DEPOSITION AND DISSOLUTION OF THE MIDDLE DEVONIAN PRAIRIE FORMATION, WILLISTON BASIN, NORTH DAKOTA AND MONTANA

by:

Chris A. Oglesby

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

Golden, Colorado
Date 8/27/88

Signed: ______________________
Chris A. Oglesby

Approved:

____
Lee C. Gerhard
Thesis Advisor

Golden, Colorado
Date ______________________

____
Samuel S. Adams, Head
Department of Geology and
Geological Engineering

ABSTRACT

Within the Williston basin, thickness variations of the Prairie Formation are common and are interpreted to originate by two processes, differential accumulation of salt during deposition, and differential removal of salt by dissolution. Unambiguous evidence for each process is rare because the Prairie/Winnipegosis interval is seldom cored within the U.S. portion of the basin. Therefore indirect methods, utilizing well logs, provide the principal method for identifying characteristics of the two processes. The results of this study indicate that the two processes can be distinguished using correlations within the Prairie Formation.

Several regionally correlative upward-brining, and probably shoaling-upward sequences occur within the Prairie Formation. Near the basin center, the lowermost sequence is transitional with the underlying Winnipegosis Formation. This transition is characterized by thinly laminated carbonates that become increasingly interbedded with anhydrites of the basin-centered Ratner Member, the remainder of the sequence progresses up through halite and culminates in the halite-dominated Esterhazy potash beds. Two overlying sequences also brine upwards, however, these sequences lack the basal anhydrite and instead begin with halite and culminate in the Belle Plaine and Mountrail potash Members, respectively. A fourth sequence is indicated by several feet of halite capping the Mountrail Member in some parts of the basin. Subsequent erosion or dissolution prior to burial may have removed the upper portion of this sequence.

Cross-sections show that the Lower Prairie gradually decreases in thickness from the basin to its margins. This thickness variation is most simply explained by decreasing accommodation potential due to decreased basin topography away from the basin

depocenter and by depositional onlap of the Prairie toward the basin margins. A depositional onlap pattern is characteristic of the basin's southern margin. In this case, there is a progressive increase in areal extent of the formation from the base to the top. By correlating the four sequences within the Prairie, some local thickness variations are shown to originate by depositional onlap onto Winnipegosis reefs. Other thickness variations occur in response to minor vertical movements across basement faults. In particular the Brockton-Froid fault zone and the Nesson anticline have affected deposition of the Prairie and Winnipegosis Formations.

In other areas, such as along the western and eastern basin margins, the basal parts of the formation are more extensive and completely preserved, but upper parts are progressively diminished in areal extent from the top down. This pattern is explained by progressive dissolution of Prairie evaporites from the top downward, suggesting that the aquifers contributing to the dissolution overlie the Prairie Formation. Although no distinct linear pattern emerged, the coincidence between tectonic features such as the Brockton-Froid fault system, the Nesson anticline and the Superior/Churchill contact and major dissolution areas suggests that dissolution is controlled primarily by tectonic fracturing.

Dissolution was also recognized over several Winnipegosis pinnacle reefs. This dissolution preferentially removed the overlying potash horizons and resulted in partial dissolution of the Prairie. These observations suggest that dissolution resulted from an upward-directed flow of waters localized by the reef facies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

ACKNOWLEDGEMENTS

I thank Dr. Lee C. Gerhard, my thesis chairman, for suggesting this topic. His dedication to industry-oriented research continues to attract petroleum geologists to his guidance. I also thank Dr. Tim Cross whose unbounded dedication to new and innovative science helped in the implementation of this project, and Dr. Tom Davis whose knowledge of Williston basin geology was a primary contribution. Additional thanks go to Dr. Sam Adams, for stimulating discussions on evaporite deposition.

Tenneco Oil Company provided generous financial and material assistance, which is greatly appreciated. The Union Oil Company, Mobil Oil Corporation and the Colorado School of Mines also provided financial assistance and, Texas Gas Exploration contributed material support. Texaco was kind enough to allow me to view a "tight holed" potash core from the Prairie Formation.

I would also like to thank, Sid Anderson and David Fischer of the North Dakota Geological Survey for enlightening discussions on the Prairie. I would also like to acknowledge Rod Stoa of the NDGS, who was a lifesaver; he helped pack and unpack far too many feet of core (and believe me, evaporites are heavy!). Thanks also go out to Dan Poe, whose drafting enhanced the clarity of the maps and cross-sections.

Finally, I would like to thank Margaret Lessenger, my wife, for her patience and support (including her brilliant Mac-editing) during completion of this project. And finally to Mom and Dad who always believed in their son and encouraged him to keep striving for the best.

INTRODUCTION

The Prairie Formation is the youngest formation in the Middle Devonian, Elk Point Group within the Williston basin (Fig. 1). The Prairie Formation, which consists of evaporites, varies both locally and regionally in thickness. Variations are both gradual (tens of feet/mile) and extreme (hundreds of feet/mile) and are attributable to several processes. Thinning within the Prairie Formation has been attributed to dissolution of halite and potash salts in vicinities of basement fractures and over Winnipegosis reefs, and to depositional thinning related to (or controlled by) underlying Winnipegosis topography. The primary objective of this study was to determine if these processes affected the Prairie Formation to different extents and in different places and if they could be differentiated using geophysical logs. Since the Prairie Formation is never exposed in outcrop due to the high solubility of the evaporite minerals, a methodology that could be applied to the subsurface was essential. Because the dissolutional and depositional processes are dissimilar, it was anticipated that their influence upon the thickness variations within the Prairie Formation would also be dissimilar.

An additional purpose of this study was to determine the original depositional limits of the Prairie Formation. Using criteria established to differentiate between depositional and dissolutional thinning, the current Prairie Formation salt edge was characterized as either depositional or dissolutional in origin. Where the present salt edge is dissolutional in origin, the boundaries of the original depositional limit were extrapolated.

The Prairie subcrop within the U.S. portion of the Williston basin (Fig. 2), was divided into three areas for mapping purposes; a western area in Montana (R60E to R43E), an area in western North Dakota (R103W to R90W), and an area in central North Dakota (R90W to R72W). Approximately 2,400 wells representing all Prairie Formation

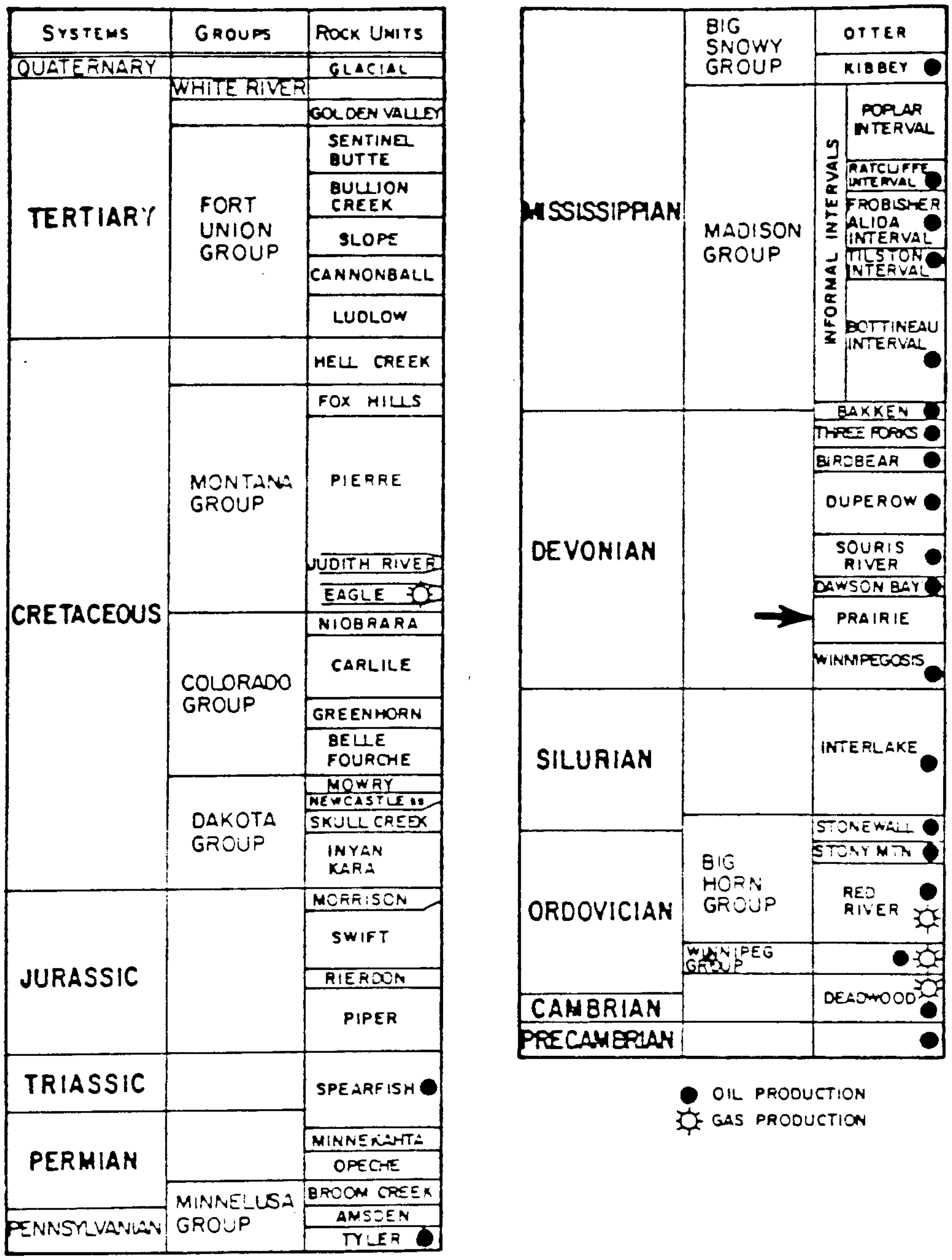


Fig. 1. Stratigraphic column for the Williston Basin (after Anderson and Bluemle, 1984)

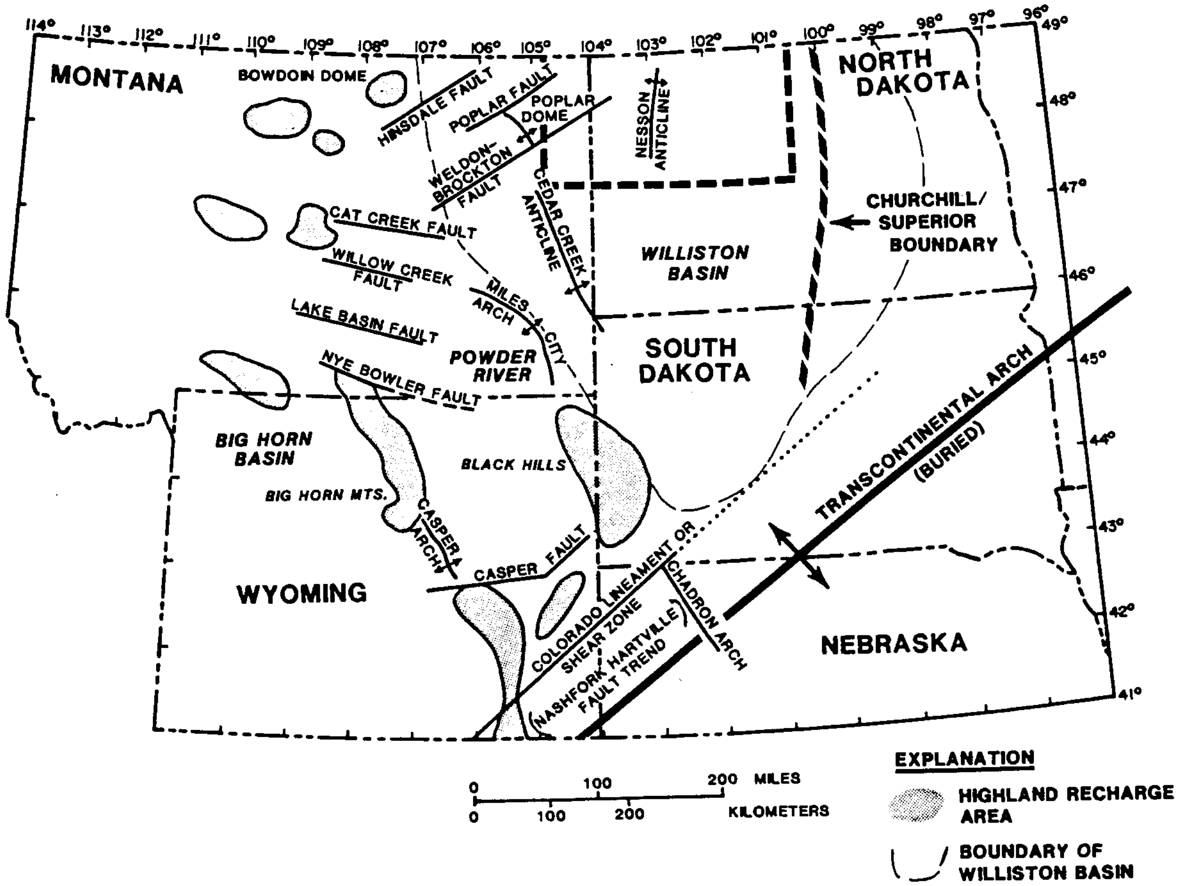


Fig. 2. Outline of the Williston basin showing major structural features. Study area (hatchured) is the area encompassed by the Prairie Formation subcrop (modified after Downey, 1987).

penetrations were used to construct the isopach maps.Three sets of isopach maps (9 maps) were constructed over the study area. Winnipegosis isopach maps were constructed to locate reefs and the Winnipegosis shelf/slope break. The Prairie salt isopach maps were used to locate local abrupt thins and define regional thickness gradients. These maps are unable to distinguish between depositional or dissolutional origins of these patterns. The final map, a Prairie Formation isopach, including the Ratner Member and the Second Red Bed, was used to test for dissolution outside the salt edge, especially in central North Dakota where the halite and potash are removed and only the Ratner and Second Red Bed remain (Anderson and Hunt, 1964).

In addition to the isopach maps, six cross-sections were constructed. The cross sections were useful in demonstrating and contrasting the various styles of thinning of the Prairie Formation. Additionally, they provided the evidence for differentiating between depositional and dissolutional thinning. Finally by constraining where dissolution occurred, the cross-sections were used to assess the flow directions responsible for dissolution.

In order to present possible tectonic and depositional controls on thinning within the Prairie Formation, this paper begins with a discussion of the tectonic framework of the Williston basin, followed by a discussion on Prairie deposition. Within this context, several models of thinning, both dissolutional and depositional are discussed. Finally, the results of this study are compared with the previously published models.

STRUCTURAL SETTING

The Williston basin, a large intracratonic basin with a dominantly circular outline is located in eastern Montana, northern South Dakota, western and central North Dakota, southern

Saskatchewan and eastern Manitoba. It is bordered by the Transcontinental Arch to the southeast, the Black Hills uplift to the southwest and the Miles City Arch and Bowdoin Dome to the west (Fig 2). Lineaments trend predominantly northeast-southwest and northwest-southeast (Fig. 3). Major structural elements are also aligned in these two directions and include such features as the Cedar Creek Creek anticline (northwest-southeast) and the Brockton-Froid lineament (northeast-southwest) (Fig. 2). Although lacking surface expression, a third prominent tectonic element trends north-south and is represented by features such as the Nesson anticline and Billings nose (Fig. 2). Timing and sense of motion along the lineations remains controversial. Gerhard *et al.* (1982) and Brown (1978) considered the motion to be dominantly left-lateral on northeast trending features, and right-lateral on northwest trending features. While Thomas (1974) suggested opposite senses of displacement.

Brown (1978), in a regional tectonostratigraphic analysis, documented changes in thickness across lineaments that demonstrated Phanerozoic reactivation. From the orientations of fracture systems, he concluded that the basement fabric was the result of wrench-style tectonics. Although Brown's (1978) work demonstrated recurrent movement along zones of basement weakness, it did not provide a solution to the horizontal motions of the individual blocks. Most Phanerozoic movement appears to have been dip-slip. Strike-slip movements, perhaps as a consequence of their difficulty of detection, are apparently rare (Billings, 1972).

A significant Precambrian feature, the contact between the Churchill (1.8-2.5 b.y.) and Superior (>2.5 b.y.) provinces, trends north-south through central North Dakota (Fig. 2). In addition to the lineations serving as boundaries between individual fault blocks, the Superior/Churchill contact has also acted as a tectonic hinge, with increasing dips and

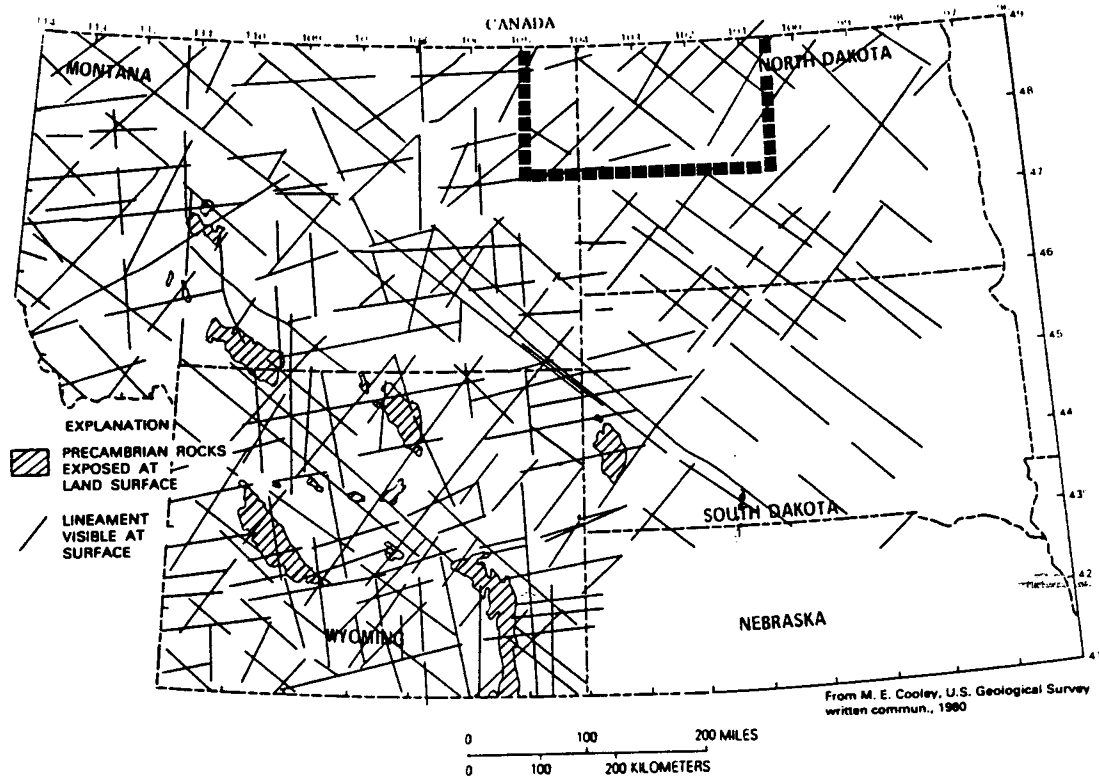


Fig. 3. Lineament patterns and major structural features in the northern Great Plains.(modified after Downey et al, 1987).

abrupt facies changes across the boundary throughout the Phanerozoic (Gerhard, et.al., 1982). This feature is interpreted as a continental suture developed during the Trans-Hudsonian orogeny (Bickford *et al.*, 1986). Basement studies, using geophysical gravity and magnetic data in conjunction with petrological studies and radiometric age dating, suggest that the present-day Williston basin lies on Precambrian accreted terrane (Bickford *et al.*, 1986). The Trans-Hudsonian orogenic collision probably produced the fractured basement fabric that exists in the Williston basin.

In addition to the wrench-fault model of basin origin suggested by Thomas (1974), Brown (1978, 1987) and Gerhard (1982), several other models have been proposed. Peterson (1981) advocated a rift-style origin, with north-south rifting forming an east-west trending aulocogen extending into the Williston basin from the Big Snowy Trough in Montana. A third origin has been proposed by Turcotte and Ahern (1977) and refined by Ahern and Mrvicka (1984). They suggested that a subcrustal thermal event and ensuing subsidence was responsible for formation of the Williston basin. Sloss (1987) recently criticized the thermal mechanism by citing several stratigraphic features within the Williston basin, and cratonic basins, in general, that this model fails to explain. Additionally, Sloss (1987) argued that a loading mechanism is also inadequate to provide the necessary subsidence. In this regard, the origin of the Williston basin remains, at best, controversial.

DEPOSITIONAL SETTING

During the Middle Devonian, the Williston basin was joined with the Alberta basin to become part of a larger basin, the Elk Point basin, created when uplift on the Transcontinental Arch tilted the basin northwestward (Gerhard, et.al., 1982) (Fig.4). Barriers to restriction were present along the northwest basin margin (Presquille reefs) and

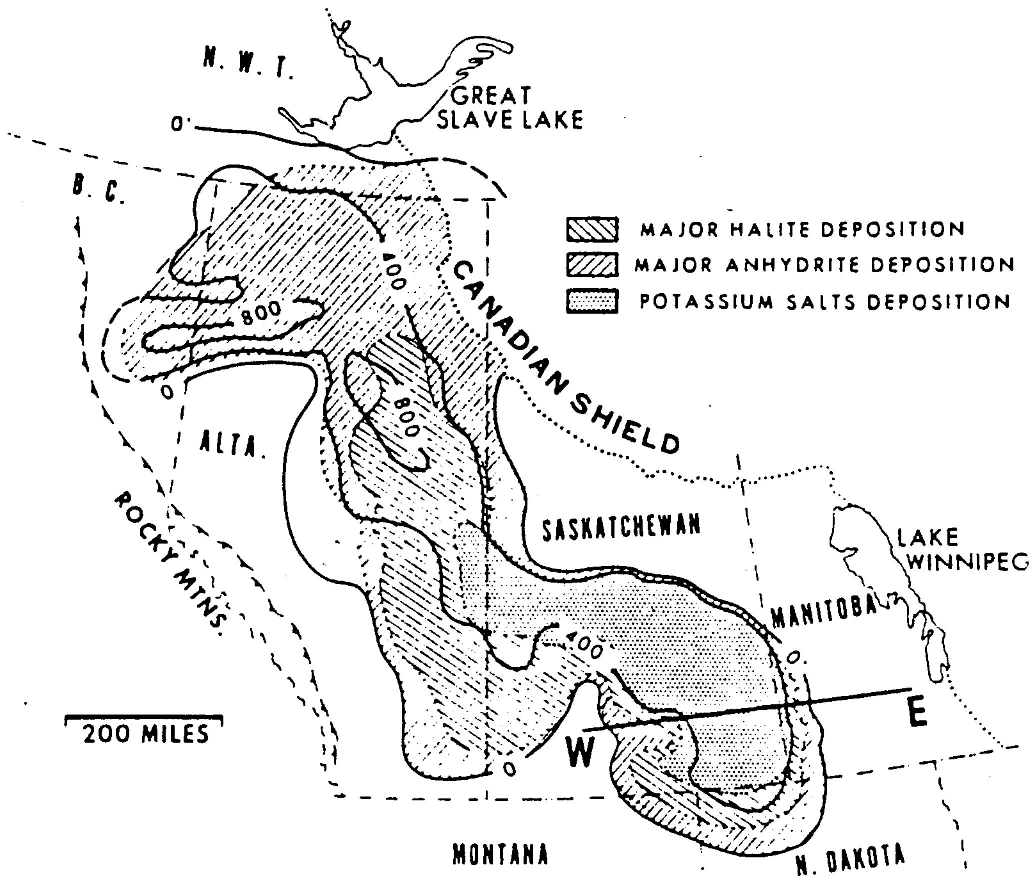


Fig. 4. Gross isopach map of the Prairie Formation or equivalents within the Elk Point basin. Hatchured patterns indicate distribution of different facies (after DeMille *et al.*, 1964).

may have been present along the northeastern margin as well (Williams, 1984). The Prairie Formation (Givetian) and its northern equivalent, the Muskeg Formation, were deposited as thick evaporitic mineral assemblages within a restricted hypersaline basin. The Prairie Formation in the Williston basin, contains primarily halite and potassium salts with minor anhydrite, whereas the Muskeg Formation to the north is predominantly anhydritic (Fig. 4). Holter (1969) suggested that this distribution of evaporite facies indicates that the Williston basin was the farthest removed from the source of normal marine waters.

Initiation of evaporite deposition within the Elk Point basin was probably a result of a relative eustatic drop, causing basin restriction across the Presquille barrier reef and other possible reefs to the north (Williams, 1984). A gradual increase in salinity is indicated by argillaceous, thinly laminated mudstones of the upper Winnipegosis becoming increasingly interbedded with anhydrite. The lowermost member of the Prairie, the Ratner Anhydrite, is confined to the basin center. Although the Ratner Member appears as a distinct unit on well logs (Fig. 5), it is actually transitional with the underlying Winnipegosis basinal laminites. The thinly laminated argillaceous laminites of the Winnipegosis Formation (Fig. 6) merge upwards with laminated anhydrite and then enterolithic and rosette-patterned anhydrite and finally massive anhydrite near the top of the Ratner Member (Figs. 7-9).

The generally dark nature of the laminites combined with a relatively high organic content suggest that depositional conditions were reducing and probably anoxic. TOC (total organic carbon) values for the laminites average 1.46 percent organic carbon (Wardlaw and Reinson, 1971). These observations combined with evidence showing that varves within the Prairie/Winnipegosis laminites were correlative for distances up to two miles and that similar appearing varved cycles were correlative over hundreds of miles lead Wardlaw and Reinson (1971) to conclude that the Upper Winnipegosis laminites and the

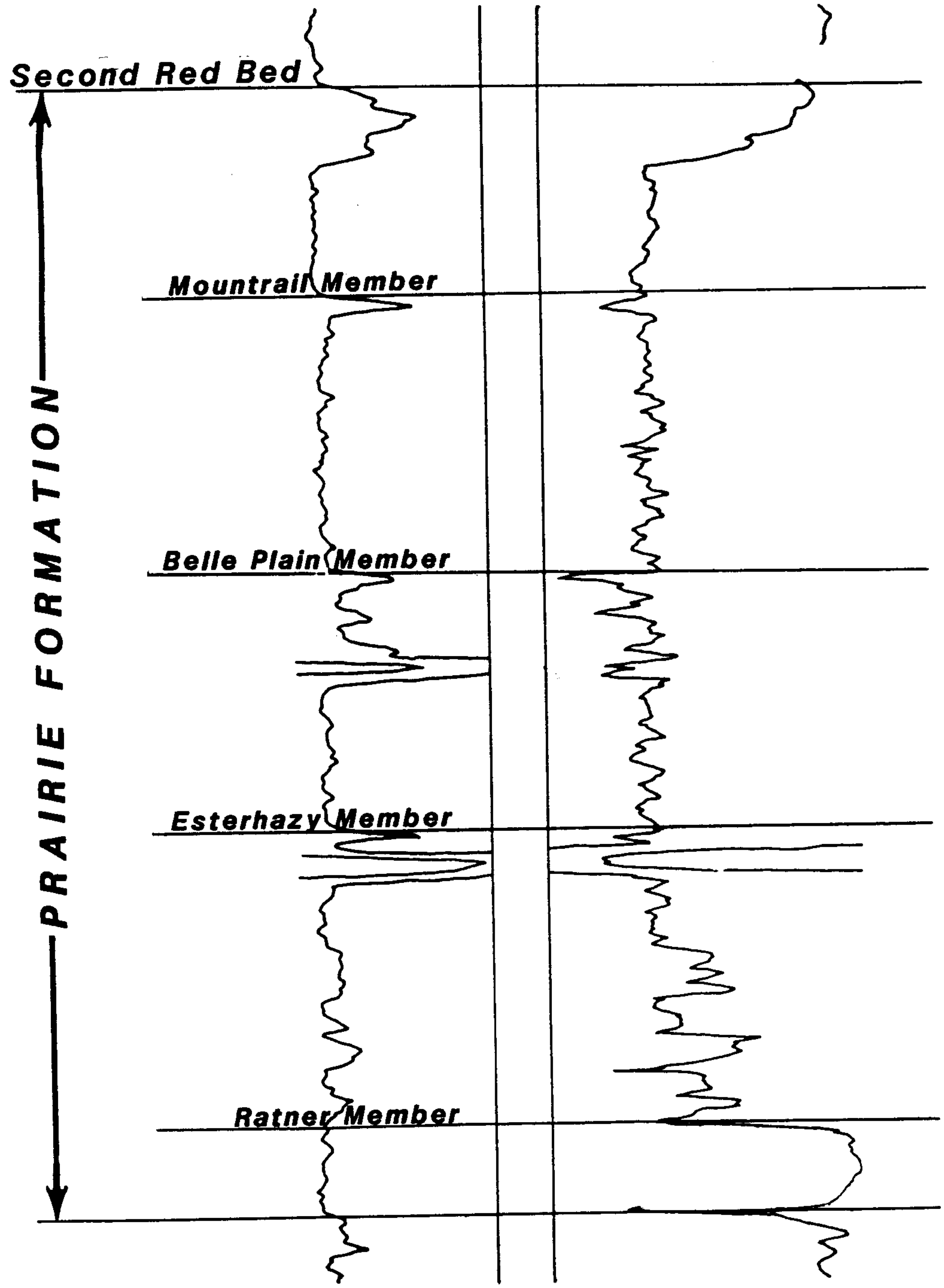


Fig. 5. Gamma ray - sonic log of the Prairie Formation

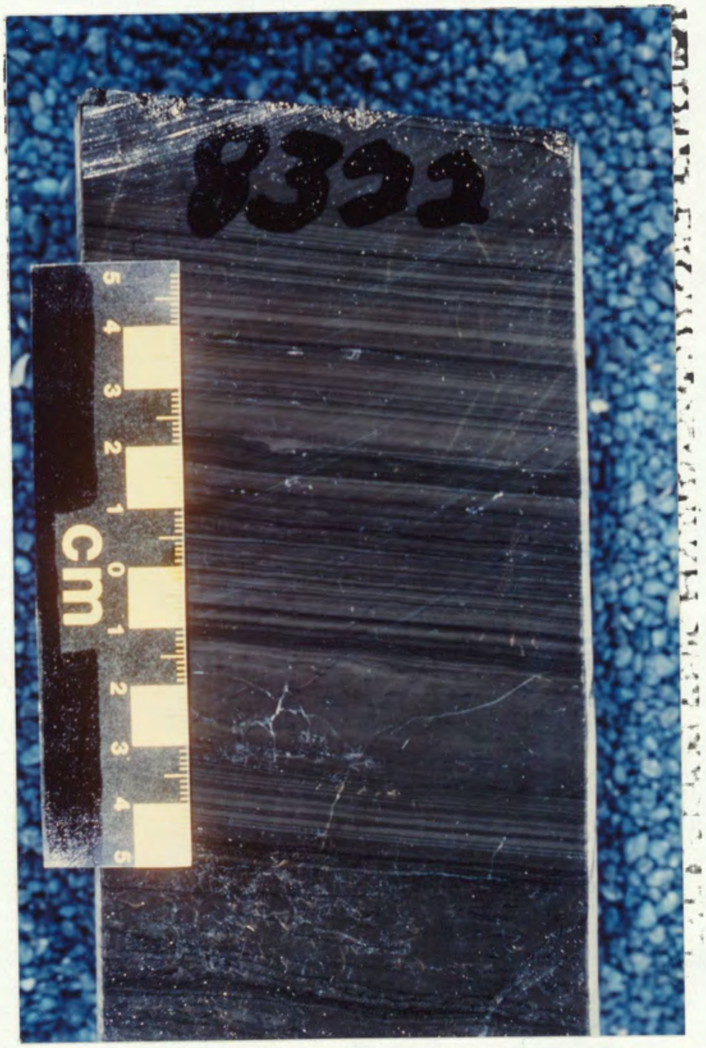


Fig. 6. Photograph of core showing the basinal, laminated carbonate facies of the Winnipegosis Formation. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,322').

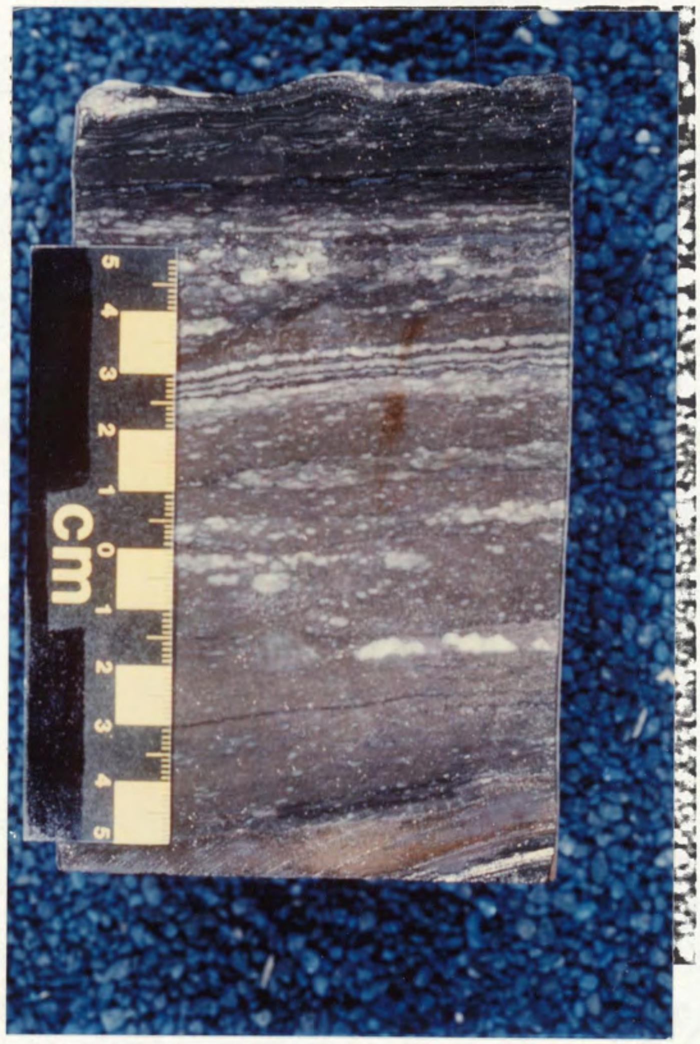


Fig. 7. Photograph of core showing the basinal, laminated carbonate and anhydrite transitional facies from the Winnipegosis Formation to the Prairie Formation. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,302').

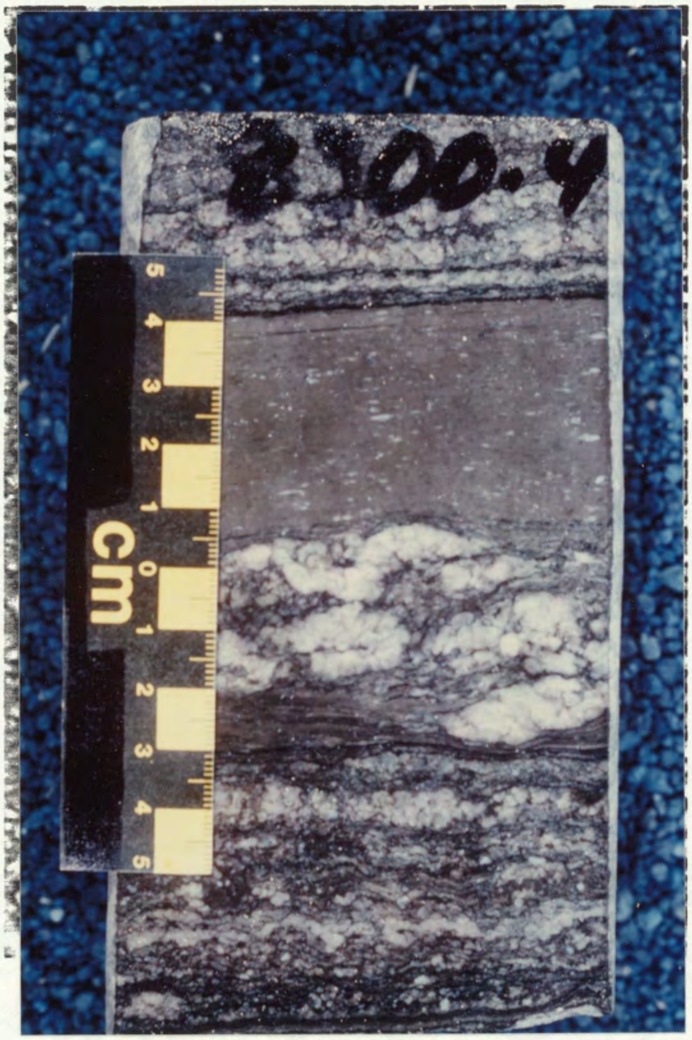


Fig. 8. Photograph of core showing the enterolithic anhydrite facies of the Ratner Member of the Prairie Formation. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,300.4').

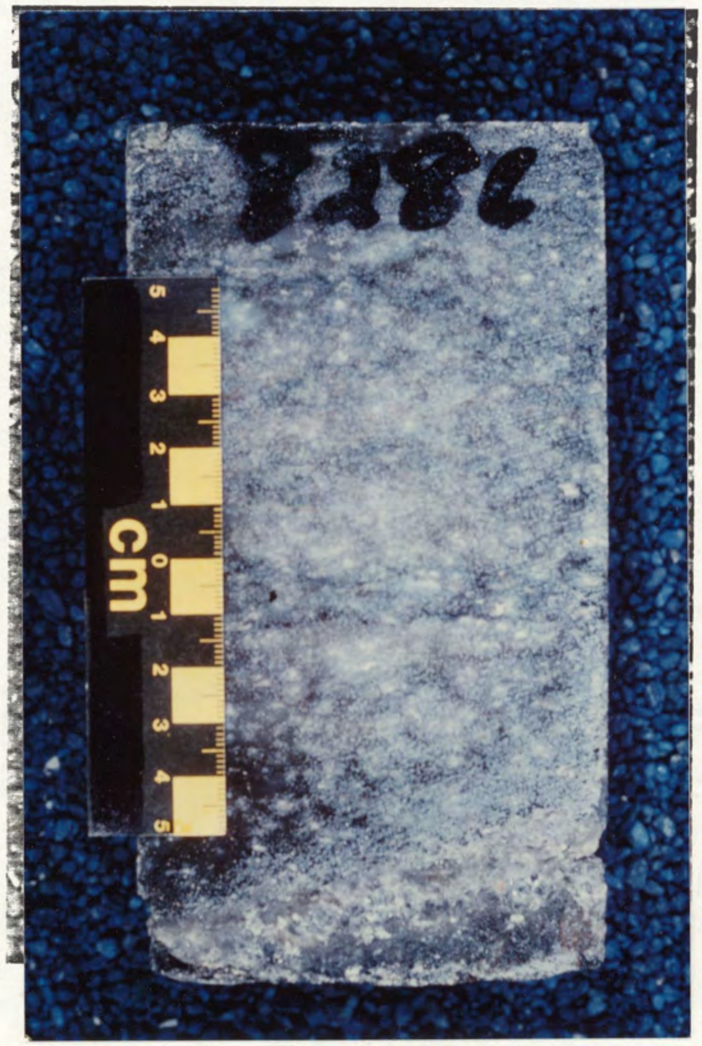


Fig. 9. Photograph of core showing the massive anhydrite facies (also note the small rosettes of anhydrite crystals) of the Ratner Member of the Prairie Formation. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,286').

Ratner Member of the Prairie were deposited under deep water conditions. Analogous observations within the Zechstein salts of Germany and the Castile Formation of Texas have been cited as evidence for deep-water evaporites (Anderson and Kirkland, 1966).

The transition between the anhydrite and the overlying halite is more abrupt but it is still gradational (Fig. 10). Within the lower Prairie Formation, halite is milky in appearance and contains chevron crystals which "V" downwards indicating a growth pattern towards the top of the formation (Fig. 11; Wardlaw, 1964). Wardlaw attributed the opacity of the crystals as a result of alternating growth of inclusion-rich and inclusion-poor layers (Wardlaw, 1964). Within the upper Prairie Formation, (above the Esterhazy Member), opaque, chevron halite is replaced by clear, inclusion-free, large hopper-shaped halite crystals (Fig. 12). This texture has been interpreted to represent recrystallization of the original chevron-halite (Wardlaw, 1964). Supporting evidence for recrystallization of the Upper Prairie is interpreted from bromine trace element concentrations. Anomalously low bromine values (0.0043 weight percent) in the overlying hopper-form halite indicates that these crystals were reprecipitated in a brine that contained significantly lower bromine concentration than seawater (Wardlaw, 1964). In contrast, bromine values of 0.003-0.0118 weight percent within the lower Prairie Formation chevron-form halite indicate precipitation from a more saline brine (Wardlaw, 1964). Because the weight percent bromine within the lower Prairie indicates crystallization near the NaCl saturation point (0.0075 wt.%; Braitsch, 1962), Wardlaw (1964) suggested that "re-solution of halite would be favored particularly at a stage of evaporation in which the concentration of the brines oscillated about the point of saturation of sodium chloride." This explanation seems reasonable in view of the abundant interbedded anhydrites within the lower Prairie (Fig. 13). These anhydrite beds or jahresringe are interpreted to represent periods of normal

Fig. 10. Photograph of core showing the transition from anhydrite facies to halite facies (lower Prairie Formation). (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,282').

Fig. 11. Photograph of core showing the milky, chevron-halite facies (lower Prairie Formation). This facies is interpreted to represent the original depositional texture. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,261').

Fig. 12. Photograph of core showing the clear, hopper-halite facies (upper Prairie Formation). This facies is interpreted to represent recrystallized halite. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,152').

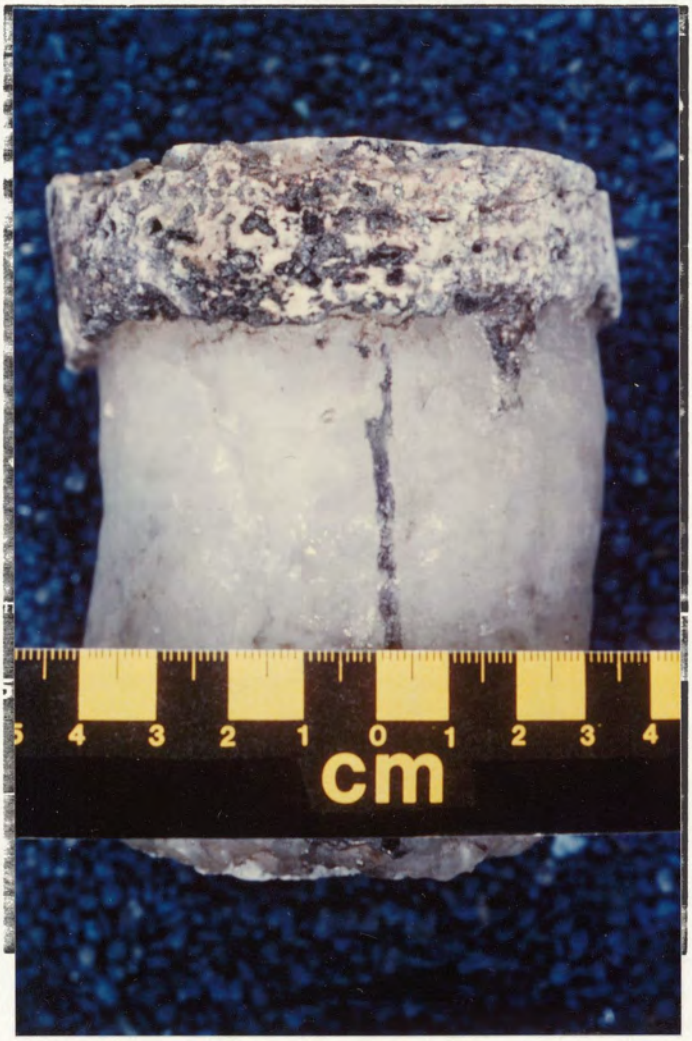


Fig. 13. "Jahresringe" are thin beds of anhydrite and are common throughout the lower Prairie Formation. They are thought to have been deposited during less saline periods of normal marine influx. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 8,233').

marine influx into the basin. The common occurrence of jahresringe within the lower Prairie suggests that periodic recharge of the Elk Point basin was common and that the brine salinities fluctuated at levels very close to the sodium chloride saturation point.

Overlying the lower Prairie halite are three cycles of potash and interbedded halite. The potash beds record the periods of highest salinity and shallowest brine depth of deposition within the Prairie Formation. The potash beds are composed primarily of halite, sylvite and carnallite, with minor amounts of other hypersaline minerals such as polyhalite (Schwerdtner and Wardlaw, 1964). Although the potash deposits are now multi-minerallic, the original mineralogy was primarily halite and carnallite (Schwerdtner and Wardlaw, 1964). Bromine geochemistry indicates that, like the upper halite beds, most of the potash is secondary, having been recrystallized from brines that were fresher than the depositional brine (Schwerdtner and Wardlaw, 1964). Two important constituents of the potash beds are clay and silt. In additon to colloidal-sized particles, large (several centimeters in diameter), subrounded claystone clasts are common (Fig. 14). The clasts and a large amount of indigenous clay remain behind as residuals from salt dissolution.

The Second Red Bed caps the Prairie Formation. A red to green, non-fossiliferous, dolomite to calcareous shale (Holter, 1969), this bed has been interpreted to represent a regional, intra-Givetian unconformity that is correlative to the Watt Mountain Break in western Canada (Williams, 1984).

"Recently, exploration for potash salts has resulted in several cores cut through the contact between the Second Red Bed and the Prairie Evaporite. There is now clear evidence for at least some erosion at this contact; also it may be that the redbeds represent not so much a flood of terrigenous clastics as a residual product of weathering and solution" (Williams, 1984).

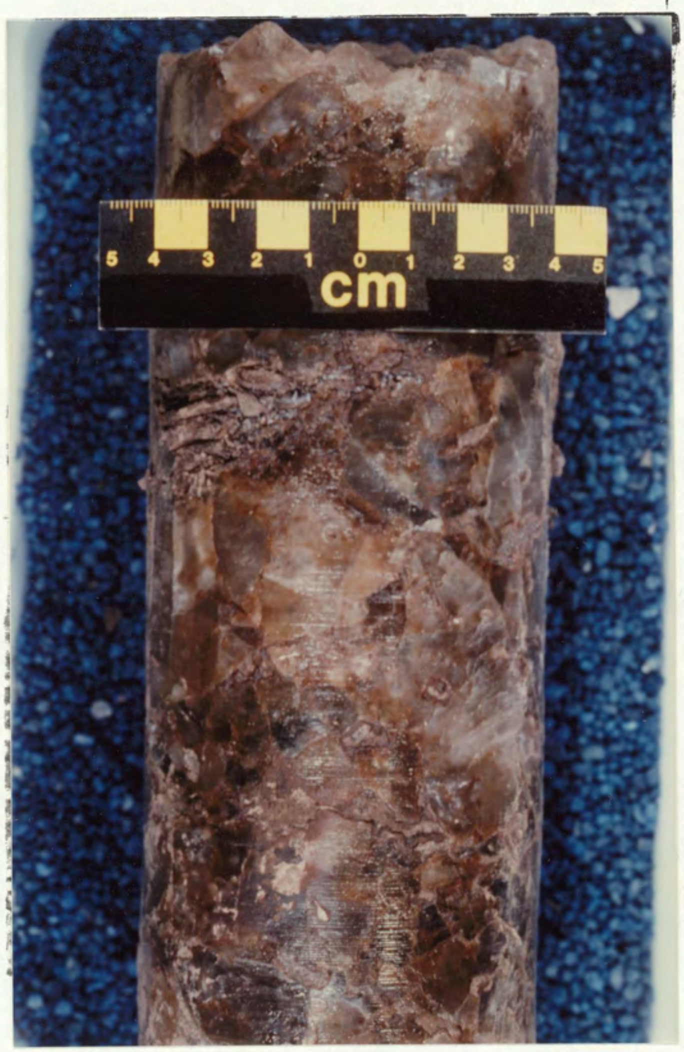


Fig. 14. Photograph of core showing the potash facies (upper Prairie Formation). Note large clasts of green mudstone. (Sunray - Gagnum #1, sw/nw, 13-163n-89w, Burke County, North Dakota, Depth = 7,971').

This impermeable regolith of shale/siltstone overlying the Prairie Formation apparently protected the Prairie salts from dissolution during the post-Prairie, Dawson Bay transgression.

METHODOLOGY

Genetic Stratigraphy

A genetic unit or genetic increment of strata has been defined as "an interval of strata representing one cycle of sedimentation in which each lithologic component is related genetically to all others; the upper boundary must be a lithologic-time marker, an unconformity, or a facies change from marine to non-marine" (Busch, 1974). Correlations based upon genetic units (sequences, cycles), rather than lithostratigraphic units, have been demonstrated to approximate time stratigraphic surfaces (*e.g.*, Campbell, 1967, 1971; Cant, 1984). Using this technique, sequences are correlated by utilizing shallowing and/or deepening events as boundaries. Then, facies tracts are constructed within these time-bounded sequences (Fig. 15). This methodology is powerful because it provides for a more natural analysis of sedimentary units and provides a framework for the reconstruction of depositional systems.

Traditionally, the top ofPrairie salt is used in the orientation of stratigraphic cross-sections and identical or similar lithologies are considered time-equivalent units. This technique emphasizes recognition of gross thickness changes within the formation and does not allow examination of changes within the intraformational sequences, nor does it allow assessment of thickness changes within the Second Red Bed. By applying sequence concepts, the tops of sequences rather than lithologies are selected as datums. This methodology provides better lateral and vertical facies resolution within individual time-

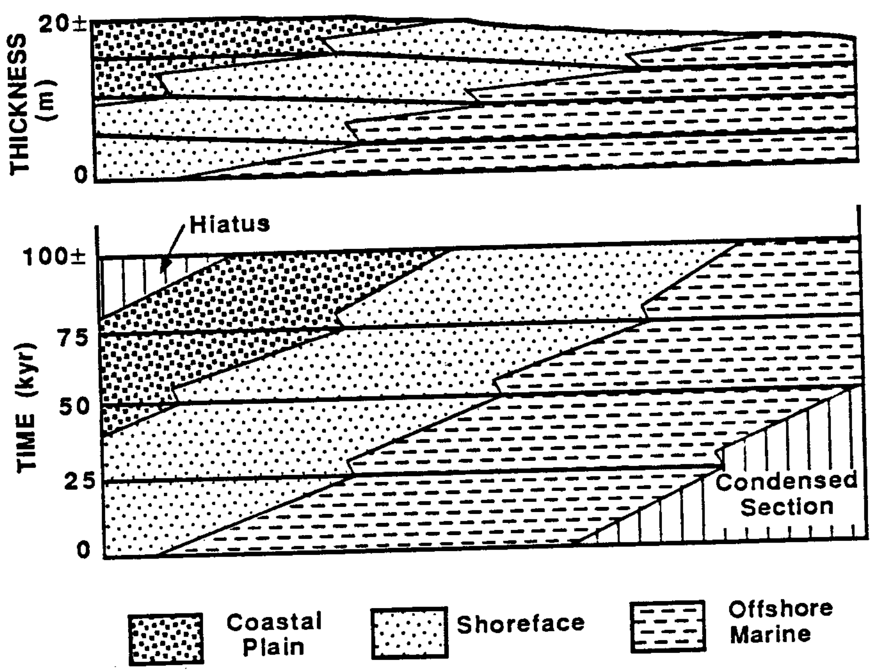


Fig. 15. Lithostratigraphic (top) and time stratigraphic (bottom) sections showing one progradational event and bounding surfaces used for correlation of genetic units. Time lines (solid lines) occur at the relative deepening events which are basinwide and correlative for long distances. Facies tracts migrate (prograde) within each time-bounded unit (after Cross and Lessenger, 1988).

bounded sequences. In this study, the datum for cross-sections is the top of the second and most continuous genetic sequence, the top of the Belle Plain potash Member. Constructing cross sections in this manner allowed for differentiating thickness changes within individual sequences and recognizing thinning below or above the potash horizons.

Evaporite sequences are similar to those in terrigenous and carbonate systems but their succession differs depending upon their relative position and depth of deposition within a basin. Kendall (1984) described three idealized brining-upwards, asymmetric, evaporite sequences which originate in three hypothetical positions within a basin; basinal, shelf, and basin margin (Fig. 16). Kendall's (1984) deep basin sequence was modeled after the lower Prairie Formation. At its base are laminated carbonates, these are overlain gradationally by laminated gypsum, laminated halite, and chevron halite. It is capped by potash salts. Similar "deep-water" evaporite sequences were described in the Paradox basin by Peterson and Hite (1969), who noted that the potash-capping sequences were asymmetrical and had a very sharp upper contact with overlying kerogenous dolomite. This sharp contact was interpreted to represent a disconformity formed by dissolution during deposition of the overlying (lower salinity) facies.

The Prairie Formation can be divided into three complete and one incomplete, regionally correlative, asymmetric sequences in which the mineral assemblages indicate an upward increasing basin salinity and probable coincident shallowing of deposition brine depth (Fig. 17). The basal sequence is transitional with the Winnipegosis Formation in the basin center, where laminated carbonates merge upwards into interbedded laminated anhydrite and carbonate, then enterolithic anhydrite and carbonate, and finally bedded anhydrites of the Ratner Member. Overlying the anhydrite is a thick section of halite and thinly bedded anhydrite (jahresringe). Capping the sequence is the Esterhazy potash

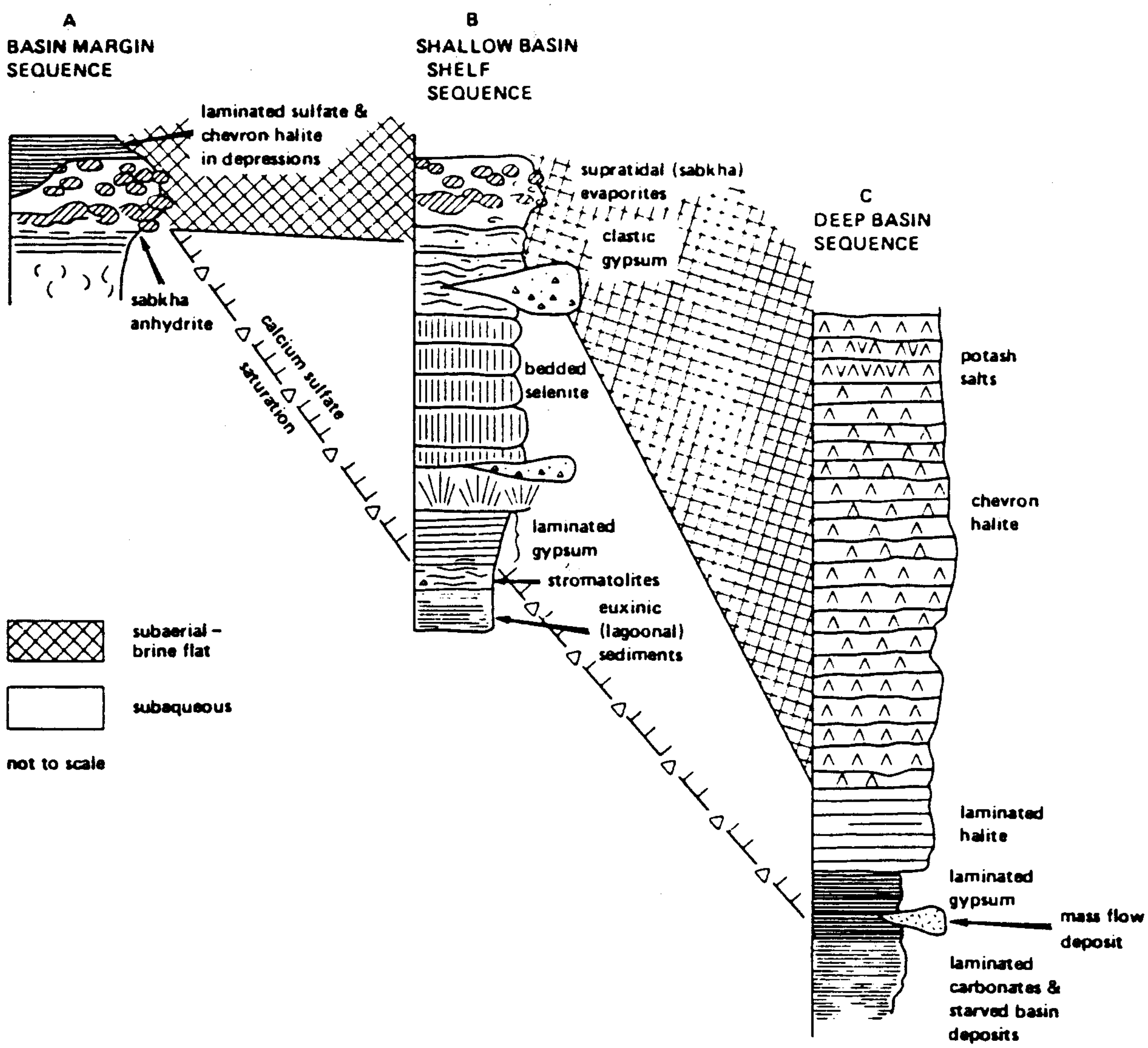


Fig. 16. Idealized evaporite sequences from the basin margin, shelf and deep basin environments (after Kendall, 1984).

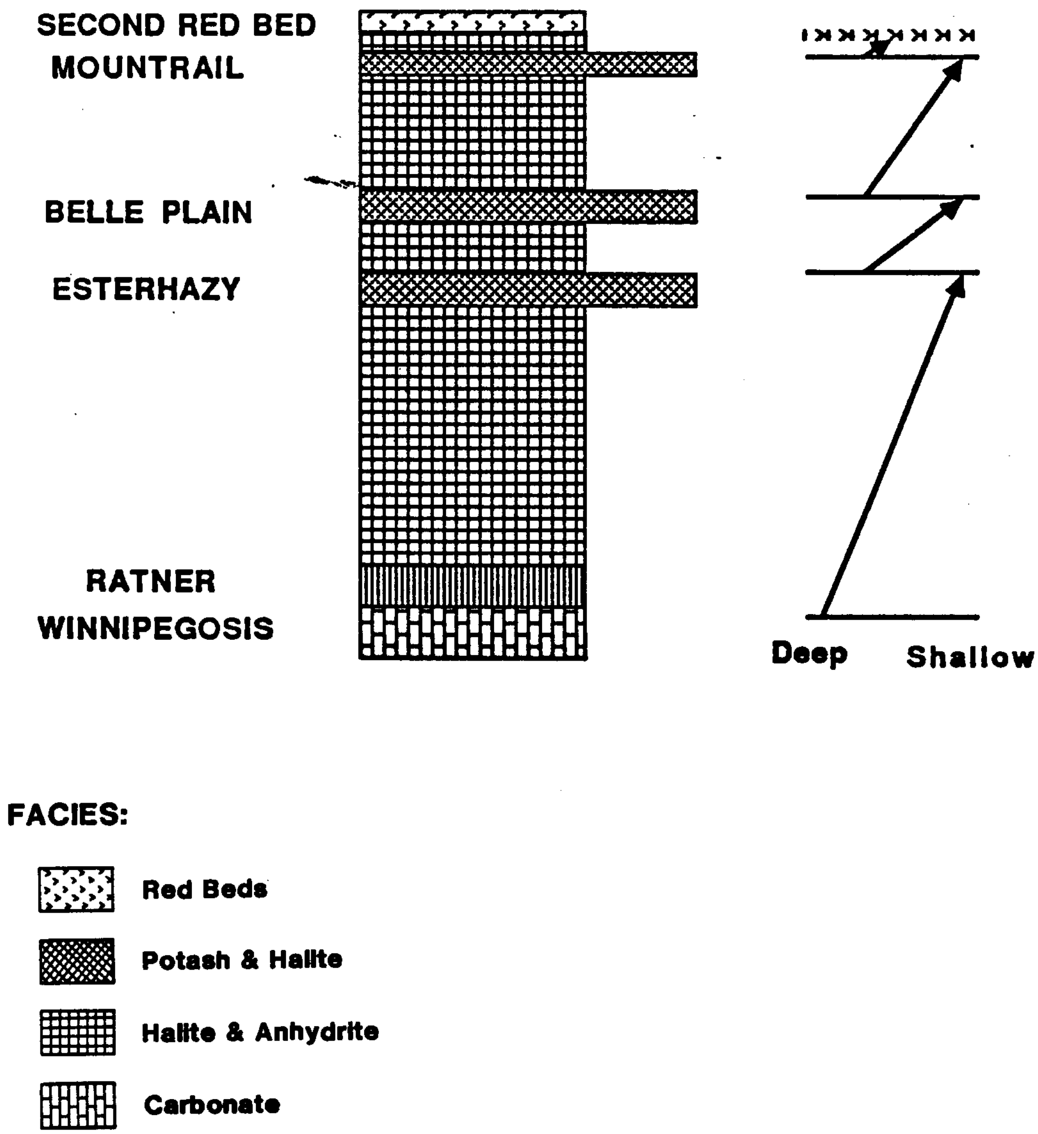


Fig. 17. Schematic diagram of asymmetric, brining (and/or shallowing) upwards sequences within the Prairie Formation.

Member.

After potash deposition of the Esterhazy Member, deposition of the overlying sequence began with brine refreshening, probably accompanied by a relative sea-level or brine level deepening, and resulted in renewed deposition of halite over the underlying potash beds. The contact between potash and overlying halite beds is sharp, suggesting that the decreased salinity resulted in a dissolutional contact. Capping the second and third sequences are the Belle Plaine Member and Mountrail Member potash horizons respectively. Unlike the Esterhazy sequence, the Belle Plain and Mountrail sequences do not contain the lowest salinity anhydrite facies. Overlying the Mountrail Member is another bed of halite capped by the regolith of the Second Red Bed (Williams, 1984), suggesting an incompletely preserved fourth sequence. As Williams (1984) noted, erosion below the Second Red Bed is suggested by the occurrence of ". . . irregular contacts, lumps of clay in the uppermost salt, regional truncation of potash seams (in Canada), and the mineralogical similarity of material in the Second Redbed to insolubles present within the Prairie Evaporite." Therefore, it is possible that this fourth sequence also was complete, however desiccation of the basin and subsequent erosion may have removed the cycle-capping potash beds.

Deposition of thick evaporite sequences

Development of a deep "starved basin" during Winnipegosis time resulted in over 300 feet of relief between the basin center and the surrounding shelves (Fig. 18). This relief greatly influenced the deposition of the Prairie Formation, by providing significant accommodation potential (the volume available to accept sediment) for the ensuing evaporite deposition. Accommodation potential is a function of the combined rates of

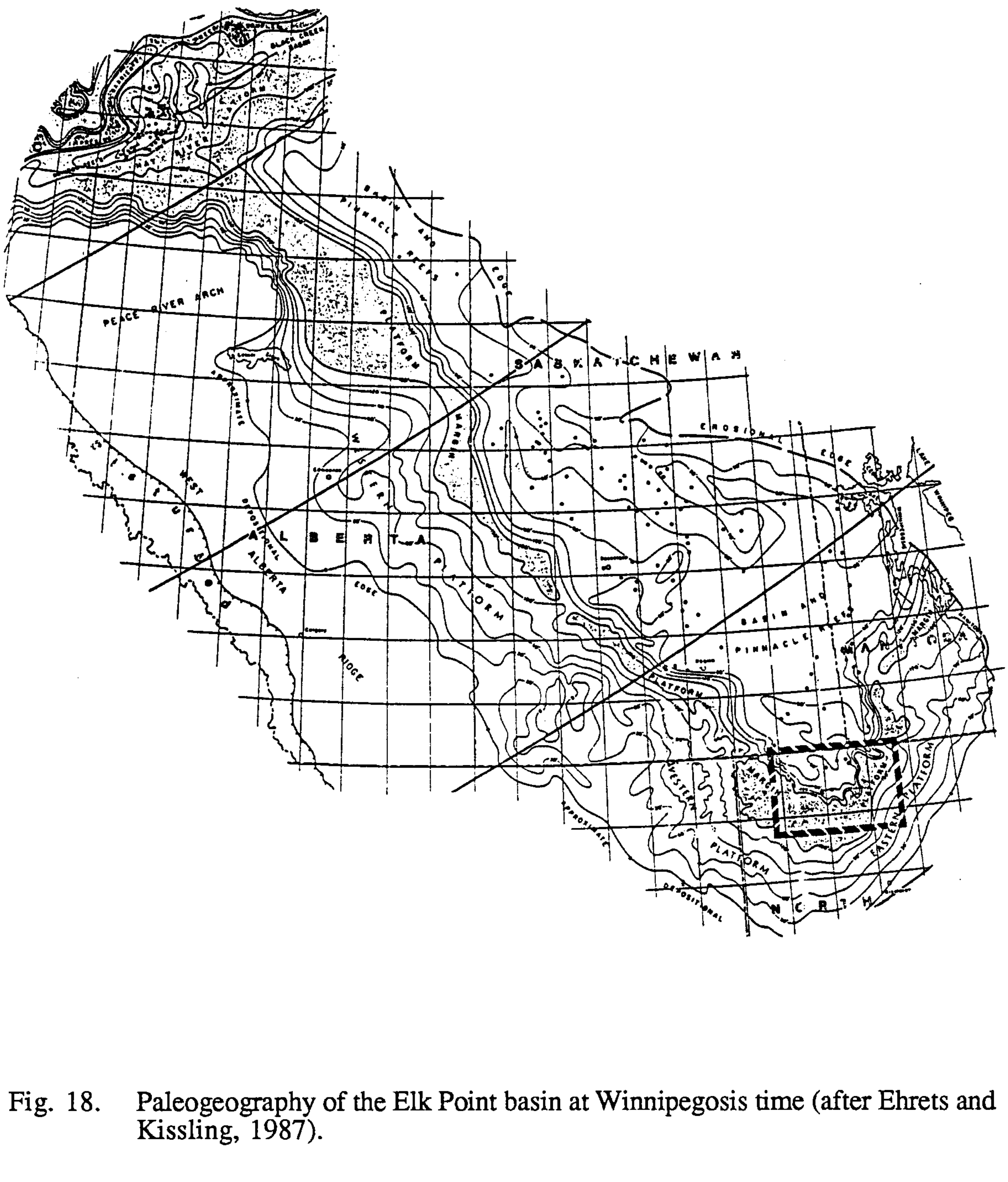


Fig. 18. Paleogeography of the Elk Point basin at Winnipegosis time (after Ehrets and Kissling, 1987).

subsidence, eustasy and sedimentation, and the topography or water depth of the basin.

Most thick sequences of evaporites are believed to accumulate rapidly (1-10 cm/yr.) (Schmalz, 1969). Under these conditions, subsidence and eustatic changes are unlikely to provide the accommodation potential necessary for the accumulation of thick evaporite deposits. Therefore the ability to accommodate thick sequences of evaporites must be primarily a function of topography existing prior to evaporite deposition. In the case of the Prairie Formation, this topography developed during formation of the Winnipegosis "starved basin" (Lineback *et al.*, 1987). Schmalz (1969) observed that formation of a starved basin was a common stage which preceded evaporite deposition and was shared by most basins containing thick evaporite sequences. Evidence of sediment starvation in the pre-Prairie rocks is provided by the sapropelic laminites at the basin center. Relief between the Winnipegosis shelf/slope break and the central basin was probably on the order of 200-300 feet, prior to deposition of the Prairie Formation.

CAUSES OF PRAIRIE FORMATION THINNING

Depositional thinning by onlap

Depositional onlap occurs when a horizontal stratum laps out against a seaward-dipping surface and has been interpreted to indicate a fall in relative sea level followed by a gradual rise in sea level (Fig. 19, Grabau, 1924, Mitchum *et al.*, 1977, Vail *et al.*, 1977). Similarly, restriction of the Elk Point basin and initiation of evaporite deposition has been interpreted to have been initiated by a relative sea-level drop (Maiklem, 1971). Evidence of subaerial exposure within the Winnipegosis pinnacle reefs and along the shelf margin suggests that up to 140 feet of relative sea-level drop occurred at the initiation of Prairie deposition (Ehrets and Kissling, 1987). This magnitude of relative sea-level lowering,

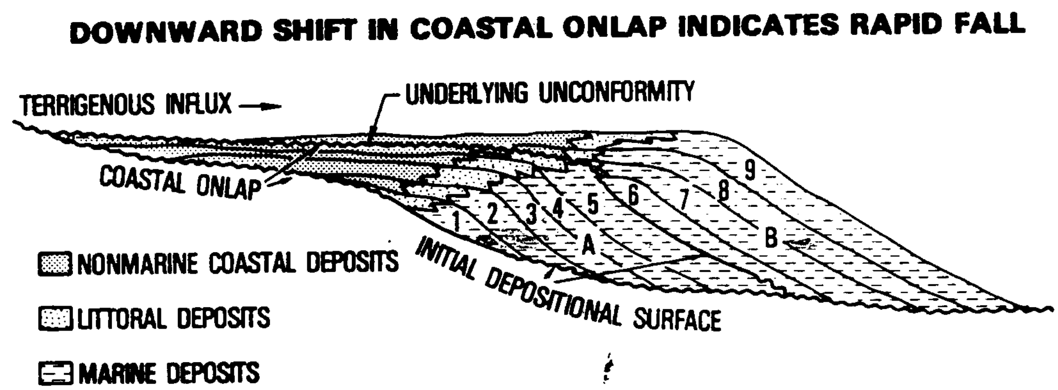


Fig. 19. Downward shift in coastal onlap results from a relative sea level drop (after Vail *et al.*, 1977).

would have resulted in base level shifting seaward below the basin margin slopes and into the relatively steep-sided basin.

Deposition of the Prairie salts onto the underlying Winnipegosis Formation has resulted in thinning patterns that were caused by depositional onlap onto the pre-existing Winnipegosis topography. Onlap of the Prairie Formation against the slope margin is indicated by increased lateral continuity of individual beds upsection (Fig. 20). Because only potash beds, can be traced definitively on well logs, the onlap relationship is best expressed as bottom to top thinning or loss of beds below the Belle Plain datum horizon against the underlying Winnipegosis carbonates (Plates 10-12). As a result of the onlapping geometry, the contact between the Winnipegosis and the Prairie is concordant near the basin center, where the Winnipegosis laminites are transitional with the Ratner Anhydrite, but becomes discordant away from the basin axis, where halite lies directly upon the Winnipegosis. The duration of this hiatus increases away from the basin center, reaching its maximum where the upper Prairie halite was deposited upon the Winnipegosis shelf (Fig. 21). Similar thinning patterns can be recognized over the Winnipegosis reefs, where the lower Prairie salts were deposited against the steeply-dipping reef flanks (Plate 12). As in the case of regional depositional onlap, this phenomena is manifested as bottom to top thinning of beds below the potash horizons (Fig. 22). Seismic interpretation has also been used to locate areas of high relief (70-100m), Winnipegosis pinnacle reefs and mounds, and the resulting Prairie thins (Lundy, et.al, 1966, and Gendzwill, 1978). The reefs display several diagnostic seismic features: 1) velocity anomalies created by the reef (generally velocity pullup of the underlying horizons), 2) seismic onlap geometries of the Prairie onto the Winnipegosis reef, and commonly 3) a structural low overlying the reef resulting from salt dissolution (Fig. 23).

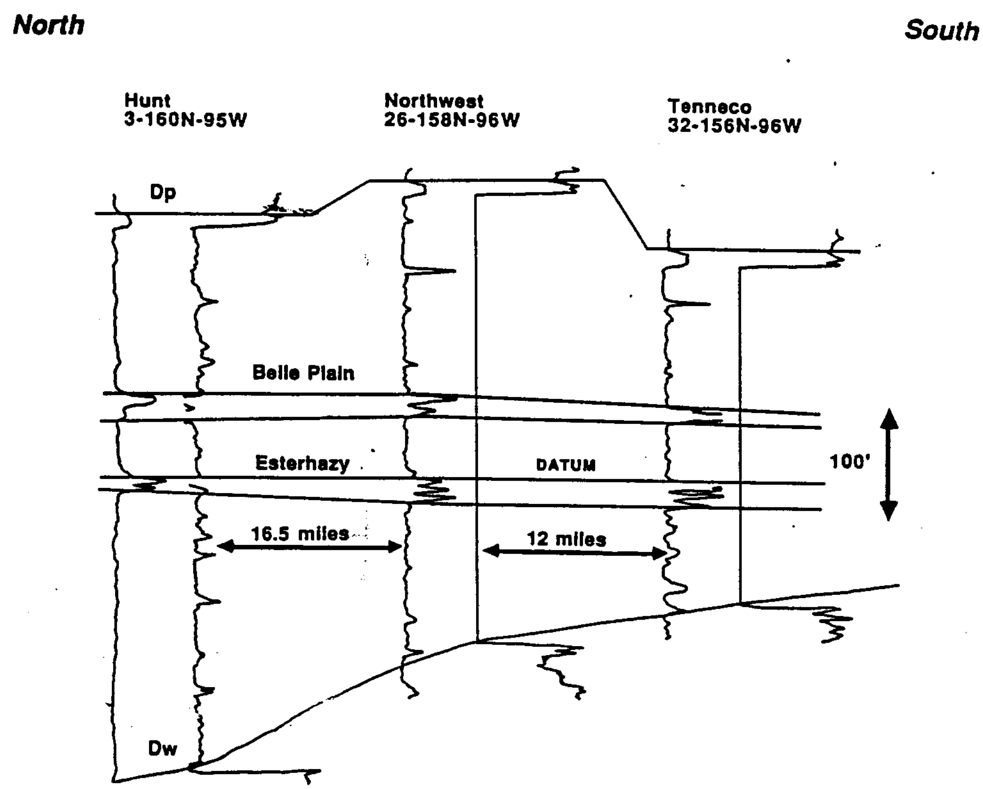


Fig. 20. Log cross section from near basin center towards basin margin displaying onlap of Prairie Formation onto Winnipegosis shelf; resulting in depositional thinning (Divide and Williams Counties., North Dakota).

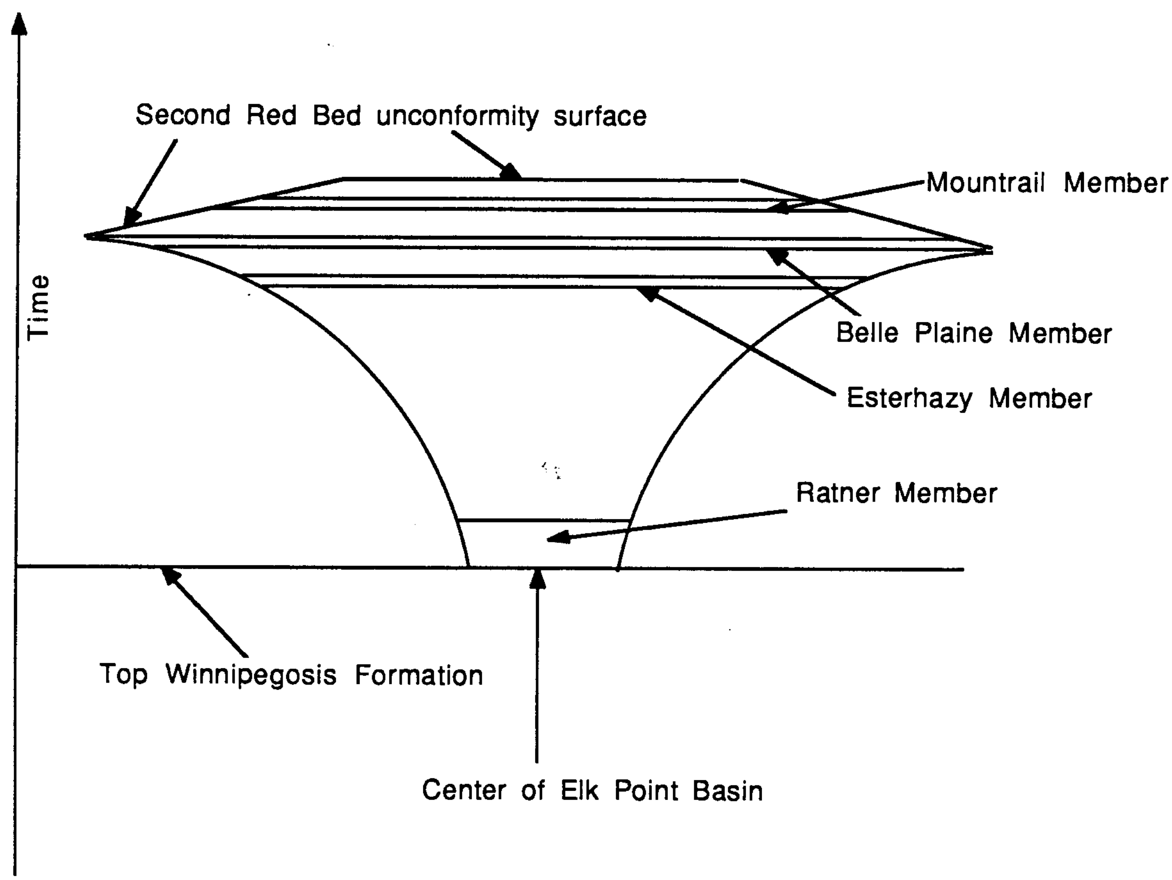


Fig. 21. Time/spatial diagram showing the temporal relationships between the Prairie and Winnipegosis Formations.

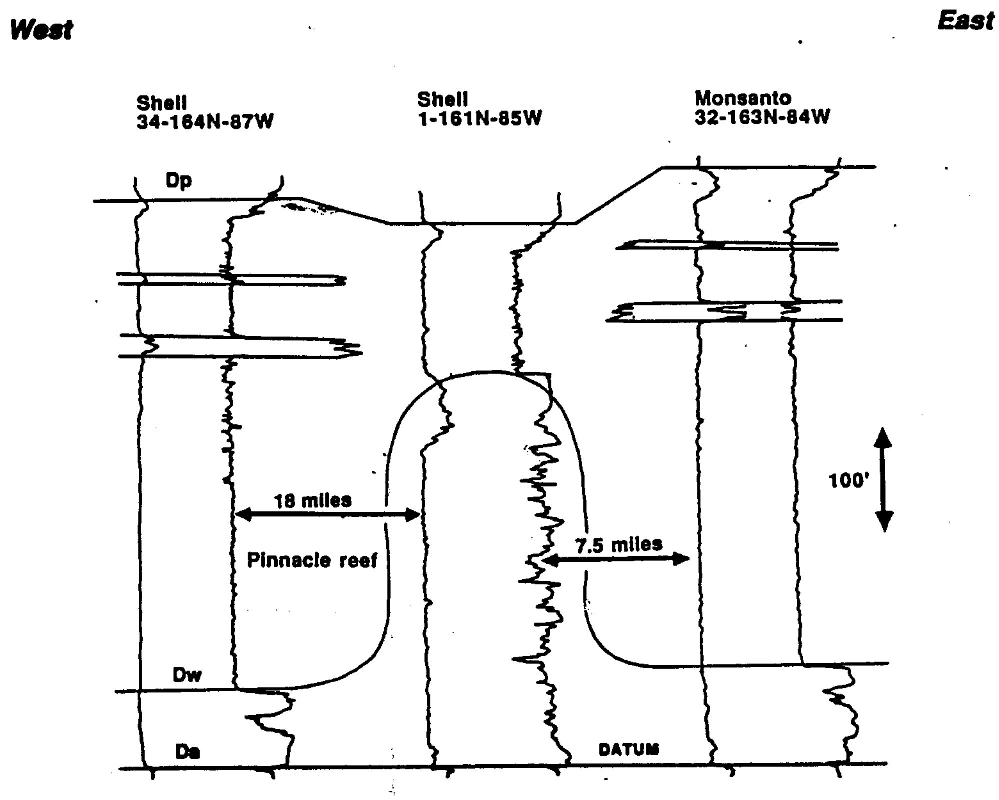


Fig. 22. Well log cross-section showing onlap of the Prairie Formation onto Winnipegosis pinnacle reef. Missing potash beds and thinning of section over reef is a result of dissolution (Renville County, North Dakota).

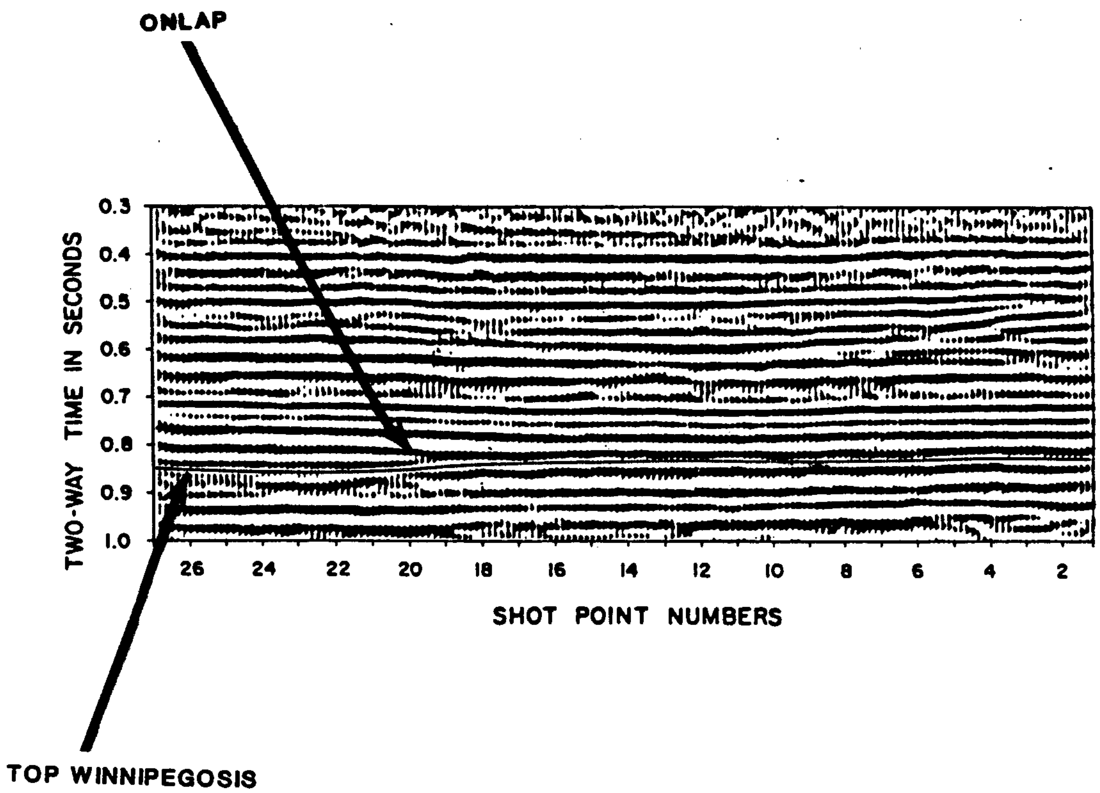


Fig. 23. Seismic response to Winnipegosis reef. Note onlap of Prairie Formation and structural sag caused by dissolution of Prairie salts and subsequent collapse (from Gendzwill, 1978).

Temporal Relationship between the Prairie Formation and Winnipegosis Formation Pinnacle Reefs

Because the Prairie Formation onlaps the Winnipegosis, it is generally interpreted as entirely younger than the Winnipegosis. However, the temporal relation between the Winnipegosis pinnacle reefs and the Prairie Formation has been controversial. The most common scenario invokes two-stages of deposition, a carbonate stage followed by an evaporite stage (*e.g.*, Fuller and Porter, 1969a, b). Reinson and Wardlaw (1971) concluded that most of the reefs were older than the Prairie Formation, but that a second stage of reef growth occurred after deposition of the Quill Lakes marker beds (post-Lower Prairie). Although Sloss (1969) supported synchronous deposition of carbonates and evaporites, he summarized the following arguments invoked to support two separate stages of deposition.

1. Organisms contributing to the accumulation of carbonate "buildup" cannot live in waters from which evaporites are precipitated.
2. The accumulation rate of salt is much greater than that of carbonate and only a few hundred to a few thousand years may be involved in major salt accumulations; therefore, carbonate and salt cannot be synchronous.
3. As a corollary, subsidence rates cannot keep pace with the sedimentation rates for salt; therefore, the deep basins in which salt has accumulated must have been present as topographic features before the start of salt deposition.
4. The euxinic sediments commonly intercalated with evaporites are evidence of deep water.
5. Breccia and conglomerate on the flanks of banks and reefs indicate an episode of exposure and erosion between carbonate-forming and evaporite-

depositing stages.

In support of synchronous deposition of carbonates and evaporites, Sloss (1969) cited work by Baltrusaitis in the Michigan basin, who traced a bentonite from shelfal carbonates into basinal evaporites. Similar evidence within the Williston basin was described by Wardlaw and Reinson (1971), who observed that a pisolitic weathering zone, approximately 30 feet thick, at the top of the Winnipegosis banks is penecontemporaneous with the offbank, interbedded, laminated, pelletal packstones, stromatolitic mudstones, pisolitic grainstones and Amphipora wackestones of the Quill Lake marker beds of the Prairie Formation in Saskatchewan (Fig.24). Wardlaw and Reinson (1971) concluded that "the [Quill Lake] marker beds overlie anhydrites and halite of the Whitkow Member, which appear to be younger than the main parts of the banks. Thus, there were at least two episodes of bank growth; one before the deposition of Whitkow anhydrite and halite, and one after."

Although depositional onlap of the Prairie Formation onto the pinnacle reefs accounts for most of the Prairie Formation thinning observed over the reefs (hundreds of feet), the absence of potash beds above the reefs and the presence of a thickened Second Red Bed are interpreted to indicate that partial dissolution also has occurred (Fig. 22). Dissolution of halite and potash salts results when undersaturated waters (with respect to KCl or NaCl) come into contact with salts and dissolve them. Several methods are successful at detecting salt dissolution.

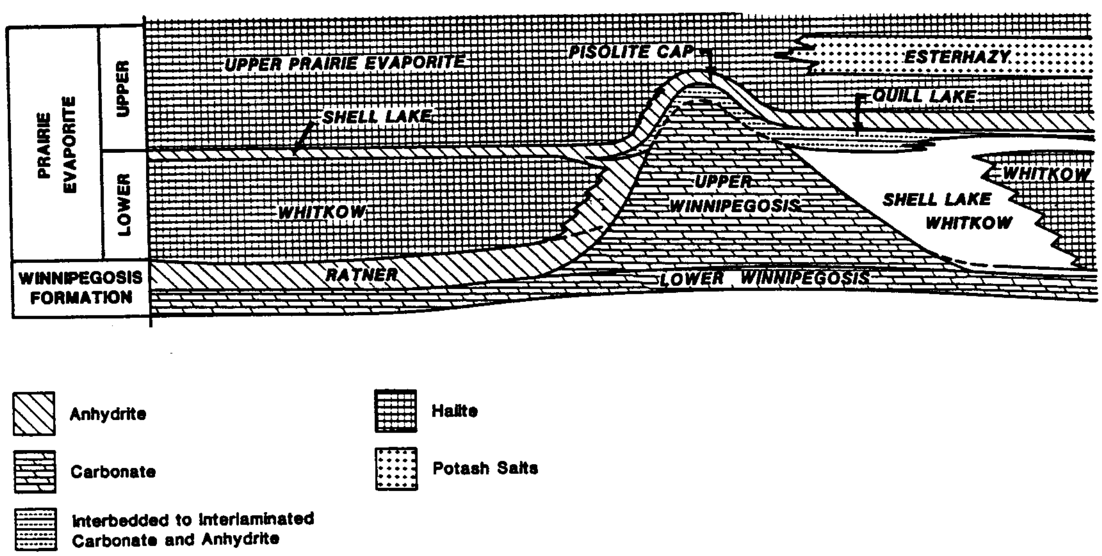


Fig. 24. Two-stage carbonate depositional model for the Prairie Formation and Winnipegosis pinnacle reefs (from Reinson and Wardlaw, 1971).

RECOGNITION OF SALT DISSOLUTION

Recognition of salt dissolution has been based primarily upon observing an absence of salt, recognizing presence of a collapse breccia, or inferring salt dissolution by observing compensating thicknening overlying areas suspected of salt dissolution. These conclusions are achieved through coring of suspected salt dissolution intervals, seismic interpretation and constructing isopach maps of intervals overlying salt dissolution areas.

Presence of collapse breccias

Polymictic breccias which have been stoped from overlying rocks into solution voids indicate collapse has occurred. Typically these breccias are gradational and fine upwards from a highly angular, well-cemented and poorly sorted breccia into a fine-grained material representing the insoluble residues (Figs. 25-27). Exposures of several of these breccia mounds, north of the Prairie subcrop in Saskatchewan, have been used as evidence to infer a greater depositional extent (beyond the current salt edge) for the Prairie Formation (Holter, 1969). Similar brecciation has been encountered in wells drilled into Prairie seismic lows thought to have resulted from solution collapse (DeMille, *et al.*, 1964) and in wells in central North Dakota east of the present-day salt edge (Anderson and Hunt, 1964). Unfortunately, lack of core and therefore lack of evidence from the Prairie to Winnipegosis interval precludes any direct observations. Most cores of the Prairie Formation are from Saskatchewan, where they are drilled to explore shallower potash horizons.

Isopach and isochron patterns

Anomalously thickened intervals above the Prairie Formation are often regarded as evidence of salt dissolution. Overthickened stratigraphic units are interpreted to result from

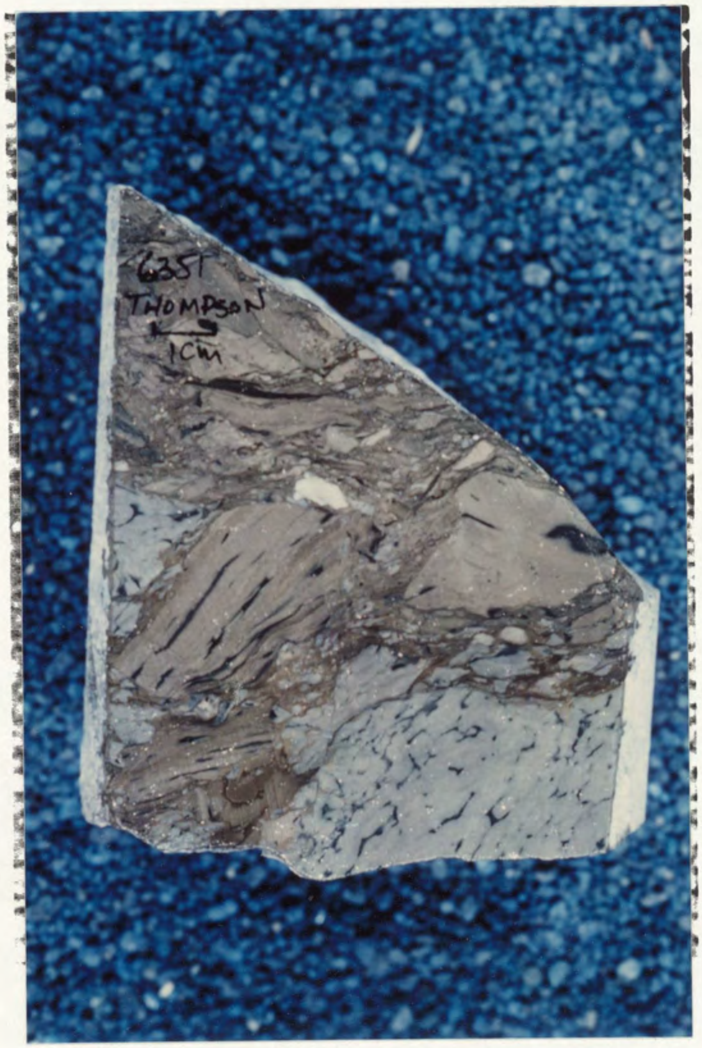


Fig. 25. Photograph of core located just above contact between Winnipegosis and the overlying collapse breccia. Note large, disoriented, polymictic clasts. (California Company - 1 Blanche Thompson, 31-160n-81w, Depth = 6,351').

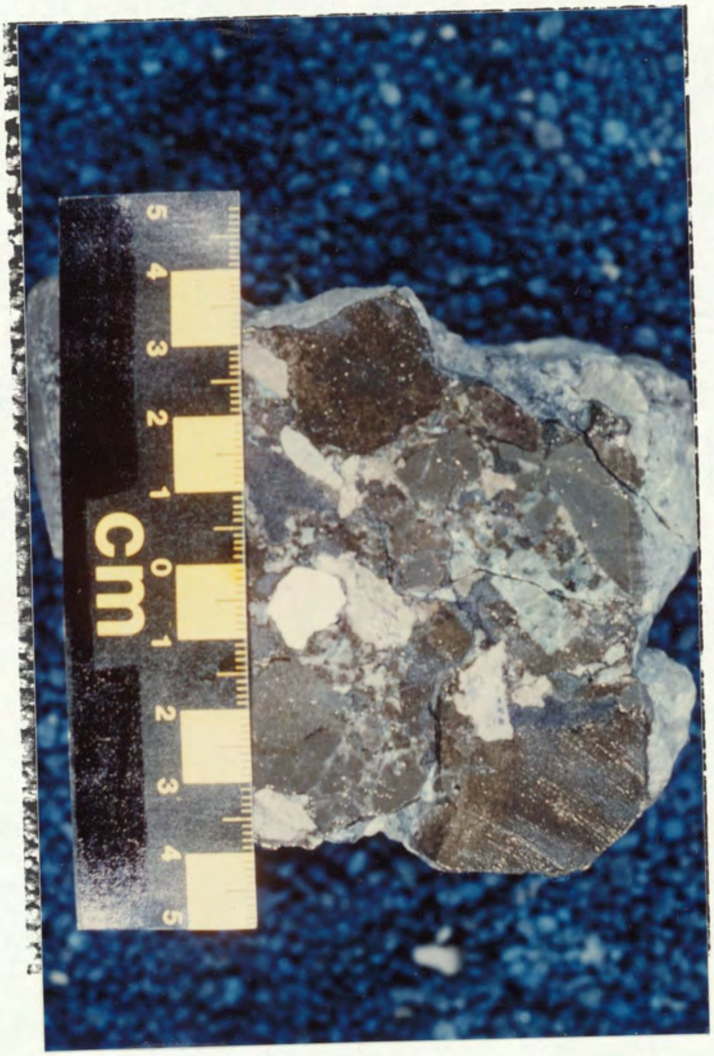


Fig. 26. Photograph of core of collapse breccia, located near the middle of the breccia. Note the smaller sizes of breccia fragments and less deformation than previous photo. (California Company - 1 Blanche Thompson, 31-160n-81w, Depth = 6,299').

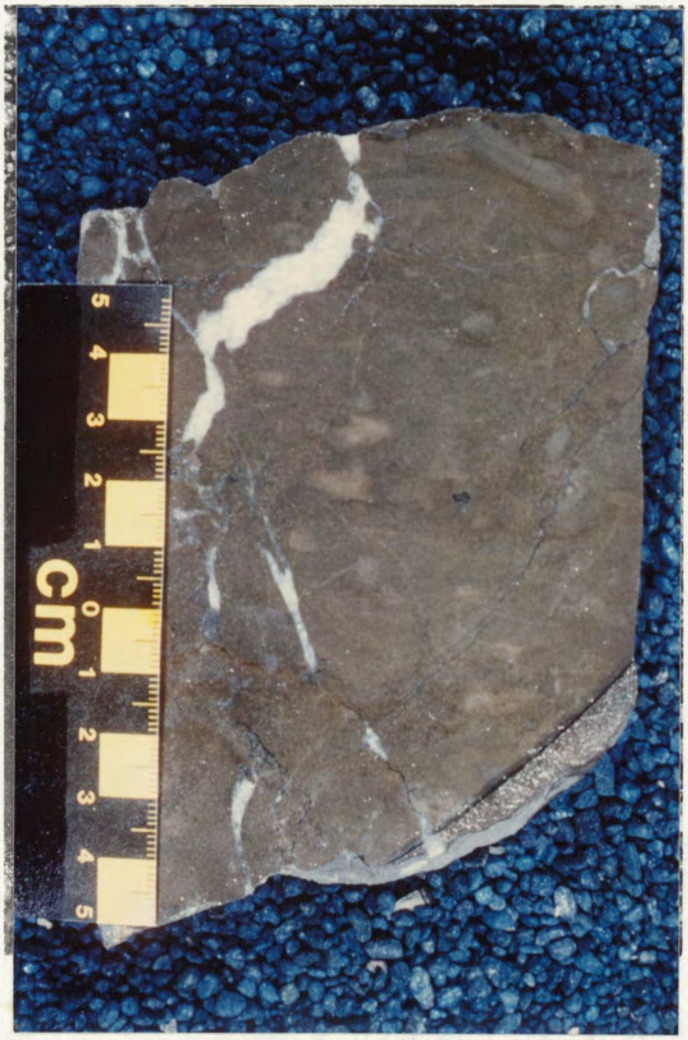


Fig. 27. Photograph of core located near the top of the collapse breccia. Deformation is limited to extensive vertical fracturing (anhydrite filled in this photo). (California Company - 1 Blanche Thompson, 31-160n-81w, Depth = 6,266).

dissolution of the Prairie evaporites with localized subsidence overlying the dissolution area and in which overthickened strata were deposited. Although this method is indirect, in that it assumes the Prairie Formation was present, it has proven useful and accurate in areas beyond the present salt edge and in areas of sparse sub-Prairie well control. Anderson and Hunt (1964) and Parker (1967) have documented thickening in overlying formations in several areas which are attributable to dissolution and fill. Langstroth (1971) has applied the same techniques using isochron (two-way travel time) data from seismic surveys. Using this technique, he mapped the dissolution front, as evidenced by localized isochron thickening in the units overlying the Prairie Formation, as it progressed through time.

Geophysical methods

Geophysical surveys have also proven effective in delineating collapse features within the main body of the salt (Rogers and Mattox, 1985). Where the salt is present, the high impedance contrast between the low density and low velocity salt as contrasted with the overlying and underlying high density and high velocity carbonates results in a high amplitude wavelet, which when missing, generally is indicative of the missing salt section (Fig. 28). Gendzwill and Hajnal (1971), Gendzwill (1978), and Rogers and Mattox (1985), have seismically documented features associated with dissolution phenomena. Commonly the dissolution features are interpreted to occur above faults and/or faulting in the underlying basement.

Gendzwill (1978) showed that dissolution-related structures occur over Winnipegosis reefs (Fig. 29). He interpreted structural drape or slumping of the overlying beds onto the reef as evidence of salt removal.

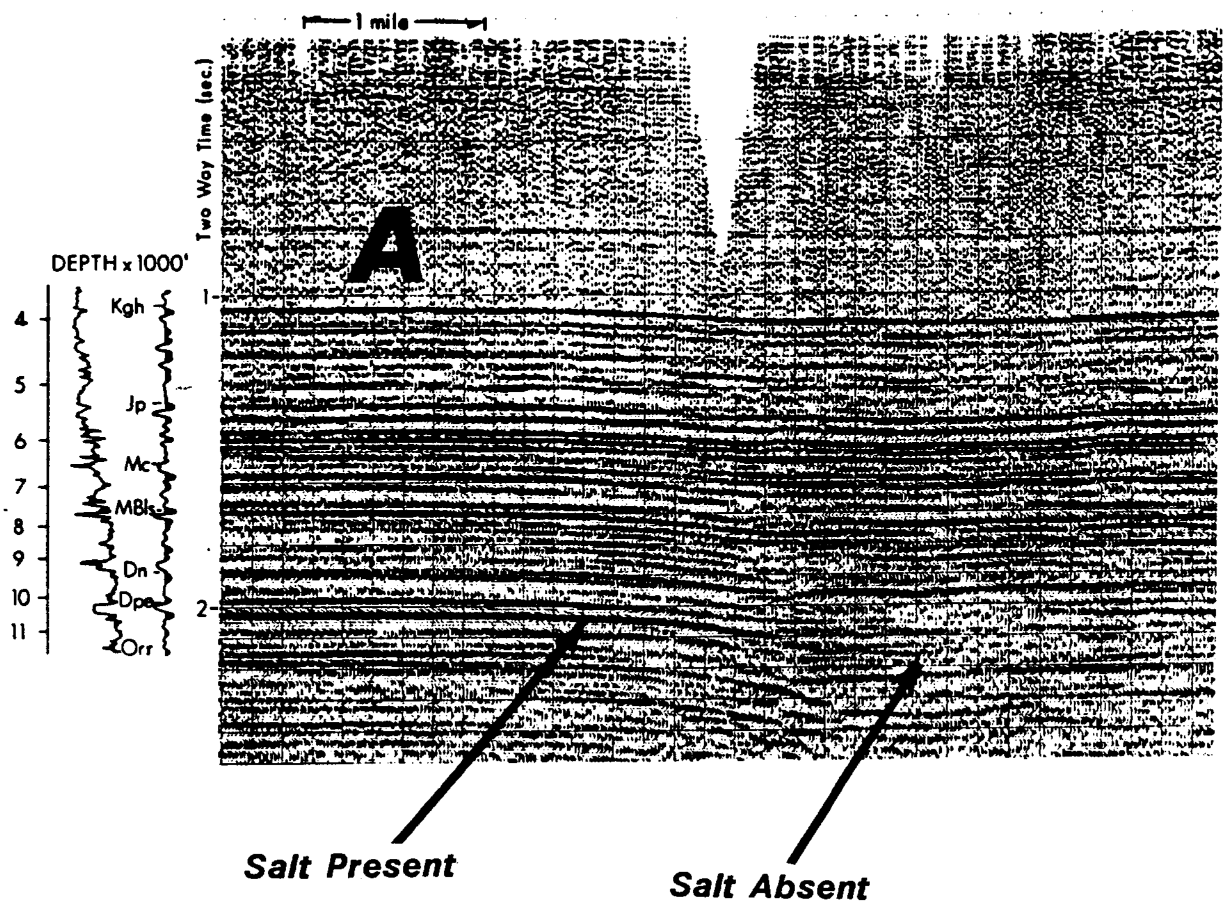


Fig. 28. Seismic response to dissolution. Prairie reflector truncates rapidly (after Rogers and Mattox, 1985).

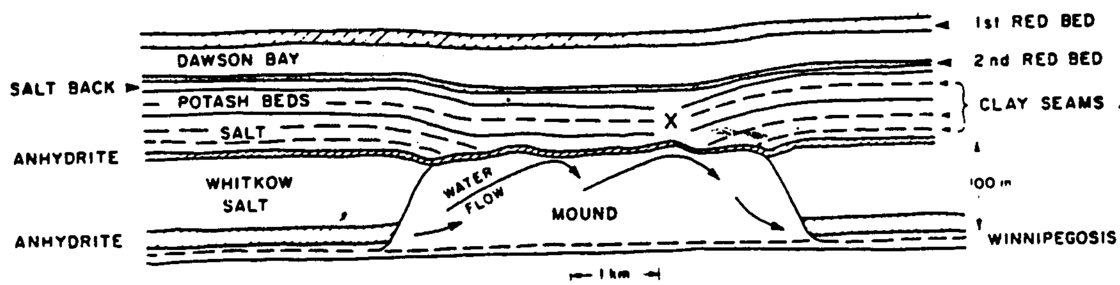


Fig. 29. Expected features resulting from dissolution if the underlying Winnipegosis were the aquifer causing dissolution (from Gendzwill, 1978).

DISSOLUTION MODELS

Three different dissolution models have been advanced to explain the Prairie Formation dissolution. Whereas all dissolution models utilize dynamic fluid movement, the driving forces and the mechanisms localizing dissolution differ.

Dissolution thinning by groundwater flow

Two potentiometric models have been advanced as the driving mechanism responsible for salt dissolution. The first model utilizes waters driven off during basin compaction and dewatering and may occur anytime during the history of the basin. The second dissolution model requires development of an active groundwater system and occurs primarily during periods of emergence when aquifer recharge occurs along the basin margins. Both of these mechanisms are interpreted as having contributed to dissolution of the Prairie Formation.

Compaction and dewatering model

Several authors (Illing, 1959, Jodry, 1969, Davis, 1972) have suggested that dissolution is caused by fluids driven out of the surrounding strata and into the adjacent, porous and permeable reef during burial and compaction. This process would result in an upward-directed water flux through the Winnipegosis and/or underlying section, which could dissolve the overlying evaporites of the Prairie Formation. Similar mechanisms have been invoked to explain increased velocity anomalies overlying Late Devonian Leduc reefs and surrounding Ireton shales in the Alberta basin (Davis, 1972).

Davis (1972), in a study of upper Devonian reefs in Alberta, noted anomalously high seismic velocity zones in the sediments adjacent to and overlying the Leduc reefs. He attributed this to diagenetic changes (primarily dolomitization, resulting in an increase in density) caused by connate fluids flowing out of the surrounding Ireton shales and up through the adjacent Leduc reefs during burial and compaction.

Finite-difference groundwater modeling (Hugo, 1985) of the Leduc reefs and the surrounding Ireton shales provided a theoretical solution to groundwater flow directions in proximity to the Leduc reefs and supports Davis' conclusions. Hugo's (1985) modeling demonstrated that the water driven out of the surrounding Ireton shales during compaction primarily resulted in a downward and upward-directed water flux and that only a much smaller flux went into the nearby reef. Waters driven down into the underlying, dolomitized and porous, Cooking Lake aquifer then flowed laterally into and away from the reef. Waters flowing into the reefs were then directed vertically by the reef facies (Fig. 30). By varying several parameters (pressure within the shale, pressure of the basal units, degree of shale anisotropy, reef and aquifer permeability), Hugo modeled a distance of influence in which fluid flow was affected by the reef. Within the Cooking Lake aquifer, the distance of influence was a maximum of a few miles within thin permeable units. Flow directly into the reef from the Ireton was confined to a distances in the hundreds of meters. Flow asymmetry was developed as a function of the reefs spatial geometry with respect to the underlying Cooking Lake aquifer. Additionally, Hugo's (1985) modeling indicated that the majority of the expelled water (85%) would be driven off at an early stage of burial, during the Paleozoic.

Surface water model

The development of an active groundwater system as the controlling mechanism for dissolution was advanced by Simpson (1978), who noted a coincidence between the periods of dissolution and the major periods of emergence or oscillatory eustatic modes

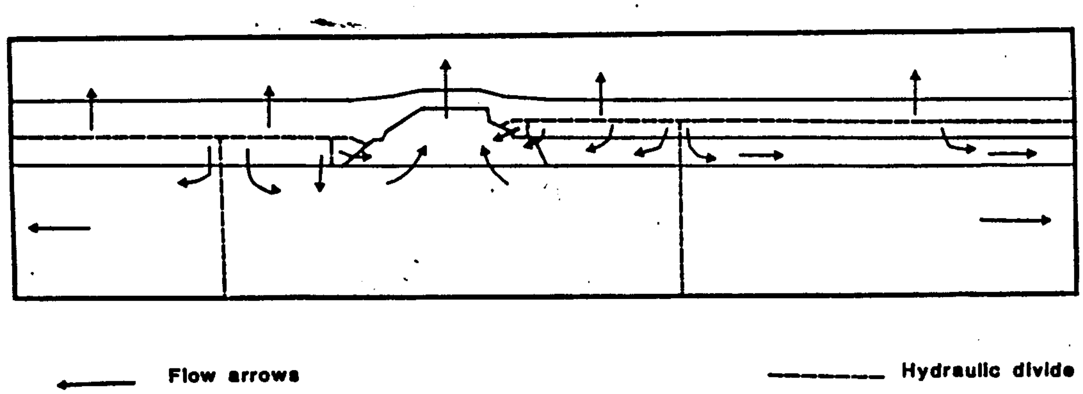


Fig. 30. Hypothetical model for groundwater flow related to the Leduc reefs and surrounding Ireton shales (after Hugo, 1985).

identified by Sloss (1963, 1974). Simpson (1978) hypothesized that during periods of emergence, an active groundwater system was created. The potentiometric system continued to be recharged by freshwater at the outcrop and the basinward flow of undersaturated water dissolved the Prairie salts.

Aquifers overlying and underlying the Prairie Formation are potential sources of waters for dissolution. However in order for dissolution to occur the aquifer must have been able to divert its flow into the Prairie Formation. Localization of dissolution may occur by tectonic fracturing or by focusing groundwater flow in the vicinity of Winnipegosis reefs.

Depositional facies controls on dissolution

Several authors (Baillie, 1953; DeMille *et al.*; 1964, Holter, 1969 Gendzwill, 1978, 1987) have suggested that Winnipegosis reefs have localized dissolution by focusing groundwater (potentiometric) flow into the porous reef facies. Additional impetus may have been derived from differential compaction and fracturing of strata overlying the reef, resulting in circulation of water downward and upward (DeMille *et al.*, 1964).

Several observations suggest that dissolution on the scale of tens of feet has occurred over all of the seven known Winnipegosis reefs within the U.S. portion of the basin (Appendix A - Winnipegosis Formation - pinnacle reef wells). In all cases the combined Winnipegosis/Prairie isopach thickness was less over the reef than over non-reef strata. Thinning of this interval has been interpreted to indicate dissolution (Gorrell and Alderman, 1968). Two additional items also support the contention that dissolution has occurred over the reefs: 1) the Second Red Bed, which when overthickened is actually the Second Red Bed plus the collapse fill resulting from dissolution plus residuals (mostly clay) from the salt dissolution process, is anomalously thick over all of the reefs, and 2) potash beds are not present over the reefs (Plate 10). Presence of an overthickened Second Red Bed on well logs (actually the Second Red Bed plus the collapse breccia) is common to all dissolutional wells in the basin. A core through this interval within a zone of dissolution was observed in the Calco - #1 Blanche Thompson (31-160N-81W). The anomalously thick interval, as observed in the core, consists of a collapse breccia and residuals of salt dissolution lying in sharp contact upon an undisturbed Winnipegosis Formation. In addition to the features described above, Gendzwill (1978) has described drape of the potash beds and development of an area of complex structural geology overlying a Winnipegosis reef which exhibited partial dissolution.

Dissolution over reefs manifested itself differently than dissolution over fractures. Unlike dissolution over fractures, dissolution over reefs resulted primarily in removal of the potash salts, leaving behind barren halite over the reefs. This suggests that the waters being focused through the reefs were saturated with respect to NaCl but undersaturated with respect to KCl. During potash dissolution, NaCl-saturated waters dissolve KCl and reprecipitate NaCl, resulting in an approximate 20% volume decrease (S.Adams, pers.comm., 1988).

Like the Leduc reefs, similar phenomena attributable to fluid movement could be expected to occur near Winnipegosis reefs. However, three differences would tend to decrease the Winnipegosis reefs' influence: 1) the surrounding strata are evaporites rather than shales, therefore upon compaction, lesser volumes of water would be available during basin dewatering and compaction; 2) waters derived from the surrounding evaporites would be saturated with respect to NaCl and therefore would not be capable of dissolving additional NaCl; and 3) the Winnipegosis laminites underlying the reefs are low permeability mudstones as evidenced by DST measurements (even where they are porous, DST's indicate low permeability), quite unlike the porous Cooking Lake dolomite (shelf platform facies) underlying the Leduc reefs (Hugo, 1985). Gorrell and Alderman (1968) noted missing potash beds over several reefs in Saskatchewan and also noted anomalous thinning in the regional Ashern to Second Red bed isopach over reefs. They attributed this evidence to indicate partial dissolution, where the more soluble potash beds and minor amounts of halite were preferentially dissolved leaving behind only halite. This character of partial dissolution, suggests that the waters moving upward through the reefs were nearly saturated with respect to NaCl but not to KCl, and therefore the potash beds were selectively removed.

Tectonic controls on dissolution

Coincidence between surface lineaments and faults with areas of salt dissolution has lead many workers to conclude that fracture permeability in strata overlying basement faults has been the primary means for allowing extraformational waters to contact and dissolve the Prairie Formation (Anderson and Hunt, 1964; DeMille *et al.*, 1964; Christiansen, 1967; Holter, 1969; Kent, 1968, 1974, 1987; Gerhard *et al.*, 1982; Rogers and Mattox, 1985). Many lineaments are interpreted to represent the surface expression of basement-derived faulting (Anna, 1986). Recurrent movement along basement faults has resulted in localized fracturing and faulting within the overlying strata (Fig. 31). Kent (1974) suggested that extensive fracturing along the lineaments has allowed vertical migration of hydrocarbons, thereby explaining the oil-bearing units in the lower Paleozoic (from the Winnipeg Formation) and the upper Devonian (from the Bakken Formation) strata. Similarly, water might have been vertically transmitted along the fractures, contributing to dissolution of

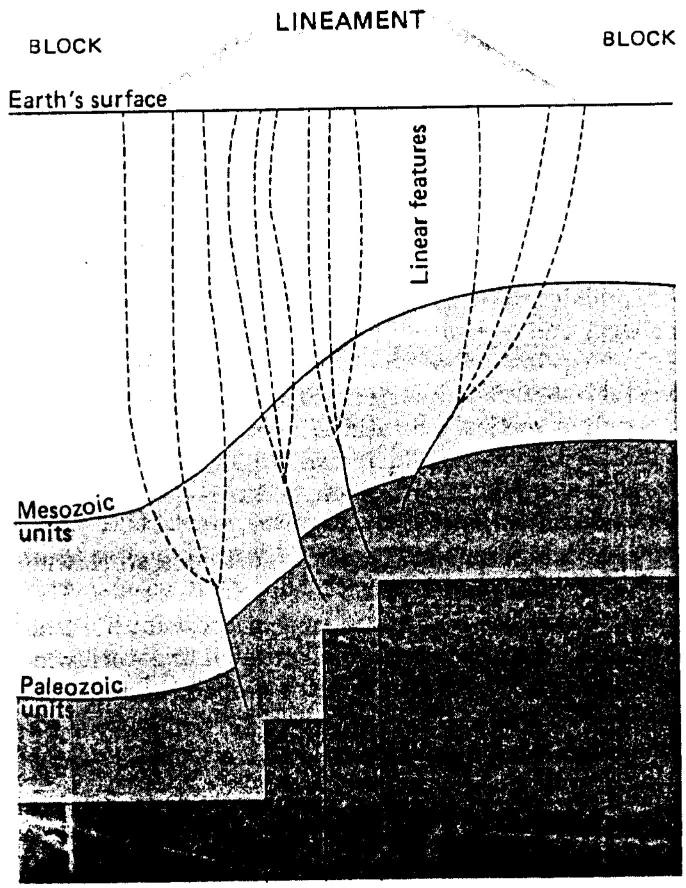


Fig. 31. Vertical fractures resulting from tectonic movement over basement faults (after Anna, 1986).

salts of the Prairie Formation during periods of potentiometric flow and/or basin dewatering. Lateral migration of fluids along these conduits would explain the linearity of many dissolution areas. Correlations between tectonic lineaments and areas of salt dissolution suggest that tectonic fracturing was responsible for localizing dissolution (Plates 7, 8, 9). Preferential dissolution along the northeast-trending lineaments seems common in the western portion of the basin as evidenced by a northeast-trending line through Tule Creek, Bredette and Outlook oilfields (all of which are salt dissolution features) and the the large dissolution area in Roosevelt County, Montana. The northeast-trending lineaments are nearly perpendicular to the potentiometric surface. This orientation enhances groundwater flow through the fractured, higher permeability rocks (Downey, 1987). Similar features would be expected along the northwest-trending lineaments on the eastern Prairie subcrop, however lack of well control precludes confirming this possibility.

Other tectonic elements may also localize water flow and Prairie dissolution. The eastern Prairie salt edge is nearly coincident with the Precambrian boundary between the Superior and Churchill provinces (Plate 9). Anderson and Hunt (1964) suggested that dissolution along the eastern Prairie salt edge is related to this tectonic feature. Gerhard *et al.* (1982) demonstrated that this feature acted as a basin hingeline through much of the Phanerozoic. Coincidence between the eastern Prairie Formation salt dissolution edge and this tectonically active area suggests that fracturing may play a prominent role in localizing dissolution in this area as well. Similarly, minor dissolution, probably related to fracturing, is also present along the Nesson anticline (Plate 8, 15).

Model for flow along fractures

Although surface lineaments and areas of dissolution commonly are coincident, the sometimes diffuse character of dissolution along fractures may be explained by examining groundwater flow paths in fractured rocks. Anna (1986) suggested that non-linear flow occurs along fracture systems when basement blocks are offset resulting in termination of lineaments (Fig. 32). When this occurs, groundwater flow is preferentially deflected along the truncating fracture. If several minor deflections were to occur along a major fault zone, the linearity of salt dissolution would probably be diminished. This phenomena may help explain the somewhat diffuse character of the dissolution in northeastern Roosevelt and southeastern Sheridan Counties, Montana, which is located along the Brockton-Froid lineament (T 29 &30N, R 57&58W, Plates 7, 8, 9). Further development of this flow model into a third dimension may also explain how aquifers overlying or underlying the Prairie can provide the waters responsible for dissolution.

Figure 33 is a block diagram illustrating intersecting lineaments. The arrows indicate the flow paths along the fractured lineaments. When lineament #1 is terminated by lineament #2, flow is deflected horizontally along lineament #2 (Anna, 1986). I propose, that at these intersections, the flow is also deflected upward and downwards along the terminating lineament. Depending upon the relative timing of dissolution, whether during shallow or deep burial, this model allows aquifers both overlying and underlying the Prairie Formation to provide the water for dissolution.

In summary, several different types of dissolution-related and deposition-related processes controlled thinning of the Prairie Formation. The responses to the different processes are unique and recognizable. These differences provide the basis for differentiating between depositional and dissolutional controls on observed thickness variations of the Prairie Formation.

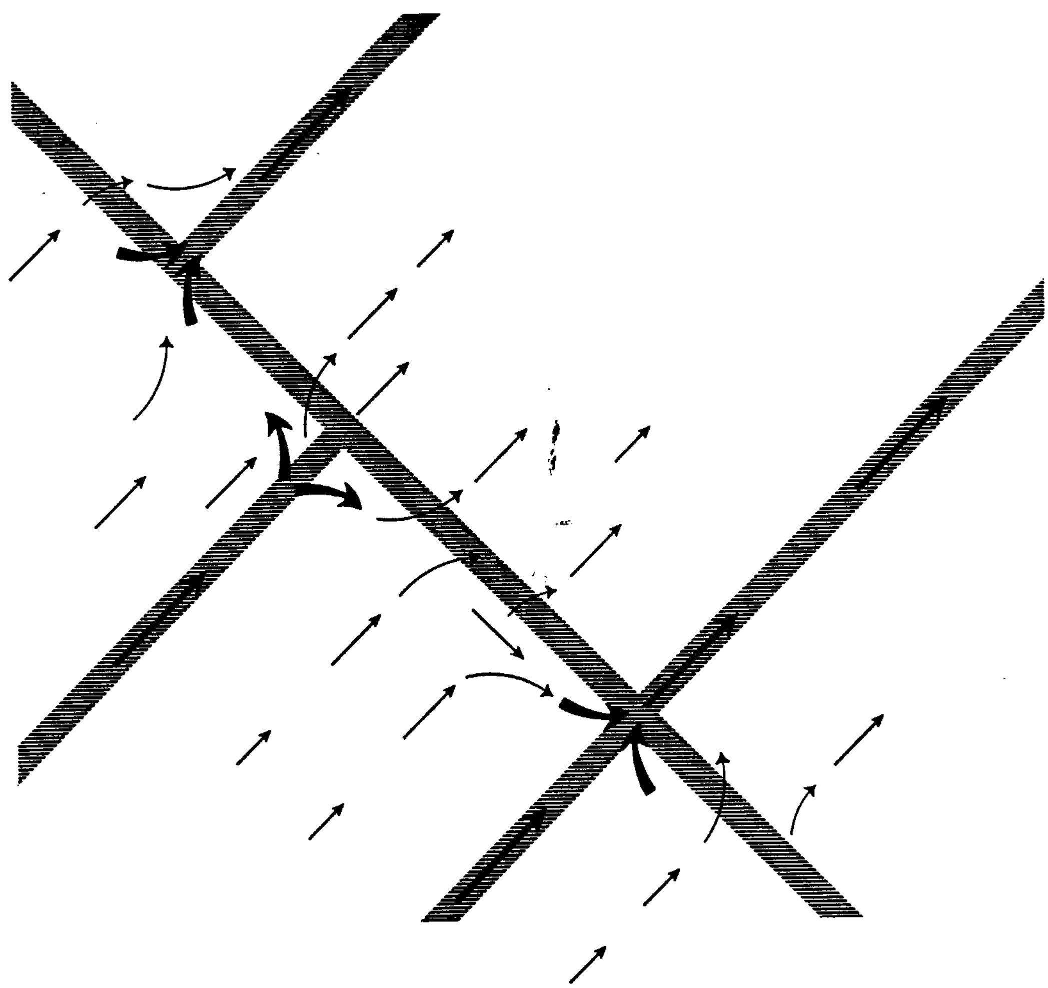


Fig. 32. Theoretical ground-water flow paths in a fractured aquifer. Arrows indicate possible flow directions; size of arrows is proportional to amount of flow. Shaded arrows are theoretical fracture zones (after Anna, 1986)

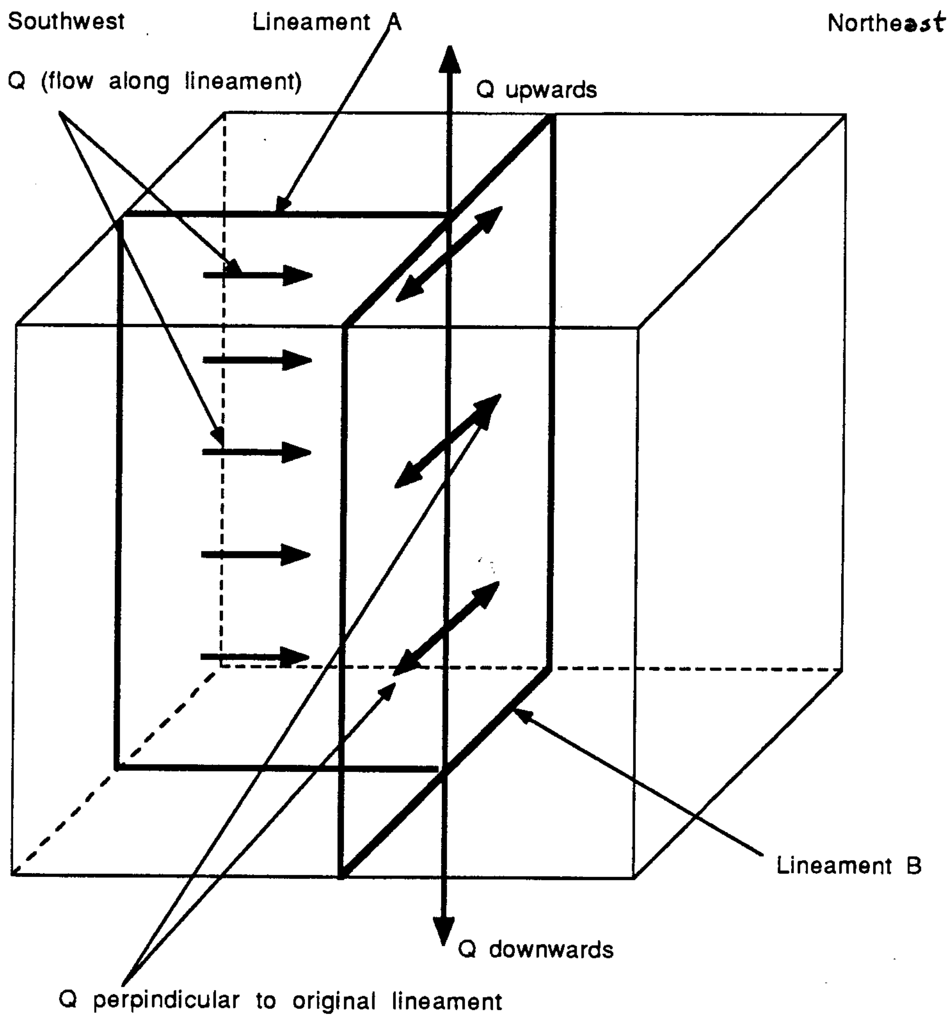


Fig. 33. Block diagram of theoretical ground-water flow paths in a fractured rock, showing vertical components of flow deflection at block boundaries.

DIFFERENTIATING BETWEEN DEPOSITIONAL AND DISSOLUTION THINNING

Dissolutional thinning over basement faults is usually abrupt, with up to several hundred feet of halite abutting a much thinner zone of collapse breccia (Fig. 34). Correlations across these contacts in areas such as the Roosevelt County, Montana salt void in T 29 &30N, R 57&58W (Plate 14) and along the northern Nesson anticline (10-161N-98W, Plate 15), show a truncation of the Prairie Formation from the top down. This relationship is interpreted to indicate that the dissolution process has occurred from the top of the formation downward, suggesting that the aquifer(s) supplying the waters responsible for dissolution overlie the Prairie Formation. This does not preclude waters from moving upward during later stages of burial, after the salt was breached, but it does show that the majority of the dissolution was initiated from above. Similar observations within the Delaware basin were interpreted by Maley and Huffington (1953) to indicate that the overlying aquifers were the source of waters resulting in dissolution of the Permian Castile and Salado Formations.

As a consequence of salt dissolution, the overlying strata collapsed into the dissolution void. This resulting collapse breccia is reflected in the well log signature as an anomalous thickening in the Second Red Bed (Plates 10, 11, 15).

The dissolution seen over the lineaments contrasts with dissolutional thinning over Winnipegosis reefs which resulted in only partial dissolution. Dissolution over the reefs was recognized by the loss of potash beds over the reefs, thickening of the Second Red Bed and localized thinning of the Prairie to Winnipegosis interval. Because of the loss of the potash horizons, the direction of water movement responsible for the partial dissolution could not be ascertained directly. The hypothesis formulated to explain the dissolution over the reefs suggests that waters would be directed upwards through the Winnipegosis reefs

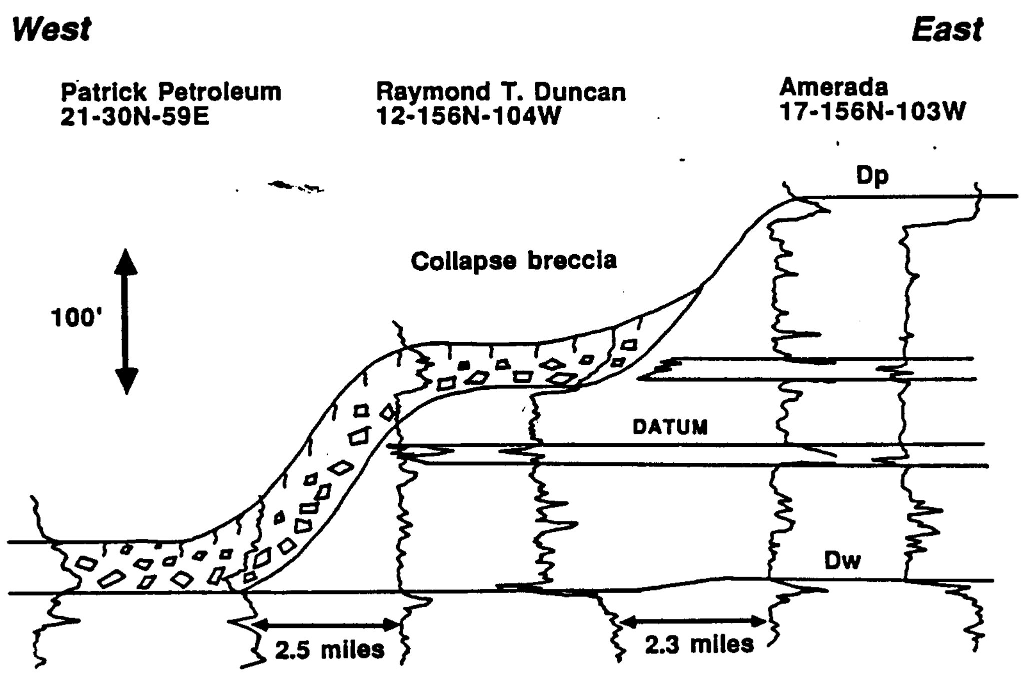


Fig. 34. Log cross section across Roosevelt County, Montana salt void showing top to bottom nature of dissolution. Note thickening of Second Red Bed due to formation of collapse breccias.

during burial and basin dewatering. As they moved upward these waters would either be saturated or become quickly saturated with respect to NaCl as they flowed up through the Prairie salts but they would still remain undersaturated with respect KCl. This model would explain the preferential dissolution of the potash over the pinnacle reefs.

In contrast, depositional thinning of the Prairie Formation occurs by depositional onlap onto the Winnipegosis. Depositional thinning gradients are low, except over pinnacle reefs, where thinning occurs over short distances (Plate 10). In cross-section this geometry is indicated by thinning below the Belle Plain Member datum. Onlap of the Prairie Formation onto the Winnipegosis reefs also results in a similar geometry.

INTERPRETATION OF ISOPACH MAPS

Anomalously thin areas of Prairie salt were observed on the isopach maps (Plates 7, 8, 9) and were evaluated to determine the cause(s) of thinning using the criteria established above. The first test was to locate thinning over the Winnipegosis Formation pinnacle reefs. Currently, there are six penetrations (Appendix A). These wells are all confined to the eastern portion of the basin (Plates 3, 6, 9), seaward of the eastern shelf/slope break. Winnipegosis reefs can be recognized by their very thick isopach values surrounded by thin "starved basin" deposits (Plates 8, 9). Prairie Formation thinning over the reefs occurs primarily by depositional onlap, with minor amounts of dissolution thinning.

The majority of thinning of the Prairie Formation is caused by depositional onlap onto the pre-existing Winnipegosis seafloor topography. Depositional onlap results in a bottom to top thinning pattern (Plates 10-13). Prairie salt deposition upon the Winnipegosis shelf is characterized by a relatively low thinning gradient (Plates 3, 6, 9). The greatest topographic relief occurs along the eastern and western Winnipegosis shelf/slope breaks.

Thinning of the Prairie Formation occurred as the "deep basin" filled and evaporite strata onlapped the shelf margins, reflecting a decrease in the basinal accommodation potential.

Deposition of the Prairie and Winnipegosis Formations also seems to have been influenced by tectonic lineaments within the basin. Although the thickness changes are subtle, they are detectable. In western North Dakota and eastern Montana, there is a conspicuous change in the strike of the Prairie and Winnipegosis Formations isopachs, from a northwest trend towards a northeast trend, paralleling the Brockton-Froid lineament (Plates 1, 2, 4, 5, 7, 8). These changes suggest that the lineaments were acting as fault boundaries with minor reactivation during deposition of the Prairie and Winnipegosis Formations.

Similar evidence of tectonic influence upon deposition can be inferred from the location of the Winnipegosis shelf/slope break in central and eastern North Dakota (Plates 2, 3). The western break, as determined by rapid thinning within the Winnipegosis, is located along the eastern margin of the Nesson anticline, suggesting that this structure was active during the Middle Devonian. Similarly, the eastern margin shelf/slope break lies approximately on the contact between the Churchill and Superior Provinces (Plate 3). Development of a thicker shelf facies to the east suggests that this feature may also have influenced deposition.

Another anomalous area of depositional thickening occurs at the southern end of the Prairie Formation subcrop (145n, 99w to 144n, 93w), where the isopach of the Prairie Formation (top of Second Red Bed to top of Winnipegosis) reverses the thinning to the south trend and begins thickening to the south. This thickening is manifested in an increased thickness of the Second Red Bed. No Prairie salts are present in this area. The presence of a thicker Second Red Bed section may result from development of a thicker paleosol on the Winnipegosis carbonates or from collapse of Prairie evaporites. No wells have been cored through this interval in this area of the basin and the cause remains undetermined. Thickening to the south suggests that a separate shallow sub-basin may have developed.

Thinning by dissolution is also present in the study area and was evaluated using the criteria established above. The areas of dissolution thinning within the present-day salt limit are denoted by a "hexagon" with the letter "D" adjacent to it (Plates 7, 8, 9). Dissolution thinning is also present along the eastern and western margins of the basin (Plates 7, 8, 9). It is expressed as the area between the postulated "original depositional limit" and the present-day salt edge. Dissolution thinning is characterized by a top to bottom thinning pattern and a large thinning gradient.

Tectonic influence upon dissolution is more difficult to assess. No strongly linear patterns of dissolution were recognized, however the fact that the dissolution features are coincident with several tectonic features, including the Brockton-Froid fault system, the Churchill-Superior province contact and along the Nesson anticline, suggests that they may be tectonically related (Plates 7, 8, 9). The largest of the dissolution features within the present-day salt limit are located in northeastern Montana and lie along a northwest trending line. I believe that these dissolution features may be caused by truncation of northeast-trending lineaments (bringing fresh water into the basin) and the resulting deflections of water flow at northwest trending lineaments. A northeast trend of dissolution is suggested by the salt thinning near the large dissolution feature in Roosevelt County, Montana (T 29 &30N, R 57&58W).

ESTIMATION OF ORIGINAL PRAIRIE FORMATION DEPOSITIONAL LIMIT

By applying the differentiating criteria discussed above, the nature of the present-day salt edge was interpreted and where it was judged to be dissolutional in origin, an estimate of the original depositional position was made. The eastern and western edge of the Prairie salt are dominantly dissolutional in origin, whereas the southern limit is predominantly depositional in origin. Where the Prairie Formation limit is dissolutional in origin, a proposed original depositional limit was estimated by projecting the original depositional thickness using depositional thinning gradients established from the basin center outwards (Plates 7, 8, 9). This technique worked well along the western basin margin. Along the eastern margin this technique was used to construct the conservative estimate for the Prairie Formation depositional limit. However, several observations suggested that this estimate was too conservative. Therefore, a less conservative depositional limit for the Prairie Formation was estimated, based upon the presence of thick Second Red Bed sections in wells outside the present-day salt limit.

PETROLEUM GEOLOGY

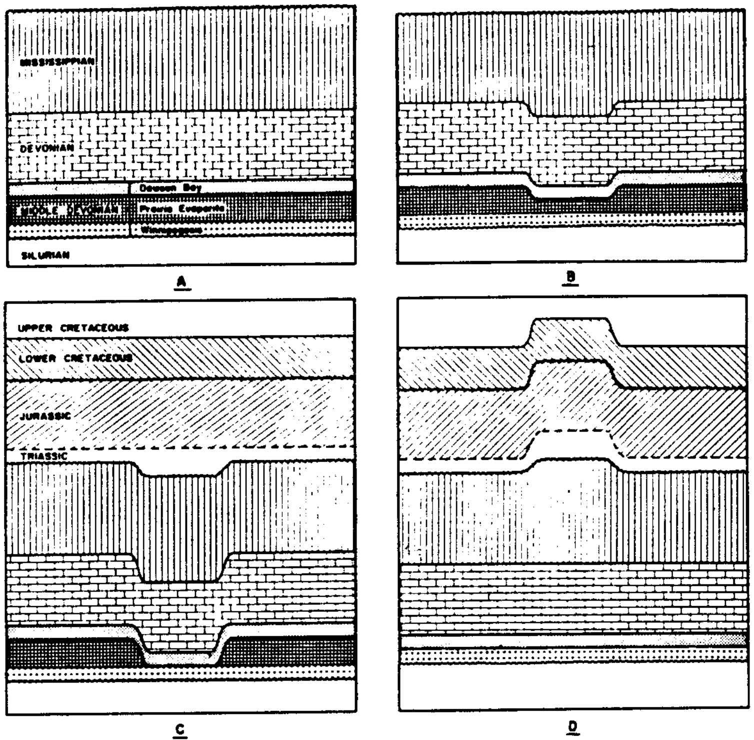
Salt dissolution is responsible for localizing both structural and stratigraphic traps within the Williston basin. Two-stage salt dissolution (Swenson, 1967, Gorrell and Alderman, 1968) has been suggested as the causal mechanism responsible for trapping at several western Williston basin oilfields including, Tule Creek (Roosevelt County, Montana), Outlook (Sheridan County, Montana), and Target (Roosevelt County, Montana).

Two-stage salt dissolution structures occur when an initial stage of dissolution occurs and the ensuing anomalously thick stratigraphic section is deposited within the depression

(Fig. 35). Continual burial of the feature creates a downward convex structure. At a later time, removal of the surrounding salt occurs and the surrounding regions subside (collapse) around the earlier feature, which is now manifested as a "false structure" with drape folding over the anomalous thick created by the earlier localized dissolution. Oil fields resulting from drape over early salt dissolution features generally are characterized by flat tops with relatively steep sides. Most oil fields of this nature are located in a small area in Roosevelt County, Montana (Fig. 36), for example Tule Creek, Tule Creek East, Volt, Benrud, Benrud East, Benrud Northeast, and Red Fox. This area lies outside of the current Prairie salt edge. The predicted thickness of Prairie salt originally in this area is approximately 50 feet, equal to the average closure on most of the two-stage, dissolution-related fields. These fields all produce from dolomites with intercrystalline porosity developed within the upper Devonian Nisku Formation (approximately 930 feet above the Prairie Formation).

Early hydrocarbon migration is not a prerequisite to form accumulations. Oil expulsion within the Bakken Formation source rocks began in the Late Cretaceous (75 Ma) and basin flank fields were not filled until the oil had migrated from the mature central basin (Webster, 1984). By using the projected original salt limit map (Plates 7, 8. 9), a north-south trending fairway (Plate 9) between the present-day and original depositional salt limits is defined. This fairway could host potential two-stage salt dissolution structures. Most of this area is lightly explored in comparison to the majority of the Williston basin.

Dissolution of the Prairie also is responsible for creating fields which are primarily formed by enhanced fracture permeability. Collapse-related fracturing of the overlying reservoir rock decreases away from the dissolution area creating a lateral seal without the necessity of a facies change or structural decrease in elevation. The Target and Red Bank



Formation of anomalous and coincident Mississippian and Triassic thicks. A, Post-Mississippian erosion; B, Later stage during Mississippian erosion and peneplanation with concurrent, local, partial removal of Prairie Evaporite salt; C, Aspect of strata subsequent to Triassic deposition and prior to removal of remaining Prairie Evaporite salt. Diagram indicates continued removal during Triassic deposition at same locality as in B; D, Final stage, following solution of remaining Prairie Evaporite salt

Fig. 35. Scenario for development of two-stage salt dissolution. Process results in formation of productive fields overlying overthickened fill (after Swenson, 1967).

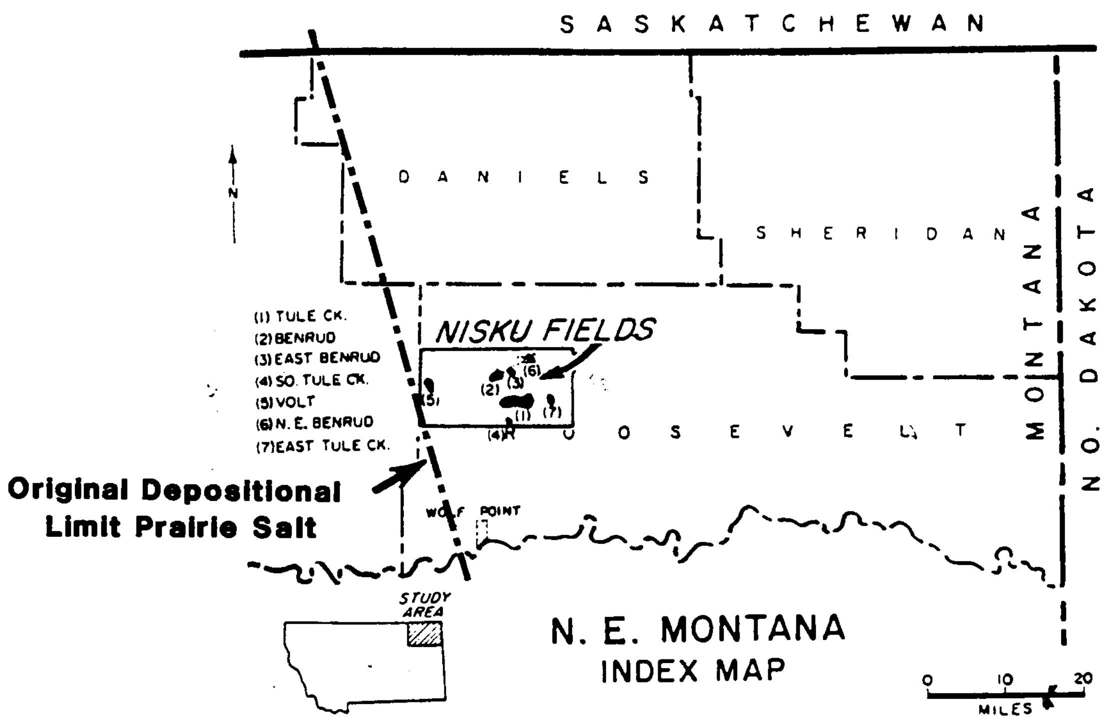


Fig. 36. Location of two-stage salt dissolution fields, Roosevelt County, Montana. Productive reservoir is the Upper Devonian Nisku (Birdbear) Formation (modified from Swenson, 1967).

fields are examples of these types of features (Rogers and Mattox, 1985) . As in the case of the dissolution "turtle" structure fields, a large area of the basin has the potential for fracture-related trapping. Areas along and a moderate distance outside the current Prairie salt edge are favorable areas for trapping, as are dissolution areas along the major lineaments. Although these fractured fields may be more difficult to locate, the size potential may be significant enough to warrant further exploration interest.

Dissolution of the Prairie Formation salts is also responsible for creating a third type of trap, a stratigraphic trap. Dissolution of the underlying Prairie Formation along a sinuous dissolution front may help to localize facies distributions in the overlying rocks. An example is the Wiley field, with Mississippian production, located in Bottineau County, North Dakota (T161N, R81W&82W). In this area Prairie dissolution may have created a subtle paleostructure which enhanced the development of a loferitic limestone reservoir facies (Gerhard *et al.*, 1978; Gerhard, 1986). Salt dissolution may also have been responsible for development of a local reentrant in the Mississippian (Glenburn Member) coastline (Fig. 37), localizing the porous carbonate reservoir facies against a updip evaporitic sabkha facies (Davis, 1985; Reeve, 1986). Similar features have been interpreted along and outside the entire eastern present-day Prairie salt edge (Langstroth, 1971). By placing emphasis upon tracking the eastern salt edge through time, this methodology should prove an effective exploration tool for helping to predict the paleo-Mississippian shorelines (Langstroth, 1971). Application of this technique to the Mississippian prospects along the western edge of the basin should not prove as useful because the Mississippian shoreline system was located much further west of the Prairie salt edge and extended into the Big Snowy Trough of western Montana (Peterson and Maccary, 1987). However, Prairie salt dissolution may have influenced facies changes

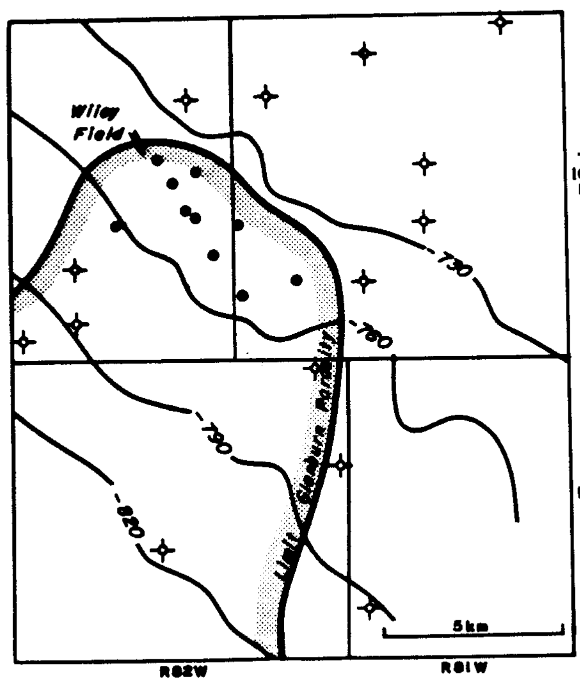


Fig. 37. Wiley field, Bottineau County, North Dakota. Dissolution of the underlying Prairie Formation may have been responsible for creating a topographic high which developed a subaerial loferite reservoir facies. Dissolution may have also created a local re-entrant which localized the marine reservoir against a non-porous, updip, supratidal facies within the Glenburn Member of the Mission Canyon Formation (modified after Davis, 1985 and Reeve, 1986).

within other hydrocarbon productive formations.

Although it has not been considered in this sense, the Prairie Formation may also be a seal to vertical migration within the Williston basin. Meissner (1982) suggested that the Triassic Spearfish production within the eastern portion of the basin all occur east of and outside of the erosional limit of the Charles salts. He argued that vertical migration is possible only outside the limit of the Mississippian (Charles) salts, and therefore sourcing from the underlying Bakken Formation is not achieved until the salts have been removed. Similar reasoning could be applied to the Prairie salts. The known early Paleozoic source beds, including the Winnipegosis (Wardlaw and Reinson, 1971) and Winnipeg (Dow, 1974), (Williams, 1974), both underlie the Prairie and therefore their ability to source the late Devonian and younger reservoirs may be precluded by lack of a vertical migration pathway, except in areas of salt absence through dissolution.

CONCLUSIONS

1. Four genetic sequences were recognized within the Prairie Formation, three complete and one incomplete. Correlation of the Prairie intraformational sequences was accomplished by recognizing asymmetric brining and/or shallowing upwards nature of the cycles.

2. The Prairie Formation displays an onlap geometry; deposition began initially in the deepest portion of the Winnipegosis basin and then onlapped the shelf.

3. Within the basin center, the lowermost portion of the Prairie, the Ratner anhydrite, is transitional with the underlying laminites of the Winnipegosis Formation. This contact becomes disconformable, with an increasing hiatus, towards the basin margins.

4. Depositional thinning, which occurs by onlap, displays thinning from the base of the formation upwards.

5. Dissolution related to fracturing is manifested by top to bottom truncation of the Prairie Formation. Recognition of the dissolution process as occurring from the top downward suggests that formations overlying the Prairie Formation were the aquifers supplying the waters responsible for dissolution.

6. Prairie Formation thinning over Winnipegosis reefs is caused by onlap of the Prairie onto the underlying reefs and by dissolution localized by the reef facies during burial and compaction. To date, only partial dissolution has been recognized over the Winnipegosis

reefs, where the dissolution process has preferentially removed the overlying potash beds. A proposed model suggests that NaCl saturated waters are focused by the reef facies and move upwards through the reef and overlying salt section, preferentially dissolving the potash beds.

7. Depositional thinning and thickening of both the Prairie and Winnipegosis Formations is controlled by local tectonic features. This is manifested in abrupt changes in the strike of isopach values in the vicinity of tectonic features.

8. Depositional thinning gradients established from the basin center outwards and the presence of overthickened Second Red Beds permits estimation of the original depositional limit of the Prairie Formation.

FUTURE WORK

As in most investigations, several new questions were formulated in this study. Below are some of the questions which need to be addressed in order to better understand the salt dissolution process.

1. Salt dissolution over the Winnipegosis reefs has preferentially removed the potash leaving behind barren halite. A core through this interval may explain whether this process results in recrystallization, flowage, or collapse of the salt, resulting in a salt breccia.
2. Groundwater modeling in the vicinity of Winnipegosis reefs and near fracture systems and intersections of fracture systems would provide greater insight into fluid movements responsible for dissolution. Inasmuch as this process may change through time, it should be investigated throughout the basin's burial history.
3. Since Winnipegosis reefs within the central basin localize dissolution, a regional potentiometric study could determine whether the surounding laminite facies is capable of transmitting fluids to the reefs. Inasmuch as the laminites are thought to be the source rocks for the reefs, this question could also address the petroleum potential, via the migration standpoint, of the Winnipegosis reefs.
4. A rock mechanics study of the salt dissolution process and the ensuing collapse fill, should help in understanding the relative timing between dissolution and fill.

5. This study suggested that a relationship may exist between amount of collapse fill and the original volume of salt. If a ratio exists between the amount of fill and the amount of salt removal, this could prove a valuable tool to estimating the original depositional limits.
6. A regional look at the timing of dissolution would help to ascertain the directions of fluid movement within the basin. Inasmuch as many petroleum trap types are related to salt dissolution, knowledge of the timing throughout the basin may suggest potential traps types in areas not currently considered prospective.
7. Seismically evaluate tectonically-related dissolution areas to determine if salt edge is linear. This would provide further evidence for fracture-controlled dissolution.

REFERENCES CITED

Ahern, J.L., and Mrvicka, S.R., 1984, A mechanical and thermal model for the evolution of the Williston Basin: Tectonics, v. 3, n. 1, p. 79-102.

Anderson, R.Y., and Kirkland, D.W., 1966, Intrabasin varve correlation: Geol. Soc. of America Bull., v. 77, p. 241-245.

Anderson, S.B., and Hunt, J.B., 1964, Devonian salt solution in north central North Dakota: *in* Third International Williston Basin Symposium, p. 93-104.

Anderson, S.B., and Bluemele, 1984, Oil exploration and development in the North Dakota Williston Basin: 1982-1983 update: North Dakota Geological Survey Misc. Series 65, 34p.

Anna, L.O., 1986, Geologic framework of the ground-water system in Jurassic and Cretaceous rocks in the northern Great Plains, in parts of Montana, North Dakota, South Dakota, and Wyoming: USGS Prof. Paper 1402-B, 36p.

Baillie, A.D., 1953, Devonian System of the Williston basin area: Manitoba Mines Branch Publication 52-5.

Bickford, M.E., Van Schmus, W.R., and Zietz, I., 1986, Proterozoic history of the midcontinent region of North America: Geology, v. 14, p. 492-496.

Billings, M.P., 1972, Chapter 12 - Strike slip faults, *in* Structural Geology (3rd edition), Prentice Hall Inc., New Jersey, 606p.

Braitsch, O., 1962, Entsehung and stoffbestand der salzlagerstatten:: Mineralogie und Petrographie in Einzeldarstellunge, Band III: Springer-Verlag, Berlin.

Brown, Donald L., 1978, Wrench-style deformational patterns associated with a meridional stress axis recognized in Paleozoic rocks in parts of Montana, South Dakota, and Wyoming: *in* Third International Williston Basin Symposium, p. 17-35.

Brown, Donald.L., and Brown, Darren L., 1987, Wrench-style deformation and paleostructural influence on sedimentation in and around a cratonic basin: *in* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 57-70.

Busch, D. A., 1974. Stratigraphic traps in sandstones -- exploration techniques. AAPG Memoir. 21. 174 pp.

Campbell, C.V., 1967, Lamina, laminaset, bed and bedset: Sedimentology, v. 8, p. 7-26.

________, 1971, Offshore equivalents of Upper Cretaceous Gallup beach sandstones, northwestern New Mexico, in Cretaceous and Tertiary rocks of the southern Colorado Plateau: Durango, Colo., Four Corners Geol. Soc., p. 78-84.

Cant, D.J., 1984, Subsurface facies analysis, Chapter 18, *in* Facies Models (2nd Edition), Roger G. Walker (ed.), Ainsworth Press Ltd., 317p.

Christiansen, E.A., 1967, Collapse structures near Saskatoon, Saskatchewan, Canada: Can. Journal of Earth Sciences, v. 8, p. 757-767.

Cross, T.A., and Lessenger, M.A., 1988 (in press), Seismic stratigraphy, Annual Report Earth and Planetary Science Review.

Davis, T.L., 1972, Velocity variations around Leduc reefs, Alberta: Geophysics, v. 37, n. 4, p. 584-604.

________, 1984, Seismic-stratigraphic facies models, chapter 19: *in* Facies Models (2nd Edition), Roger G. Walker (ed.), Ainsworth Press Ltd., 317p.

DeMille, G., Shouldice, J.R., and Nelson, H.W., 1964, Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Geol. Soc. of America Bull., v. 75, p. 307-316.

Dow, W.G., 1974, Application of oil-correlation and source-rock data to exploration in Williston basin: AAPG Bulletin, v. 58, n. 7, p. 1253-1262.

Downey, J.S., Busby, J.F., and Dinwidde, G.A., 1987, Regional aquifers and petroleum in the Williston basin region of the United States: *in* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 299-312.

Ehrets, J.R., and Kissling, D.L., 1987, Winnipegosis platform margin and pinnacle reefs reservoirs, northwestern North Dakota: unpublished report presented as a core workshop at the Fifth International Williston Basin Symposium, University of North Dakota, Grand Forks, North Dakota, 34p.

Fuller, J.G.C.M., and Porter, J.W., 1969a, Evaporite formations with petroleum reservoirs in Devonian and Mississippian of Alberta, Saskatchewan, and North Dakota: AAPG Bull., v. 53, p. 909-926.

________, 1969b, Evaporites and carbonates; two Devonian basins of western Canada: Bulletin of Canadian Petroleum Geology, v. 17, p. 182-193.

Gendzwill, D.J., and Hajnal, Z., 1971, Seismic investigation of the Crater Lake collapse structure in southeastern Saskatchewan: Can. Jour. of Earth Sciences, v. 8, p. 1514-1524.

Gendzwill, D.J., 1978, Winnipegosis mounds and Prairie Evaporite Formation of Saskatchewan-seismic study: *in* Third International Williston Basin Symposium, p. 121-130.

Gendzwill, D.J., and Wilson, N.L., 1987, Form and distribution of Winnipegosis mounds in Saskatchewan: *in* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 109-117.

Gerhard, L.C., 1986, Porosity development in the Mississippian pisolitic limestones of the Mission Canyon Formation, Glenburn Field, Williston Basin, North Dakota: *in* Carbonate Petroleum Reservoirs, Roehl, P., ed., p. 193-205, Springer-Verlag.

Gerhard, L.C., Anderson, S.B., and Berg, J., 1978, Mission Canyon porosity development, Glenburn Field, North Dakota, Williston Basin: *in* Economic Geology of the Williston Basin: Williston Basin Symposium, Montana Geol. Soc., p. 177-188.

Gerhard, L.C., Anderson, S.B., Lefever, J.A., and Carlson, C.G., 1982, Geological development, origin, and energy mineral resources of Williston basin, North Dakota: AAPG Bull., v. 66, n. 8, p. 989-1020.

Gorrell, H.A., and Alderman, G.R., 1968, Elk Point Group saline basins of Alberta, Saskatchewan, and Manitoba, Canada *in* Saline Deposits, A Symposium based on papers from the International Conference on Saline Deposits, Houston, Texas, 1962, R.B. Mattox (ed).

Grabau, A., 1924, Principles of Stratigraphy. New York: Siler. 1185 pp. 2nd ed.

Holter, M.E., 1969, The middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources, Report 123, 133p.

Hugo, K., 1985, Hydrodynamic flow associated with Leduc reefs, M.Sc. thesis, University of Alberta, 149p.

Illing, L. V., 1959, Deposition and diagenesis of some Upper Paleozoic carbonate sediments in Western Canada: 5th World Petrl. Cong. Proc, sec. 1, p. 23-52.

Jodry, R.L., 1969, Growth and dolomitization of Silurian reefs, St. Clair County, Michigan: AAPG Bull., v. 53, p. 957-981.

Kendall, A.C., 1984, Evaporites, Chapter 17, *in* Facies Models (2nd Edition), Roger G. Walker (ed.), Ainsworth Press Ltd., 317p.

Kent, D.M., 1968, The geology of the Upper Devonian Saskatchewan Group and equivalent rocks in western Saskatchewan: Saskatchewan Dept. of Min. Resources, Rept. No. 98.

________, 1974, The relationship between hydrocarbon accumulations and basement structural elements in the northern Williston basin: *in* Fuels: a geological appraisal, Proceedings of a symposium held on 7-8 November 1974, Saskatchewan Geological Society Special Publication No. 2., p. 63-79.

________, 1987, Paleotectonic controls on sedimentation in northern Williston basin, Saskatchewan: *in* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 45-56.

Langstroth, Ward T., 1971, Seismic study along a portion of the Devonian salt front in North Dakota: Geophysics, v. 36, n. 2, p. 330-338.

Lineback, J.A., Roth, M., and Davidson, M.L., 1987, Sediment starvation in the Williston and Illinois basins during the Devonian and Mississippian: *n* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 147-155.

Lundy, B.R., Gordon, D.C., and Robinson, J.L., 1966, Seismic applications to potash exploration and development in Saskatchewan and evidence of Winnipegosis reef build-up from reflection seismic data: Century Geophysical Corporation of Canada Report, 44p.

Maiklem, W.R., 1971, Evaporative drawdown - a mechanism for water-level lowering and diagenesis in the Elk Point basin: Bulletin of Canadian Petroleum Geology, v. 19, n. 2, p. 487-503.

Maley, V.C., and Huffington, R.M., 1953, Cenozoic fill and evaporite solution in the Delaware basin, Texas and New Mexico: Geological Society of America Bulletin, n. 64, p. 539-546.

Mitchum, Jr., R.M., Vail, P.R., and Thompson III, S., 1977, Seismic stratigraphy and global changes of sea level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis: *in* Seismic Stratigraphy - applications to hydrocarbon exploration, AAPG Memoir 26.

Parker, J.M., 1967, Salt solution and subsidence structures, Wyoming, North Dakota and Montana: AAPG Bull., v. 51, n. 10, p. 1929-1947.

Peterson, J. A., and Hite, R.J., 1969, Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrence, southern Rocky Mountains: AAPG Bull., v. 53, n. 4, p. 884-908.

Peterson, J.A., 1981, General stratigraphy and regional paleostructure of the western Montana overthrust belt: in Southwest Montana Guidebook, Montana Geological Society, p. 5-35.

Peterson, J.A., and Maccary, L.M., 1987, Regional stratigraphy and general petroleum geology of the U.S. portion of the Williston basin and adjacent areas: *in* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 9-43.

Reeve, D.M., 1986, Seismic detection of Mississippian Frobisher-Alida facies, Wiley and Mouse River Park fields, Bottineau and Renville Counties, Williston basin, North Dakota, 87p.

Rogers, M., and Mattox, W., 1985, Solution of the Devonian Prairie Formation salt: seismic recognition and exploration implications, *in* Seismic Exploration of the Rocky Mountain Region, Rocky Mountain Association of Geologists and Denver Geophysical Society, p. 137-141.

Schmalz, R.F., 1969, Deep-water evaporite deposition: a genetic model: AAPG Bull., v. 53, n. 4, p. 798-823.

Schwerdtner, W. M., and Wardlaw, N.C., 1964, Comparison of a Middle Devonian evaporite profile in Saskatchewan with hypothetical model: *in* Third International Williston Basin Symposium, p. 266-269.

Simpson, F., 1978, Plate-tectonic scenario for solution-controlled collapse structures in Paleozoic carbonate-evaporite sequence of the northern Williston basin region: *in* Third International Williston Basin Symposium, p. 147-150.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: GSA Bull., v. 74, p. 93-114.

________, 1969, Evaporite deposition from layered solutions: AAPG Bull., v. 53, n. 4, p. 776-789.

________, 1987, The Williston basin in the family of cratonic basins: *in* Williston Basin, Rocky Mountain Association of Geologists Guidebook, p. 1-8.

Sloss, L.L., and Speed, R. C., 1974, Relationships of cratonic and continental-margin tectonic episodes, in W. R. Dickinson, ed., Tectonics and Sedimentation: SEPM Spec. Publ. 22, p. 98-119.

Swenson, R.E., 1967, Trap mechanics in Nisku Formation of northeast Montana: AAPG Bulletin, v. 51, n. 10, p. 1948-1958.

Thomas, G.E., 1974, Lineament-block tectonics: Williston-Blood Creek basin: AAPG Bull., v. 58, n. 7, p. 1305-1322.

Turcotte, D.L., and Ahern, J.L., 1977, On the thermal and subsidence history of subsidence basins: Journal of Geophysical Research, v. 82, p. 3762-3766.

Vail, P.R., Mitchum, R.M., and Thompson, III, S., 1977, Seismic stratigraphy and global changes of sea level, part 3: relative changes of sea level from coastal onlap: *in* Seismic Stratigraphy - Applications to Hydrocarbon Exploration, Payton, C.E., ed., AAPG Memoir 26, p. 53-62.

Wardlaw, N.C., 1964, Bromide in some Middle Devonian salt rocks of Alberta and Saskatchewan: *in* Third International Williston Basin Symposium, p. 270-273.

Wardlaw, N.C., and Reinson, G.E., 1971, Carbonate and evaporite deposition and diagenesis, middle Devonian Winnipegosis and Prairie Evaporite Formations of south-central Saskatchewan: AAPG Bull., v. 55, n. 10, p. 1759-1786.

Webster, R.L., 1984, Petroleum source rocks and stratigraphy of the Bakken Formation in North Dakota: *in* Hydrocarbon Source Rocks of the Greater Rocky Mountain Region, J. Woodward, F. Meissner, J. Clayton, eds., Rocky Mountain Association of Geologists Symposium, p. 57-81.

Williams, G.K.,1984, Some musings on the Devonian Elk Point basin, Western Canada: Bulletin of Canadian Petroleum Geology, v. 32, n. 2, p. 216-232.

Williams, J.A., 1974, Characterization of oil types in the Williston basin: AAPG Bulletin, v. 58, n. 7, p. 1242-1252.

APPENDIX

Wells penetrating Winnipegosis Formation pinnacle reefs in U.S. portion of the Williston basin.

Winnipegosis Pinnacle Reef wells

Shell - Golden 34-34X
Des Lacs (Eastward)
Renville Co., North Dakota
34-161N-87W

Shell - Osterberg No. 22-1
Wildcat
Renville Co., North Dakota
1 - 161N- 85W

Shell - Greek No. 44-2
Wildcat
Bottineau Co., North Dakota
2 - 161N - 83W

Marathon - George Adams #1
Wildcat
Bottineau Co., North Dakota
33 - 161N - 82W

Challenger Minerals - Alvstad 31-29
Wildcat
Mountrail Co., North Dakota
29 - 157N - 88W

Inexco - Erickson No. 1-18
Wildcat
Ward Co., North Dakota