeast trend, becoming more easterly across the state boundary because of the influence of the Culbertson-Grenora feature. Renewed structural activities along the Culbertson-Grenora feature occurred throughout most of the Mississippian as detailed by cross sections MT-A, MT-B, MT-C and MT-D which show counter regional thinning and anomalous thickening in the Lodgepole, Mission Canyon and Charles formations across various faults identified in the zone. Along the Nesson anticline, tectonic activity was generally mild except in the Charlson fault block, where the Lodgepole shows a counter regional thinning of 85 feet or 11% across the down-to-the-north Charlson fault. Mission Canyon also thins by 47 feet (11%) and Charles by 34 feet or 7% across the same structure (Plate 37b). The stratigraphic thinning in the Mississippian Charles Formation especially at the top, was caused by structural movement which preceded erosion but climaxed during the time of deposition of the top Charles. Recognition of the unconformity which was preceded by tectonic activity during the time of deposition of the Mississippian rocks is very important because syngenetic tectonic movement controlled its deposition and could promote stratigraphic entrapment (Gerhard et al, 1982).

Distribution of the Absaroka sequence rocks was influenced by northwest paleostructures, the trend and position of which coincide with older paleostructures. The main salt dissolution area in Montana was now associated with a conspicuous area of thick rocks located along a northwest -trending linear. The coincidence of this thick rock area with the salt-dissolution area is indicative of thickness compensation in response to salt dissolution. Structural activities to the east were a little subdued at this time even though

the fault systems on both flanks of the Nesson anticline were still apparent. Detailed E-W stratigraphic cross sections NDAA' (Plate 29a, b & c) and NDBB' (Plates 30a, b c) document reversed structural movement on the East Nesson fault in the Pennsylvanian during the time of deposition of the Tyler Formation. Similar reversal was documented on the East Temple fault in the Permian. The effect of structural reversal on the eastern system of faults while normal differentiation continued on the western system, could lead to block tilting which may enhance hydrocarbon entrapment.

Structural activity was considerably reduced in the area by lower Zuni time as shown by the relatively uniform and persistent thickness displayed on the Spearfish to Greenhorn isopach map (Plate 11). There are no strong linears although local thick and thin areas trending northwest and northeast suggest continued structural influence in these directions. Fault blocks on the Nesson which had constantly shown up as thin positive areas are now subdued .

Structure maps prepared on key stratigraphic horizons display essentially similar features throughout with respect to the general trend of dominant linears in northwest and northeast directions. These trends were fairly repetitive from time to time. The major difference between the structure maps lie in the variation of magnitude of the dip gradients through time. Calculated dip gradients for various parts of the study area at different stratigraphic horizons indicate increase in dip with depth (Table 1). Relative displacements along the West Nesson and East Nesson faults measured using the closest wells on either side of the faults, and calculating the structural offsets of correlated horizons, show increase in offsets from the youngest to the oldest unit (Table 2). Also, average structural throw across the same faults deduced from structural cross section NDAA" (Plates 27)

and dip data from structure contour maps, indicate gradual increase in throw with depth, suggesting structural accentuation.

In summary, northwest and northeast paleostructural trends were alternately dominant throughout the Phanerozoic geological development of the study area. These trends were primarily influenced by the northeast-trending Culbertson-Grenora feature, a part of the Brockton-Froid-Fromberg fault system to the west and the Nesson anticline to the east. Recurrent structural movement was the dominant style of deformation. Fault blocks along the trend of the Brockton-Froid-Fromberg system moved recurrently in Ordovician, Devonian, Mississippian, Permian and Triassic.

The Nesson anticline consists of a mosaic of fault-bounded structural blocks, six of which are identified by this work. Structural activities in each fault block were not exactly the same as in other blocks even though the Devonian deformation was common to all the fault blocks. Structural reversal was documented on the Beaver Lodge block along the East Nesson fault in Pennsylvanian and on Temple fault block along the East Temple fault in the Permian. Interpreted faults are oriented en echelon in two primary directions, northeast and northwest, and intersect to form a mosaic of fault blocks. Faulting was both syndepositional and post depositional. Basin depths varied from time to time but was mostly shallow marine, a few tens of meters throughout most of the Paleozoic, for example in the Devonian, water depths varied within the same stratigraphic unit, say Souris River Formation, as the different facies were being deposited during faulting. Basin depths also varied generally upsection, decreasing from Souris River time to the time of deposition of Nisku and Three Forks formations. The faults probably owe their origin to the various tectonic activities going on around the continental margins. The segmented basement, in response to the various stress fields set up by the prevailing orogeny, had to adjust by

moving along zones of weakness. Subduction of the western continental margin led to the general instability of the continent in the Paleozoic era, leading to series of orogenies including the Antler orogeny of late Devonian which is regarded as the first major series of events in which the present Cordillera evolved. At the eastern margin, there was the Taconic orogeny of middle Ordovician, the events of which are attributed to the development of a subduction zone along the Appalachian edge as a result of the closing of Iapetus.

A summary of timing of major structural movements across interpreted faults is given below.

#### West Nesson Fault

The northwest-trending West Nesson fault bounds the Beaver Lodge fault block to the west and is downthrown to the west. Structural movements occurred in Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian and Permian.

#### East Nesson Fault

The northwest-trending East Nesson fault bounds Beaver Lodge fault block to the east and is downthrown to the east. Normal structural movement was in Silurian and Devonian. Structural reversal took place in the Pennsylvanian and returned to normal in Permian.

#### West Temple Fault

The West Temple fault also trends northwest and is downthrown to the west. It bounds Temple fault block to the west. Documented times of structural movements were Silurian, Devonian, Mississippian and Permian.

### East Temple Fault

The northwest-trending fault is normally downthrown to the east and bounds Temple fault block to the east. Documented times of structural movement were Silurian and Devonian, with structural reversal in the Mississippian and Permian.

### Charlson Fault

Charlson fault trends east-west and is downthrown to the north. It separates Beaver Lodge fault block from Charlson block. Structural movements were documented in the Devonian, Mississippian and Pennsylvanian.

### Beaver Lodge Crestal Faults

Intrablock structural differentiation gave rise to the formation of several crestal fault blocks on the Beaver Lodge block, two of which are documented in this study. Beaver Lodge crestal fault 1 is located to the east of Beaver Lodge crestal fault 2, and both trend approximately north-south and are downthrown to the west. Structural movements on the Beaver Lodge crestal fault 1 were documented in the Ordovician, Silurian, Mississippian and Permian. Documented times of movement on Beaver Lodge crestal fault 2 were Devonian, Mississippian, Permian and Triassic.

Fault block 3 containing the southern tip of Tioga field could not be well documented because of scarcity of deep well data. It is however considered as a "buffer" block, bounded north and south by northeast-trending linears L1L2 and L3L4, between the Temple block and the Beaver Lodge block.

The fault block geometry outlined in this thesis for the Nesson anticline could be used as a predictive tool in hydrocarbon exploration.

## FUTURE WORK

The following are suggestions for future work in this area :

1. Incorporation of detailed seismic interpretation across the major features to assist in the structural analysis.

2. Since deformation spanned quite a large period of geological time in this area, further work should concentrate on smaller time slices at a time, and correlation of stratigraphic units should be taken to the finest detail. This will help in refining the paleostructural interpretation, and by focussing on the Culbertson-Grenora feature and the Nesson anticline, the structural link between the two can be adequately worked out. The results may enlighten us more on the origin of the Williston basin.

3. Tectonic control on sedimentation was approached from a well log interpretation stand point. Detailed core study is necessary to study the influence of recurrent movement on sedimentary facies.

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