SALTS IN THE WILLISTON BASIN, NORTH DAKOTA

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ABSTRACT

Salts deposits are widespread throughout the Williston Basin. Traceable salts range in age from Silurian through Jurassic. For this study, thicknesses of 24 major and minor salts were obtained from about 5,600 wireline logs throughout North Dakota. From these data, isopach maps of all of the salts were constructed. Areas of salt dissolution were identified by linking thinning on the salt isopach maps with thicker compensating sections in the overlying strata.

The lowermost salts in the stratigraphic section are located within the Interlake (Silurian) and the Ashern, Prairie, Duperow and Souris River (Devonian) Formations. The Interlake salts reach a maximum thickness of 7 ft (2 m) and are scattered through southern Williams County. Five salts occur in the Ashern Formation to the east of the Nesson anticline in Mountrail County; each of the salts reaches a maximum thickness of about 20 ft (6 m). In North Dakota, the Duperow and Souris River salts are restricted to northern Divide County, although they are extensive north of the international border.

The most significant salt in the basin occurs within the Prairie Formation. Trapping of hydrocarbons and significant production related to dissolution of the Prairie Salt has been documented in several cases in Montana, Saskatchewan, and North Dakota. Dissolution was, in part, multistage. The limit of the Prairie Salt in central and western North Dakota has long been considered to be the depositional limit. Close examination of Devonian and Mississippian strata surrounding the Prairie edge shows the limit is largely, if not entirely, the result of dissolution, and that the edge of the salt gradually migrated basinward from the Devonian until the early stages of Charles salt deposition.

Distribution of the upper Charles salts (F-A) becomes more limited upsection, and reflects the withdrawal or restriction of the Charles sea. This sequence of 7 salts locally shows dissolution related to tectonic movement along structural elements, including the Nesson anticline and a probable extension of the Hummingbird trough from Saskatchewan into Montana and North Dakota.

The uppermost salts, the Pine, “G” and Dunham Salts, also reflect basement movement that may affect hydrocarbon trapping and production. Many of the salts appear to have been affected by a Late Jurassic-Early Cretaceous event. Some dissolution of the Pine Salt has also occurred locally in Late Cenozoic time.

Salts have had a profound effect on hydrocarbon accumulation within the Williston Basin. There are a number of successful fields where hydrocarbons have been trapped due to dissolution and related collapse of underlying salts. There are numerous examples where potential oil reservoirs have been destroyed by salt occlusion of the available porosity and permeability.

The best-known examples of hydrocarbon trapping and significant production related to salt dissolution involve the Prairie Salt. However, examination of other salts within the North Dakota part of the basin suggests that such trapping can be documented for several other salts; in many cases, such dissolution appears to have occurred as a multi-stage process.

INTRODUCTION

Salts have played an important role in oil exploration and production of the Williston Basin. They occur basinwide and are present at several stratigraphic horizons from Silurian to Jurassic (Fig. 1). Given the knowledge of their existence, distribution and thickness, the salts can be beneficial to exploration in providing insight into a variety of different trapping mechanisms.

This paper examines all of the salts in the North Dakota portion of the Williston Basin, from earliest Silurian to latest Jurassic, with emphasis on trapping mechanisms. This examination includes relative stratigraphic position, areal distribution and thickness.

METHODS

The study area encompasses the western half of North Dakota (Fig. 2). Over 5,500 wireline logs were examined for salts.

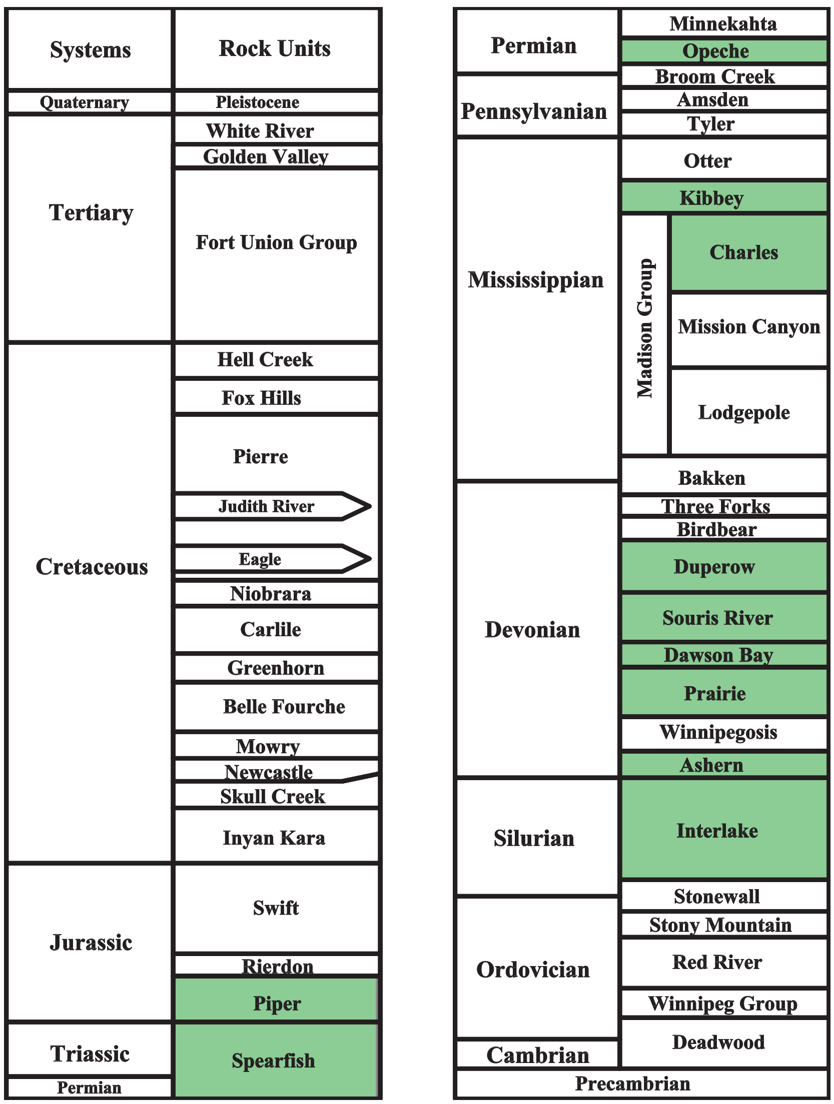


Figure 1. Stratigraphic column of North Dakota. Shaded formations have salts.

Wherever possible, sonic or density logs were used to identify salts. Data obtained were then plotted and an isopach map was generated for each salt. Salts with limited distribution are plotted, but isopach maps were not prepared.

Several initial assumptions are made in this study. Salts are assumed to have been deposited fairly uniformly over their areal extent unless there was an underlying stratigraphic reason; for example, the thickness of the Prairie Salt is greatly affected by Winnipegosis pinnacle reefs. Anomalous absences or thins of individual salts are assumed to have resulted from complete or partial dissolution of the salt.

MINOR SALTS

Silurian

Interlake Formation

These salts were first described in North Dakota by Fischer and Anderson (1984) and are recognizable on wireline logs above the prominent gamma-ray marker of the middle Interlake (Fig. 3a). They have limited distribution and occur randomly through southern Williams County (Fig. 3b). LoBue (1983) interpreted the gamma-ray marker to be an unconformity surface. Associated with this surface are several topographic highs that eventually developed into islands. Calcretes and ferricretes were deposited on the islands; the salts are interbedded with them. The maximum thickness of the salts in this interval has been reported at 7 ft (2.1 m).

Devonian

Ashern Formation

The salts that occur in the Ashern Formation are thin, discontinuous beds, similar to those in the Interlake Formation, and were first reported in North Dakota by Lobdell (1984). Fischer and Anderson (1984) informally subdivided the salts into two groups, N and M, in ascending stratigraphic order, and further subdivided them into separate beds, N_1 through N_3, and M_1 and M_2 (Fig. 4a).

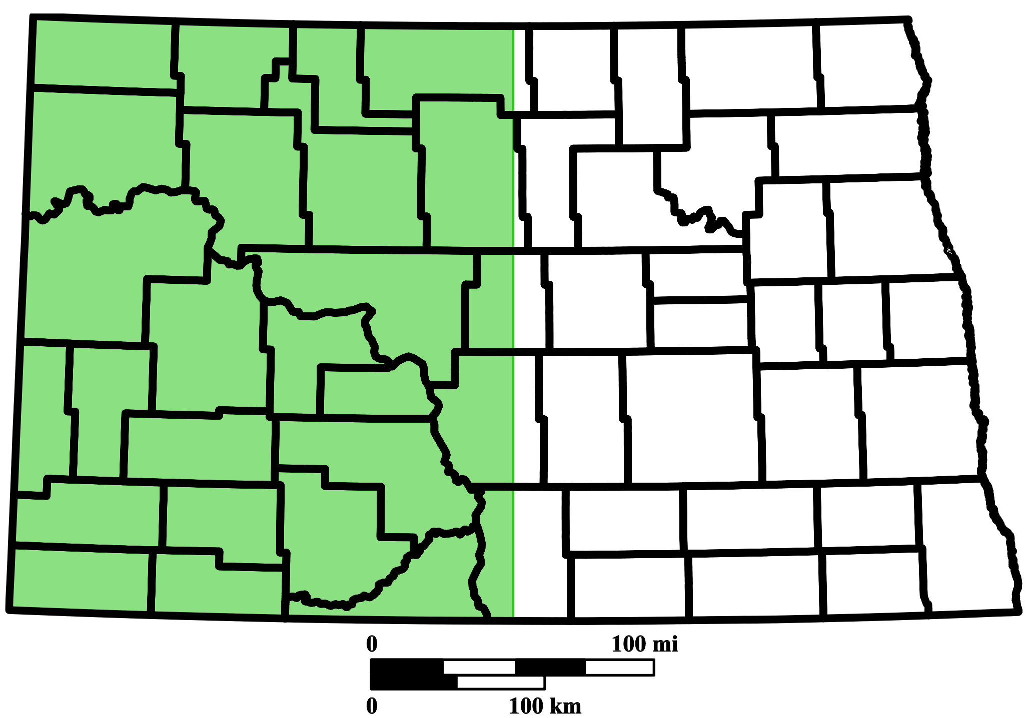
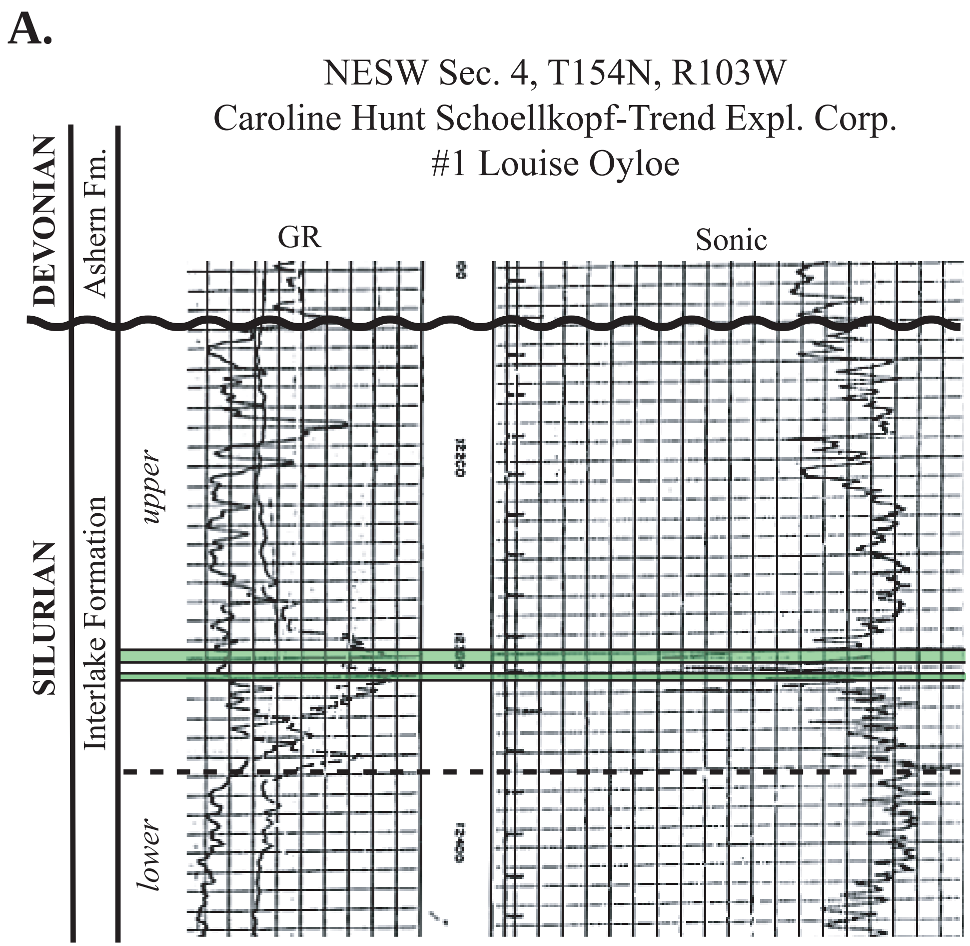


Figure 2. *Index map showing the location of the study area.*



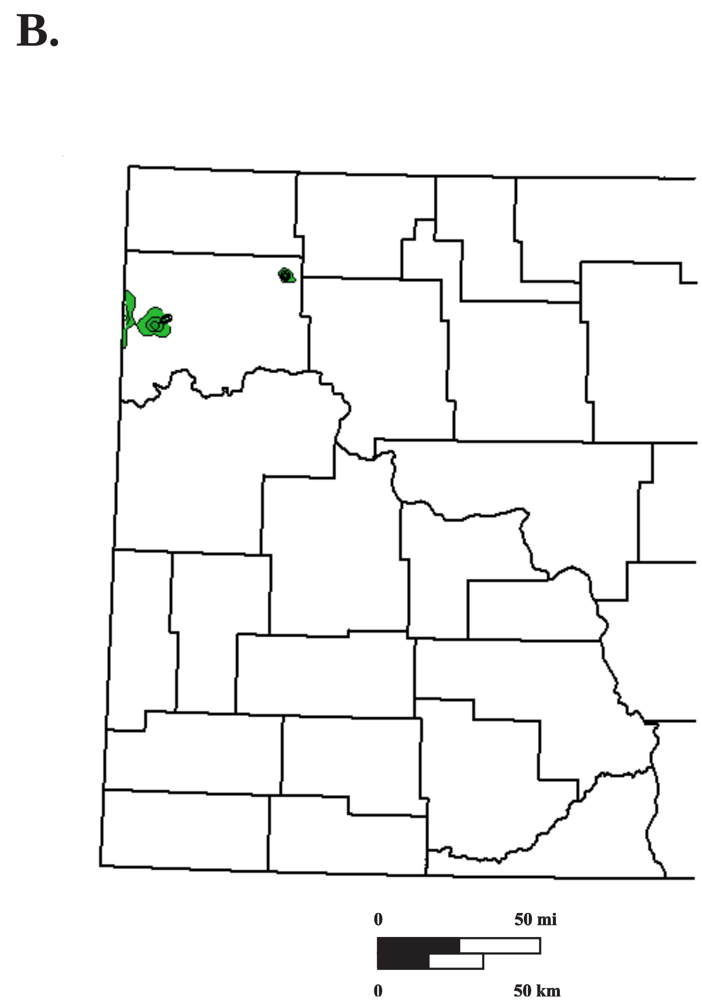


Figure 3. *A.) Typical log characteristics of Interlake salts. B.) Isopach of the combined Interlake salts (C.I. = 5 ft).*

They are restricted to an area surrounding the Nesson anticline in McKenzie, Mountrail, and Williams Counties (Figs. 4b, c).

Lobdell (1984) placed the salts in the "upper grey member" of the Ashern Formation. The member is interpreted to have been deposited in an embayment with restricted circulation.

Maximum combined thicknesses reported for the N salts are 14 ft (4.3 m) and for the M salts are 33 ft (10.1 m).

Souris River Formation

The salt in the Souris River Formation, originally named by Baillie (1953) and later revised by Lane (1964), is referred to as the Davidson Evaporite. It is extensive throughout southern Saskatchewan, where it reaches a thickness of over 209 ft (63.9 m). The Souris River Formation is divided into three members in Saskatchewan. The Davidson Evaporite (salt) occurs at the top of the Davidson Member (Fig. 5a). In North Dakota, it occurs only in the northwestern corner of the state (Fig. 5b) where it reaches a maximum thickness of 10 ft (3.0 m).

Fischer and Anderson (1984) reported that the Davidson Evaporite (salt) appears clear to amber in cuttings, and is probably massive and crystalline. The Davidson salt grades laterally into an anhydrite. The change from salt to anhydrite distinguishes the basin from the shelf.

Duperow Formation

The Flat Lake Evaporite is the formal name for the salt within the upper portion of the Duperow Formation. This name originated in Canada, having been proposed by Dunn in 1975. Only two small lobes of the Flat Lake salt extend into northern Divide County, and represent the southernmost limit of the salt. The salt has a maximum reported thickness of 21 ft (6.4 m) in North Dakota (Figs. 6a, b).

Mississippian

Charles Formation

The Charles Formation is predominantly evaporitic in the North Dakota portion of the Williston Basin, and consists of numerous repetitions of salts, anhydrites, thin shales, and dense limestones. Six major and seven minor salt beds comprise the evaporite section. The major salts were designated A through F by Anderson and Hansen (1957). Some of the minor salts have limited occurrence and are associated with major salt facies. These salts are indicated by the adjacent letter designation with a number subscript (e.g., F_1). The X salt reported by Anderson and Hansen (1957) has been split into two individual salt beds, referred to by the name of the producing horizon, Sherwood or Bluell, in which they occur. Two other salts that are similar to the Bluell and Sherwood but have a more limited occurrence are the Rival and Midale salts (Fig 7).

The Sherwood, Bluell and Rival salts are different from the major salts in that they occur only in a discontinuous band along the eastern side of the basin. The Rival salt has a more limited distribution and occurs basinward of the Bluell and Sherwood. These salts were probably deposited in a sabkha or salt flat environment. They have a maximum thickness of 44 ft (13.4 m)

Kibbey Formation

Thin, localized beds of salt occur in the basal portion of the Kibbey Formation in Billings and McKenzie counties (Fig. 8). Sedimentation patterns established during Charles deposition continued into Kibbey time, and shallow water conditions were responsible for localized restriction leading to salt deposition. The salt reaches a maximum thickness of 21 ft.

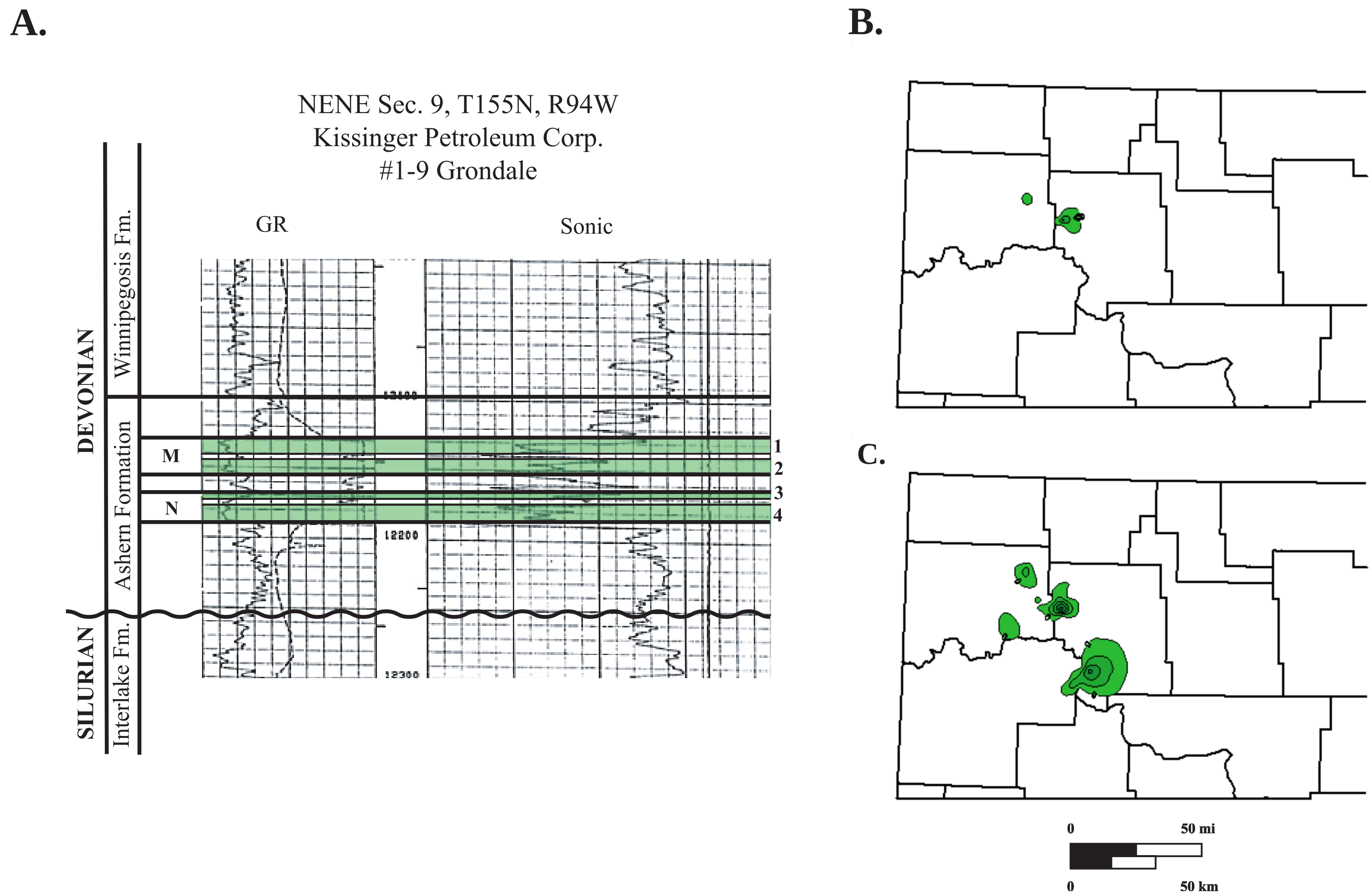


Figure 4. *A.) Typical log characteristics of Ashern salts, N and M (modified from Fischer and Anderson, 1984). B.) Isopach map of the N salts (C.I. = 5 ft.). C.) Isopach map of M salts (C.I. = 5 ft.) .*

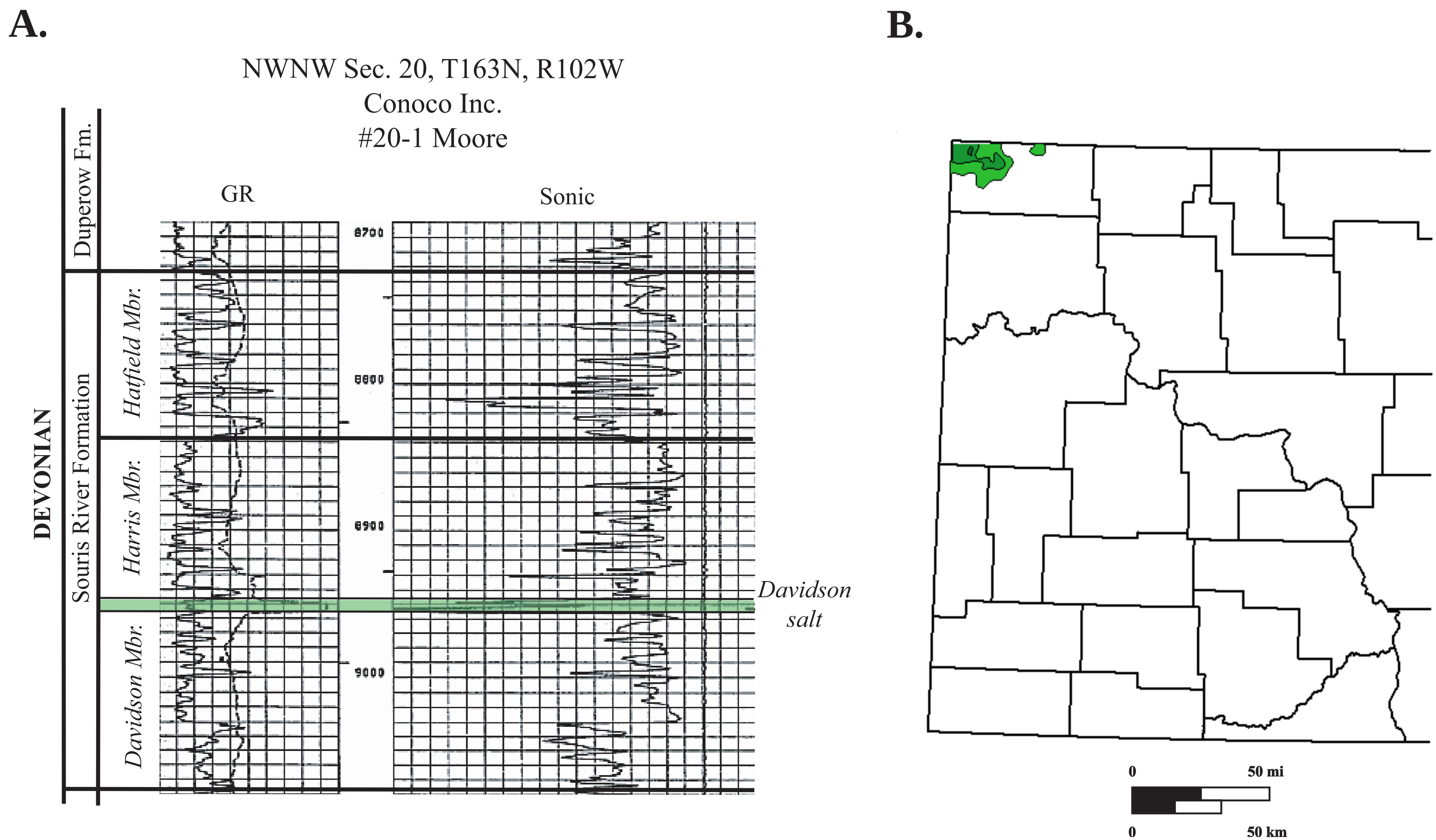


__Figure 5.__ A.) Typical log characteristics of the Davidson salt, Souris River Formation. B.) Isopach map of the Davidson salt (C.I. = 5 ft.).

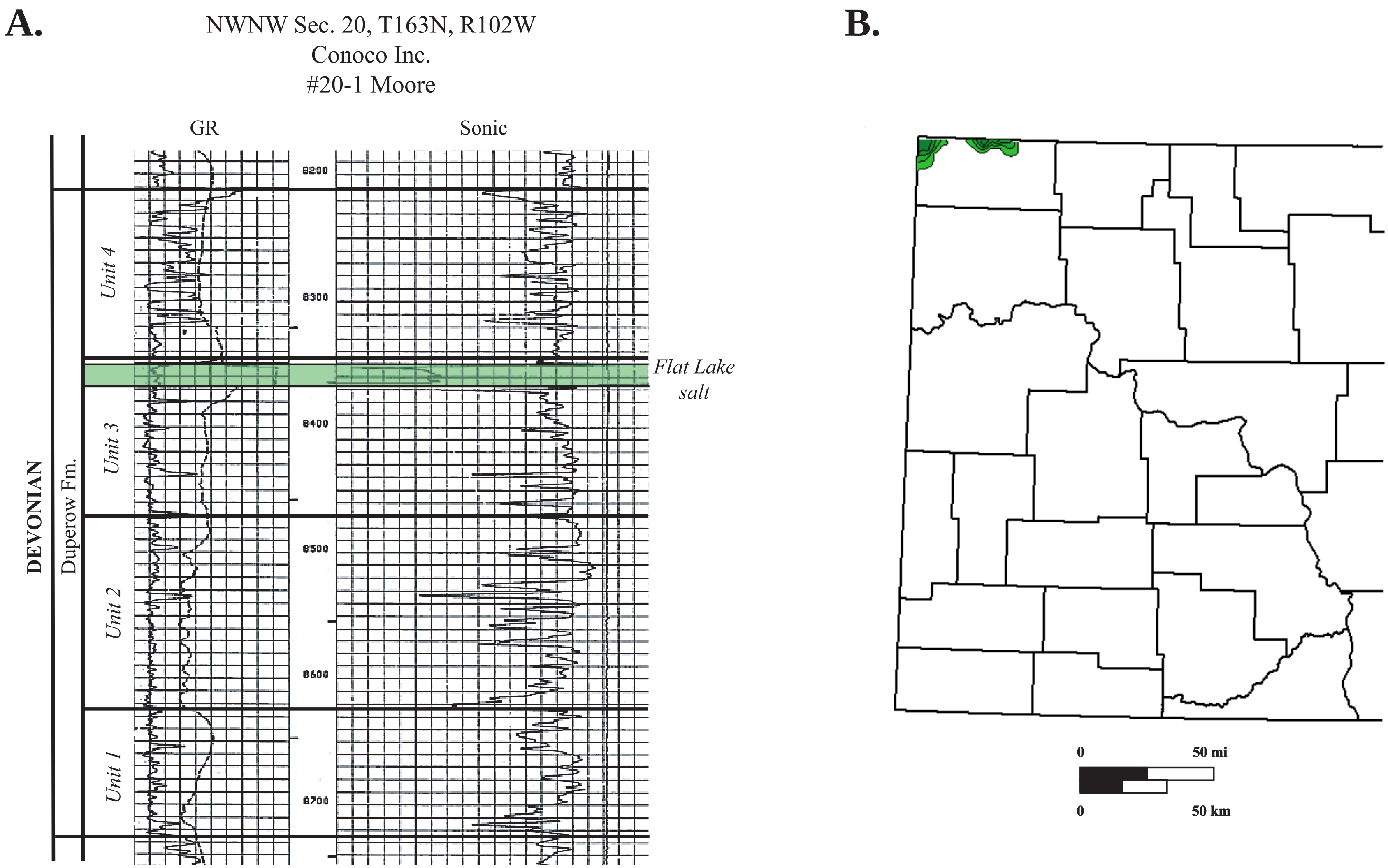
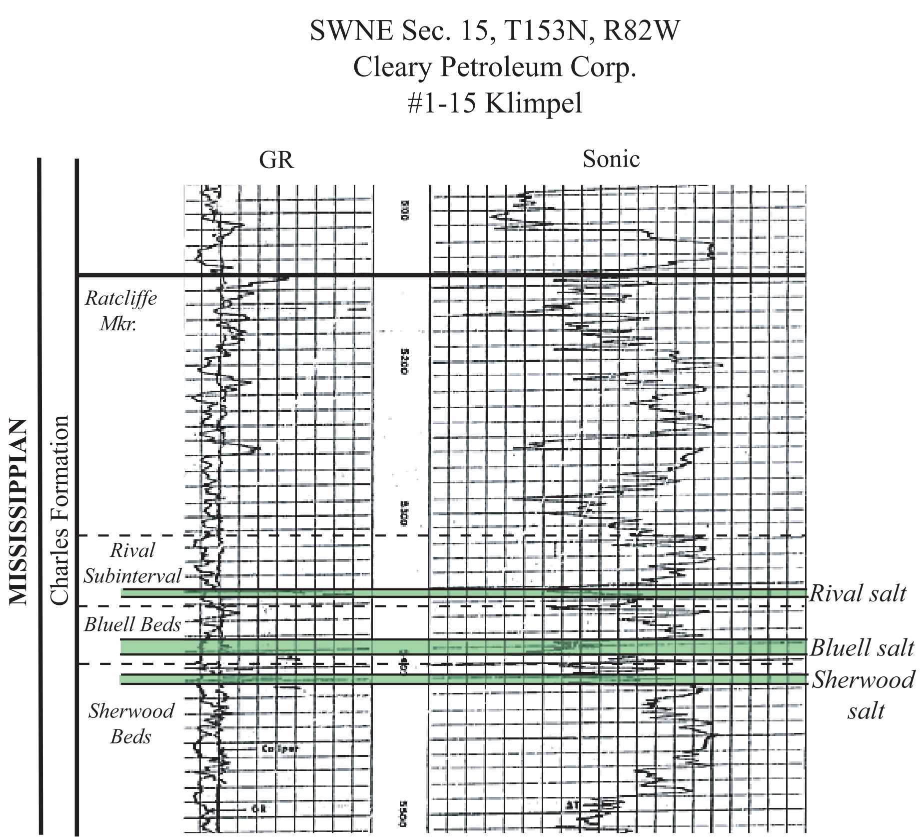


Figure 6. *A.) Typical log characteristics of the Flat Lake salt, Duperow Formation. B.) Isopach map of the Flat Lake salt (C.I. = 5 ft.).*

A.



B.

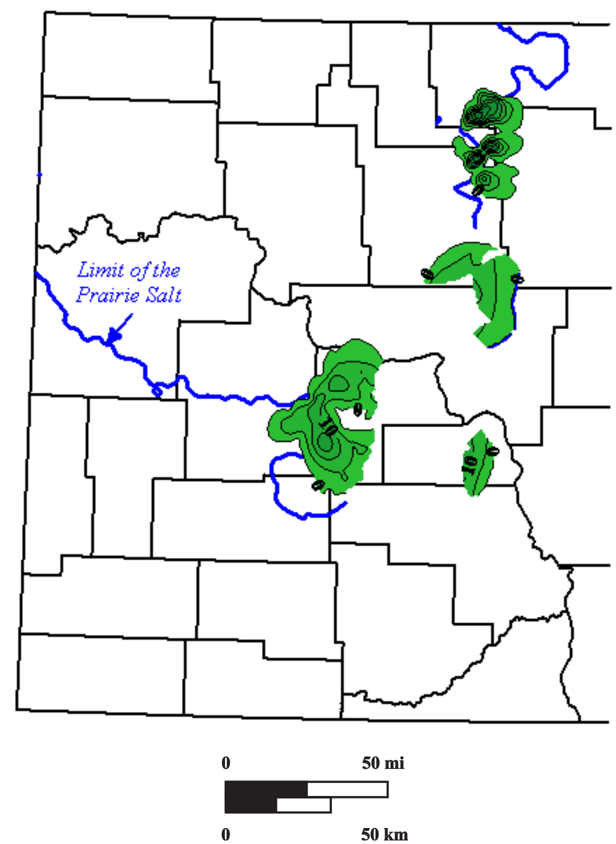


Figure 7. *A.) Typical log characteristics of the Sherwood, Bluell, and Rival salts of the lower Charles Formation. B.) Isopach map of the Sherwood salt (C.I. = 5 ft.).*

C. D.

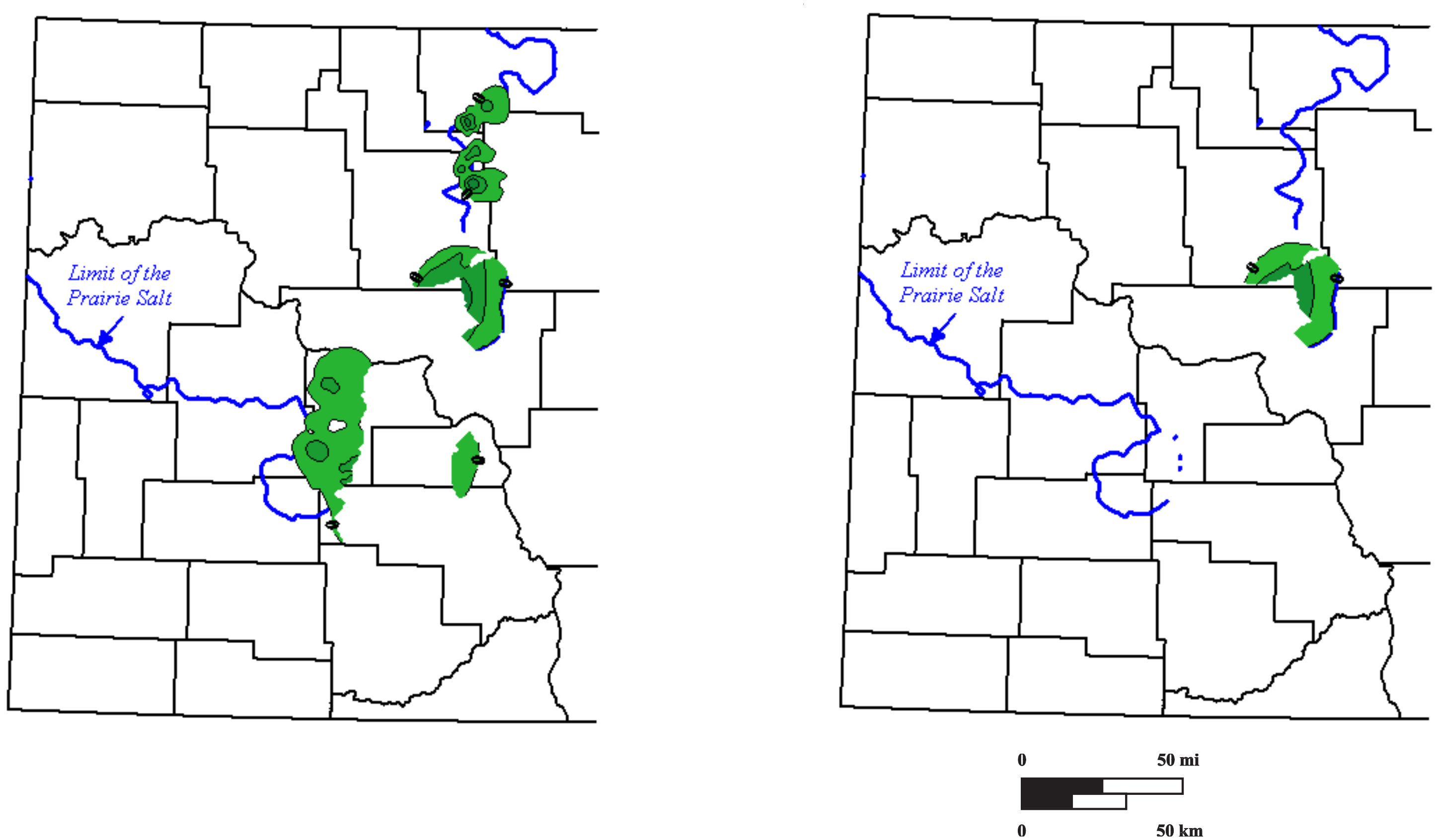
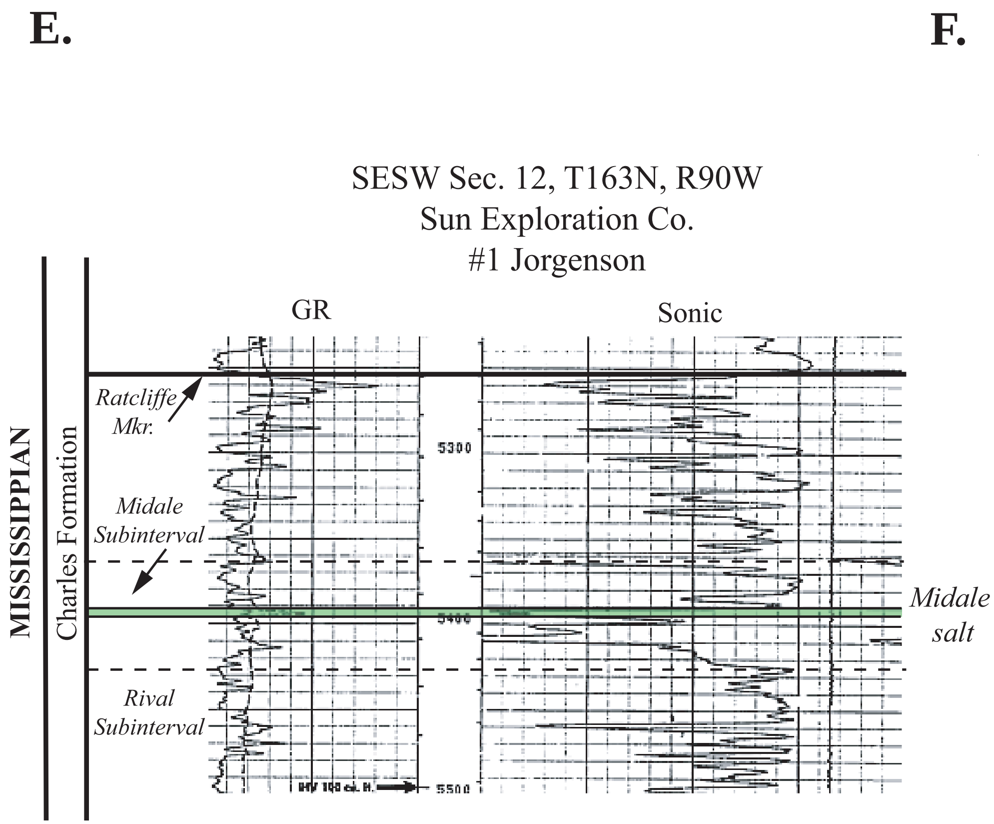


Figure 7 (con't). *C.) Isopach map of the Bluell salt (C.I. = 5 ft.). D.) Isopach map of the Rival salt (C.I. = 5 ft.).*



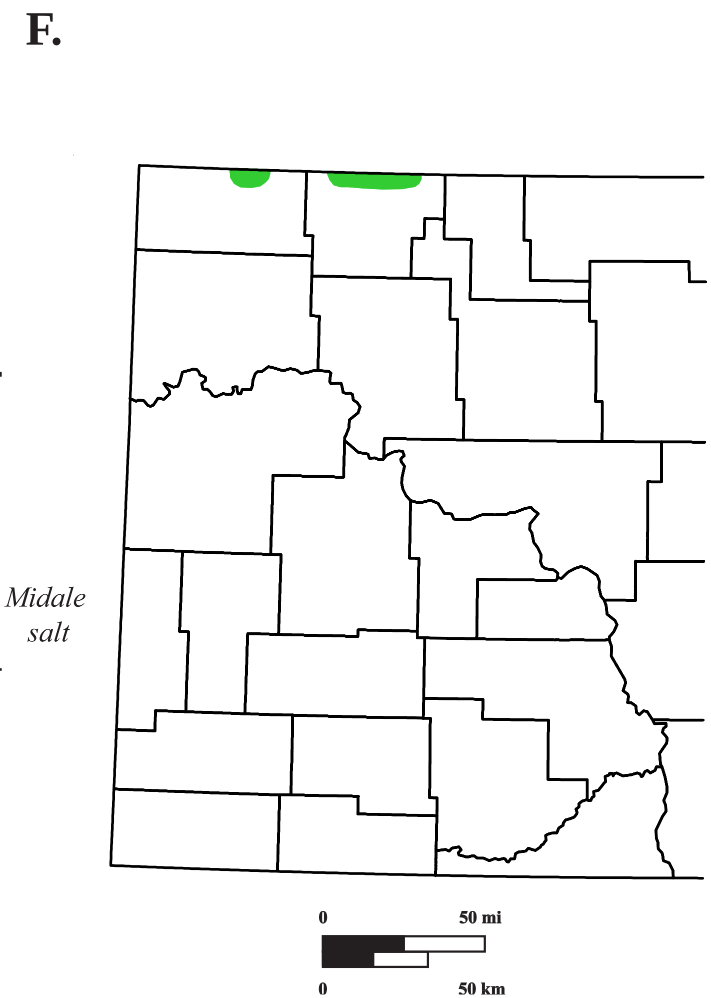
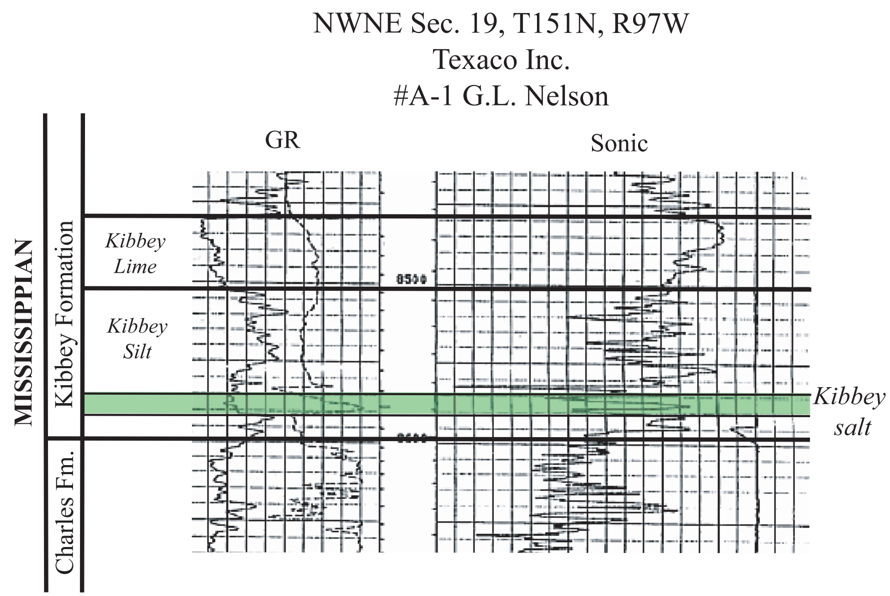


Figure 7 (con't). *E.) Typical log characteristics of the Midale salt. F.) Areal distribution of the Midale salt.*

A.



B.

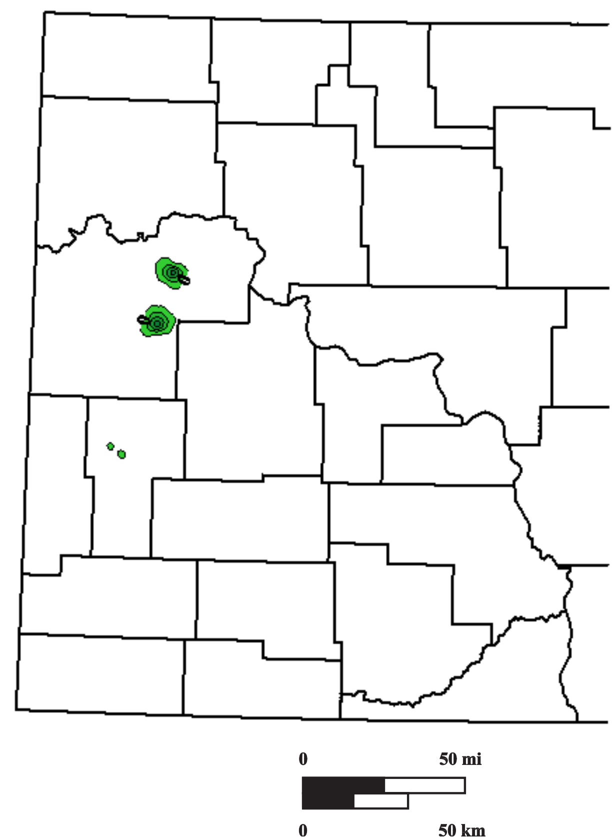


Figure 8. *A.) Typical log characteristics of the salt in the Kibbey Formation. B.) Isopach map of the Kibbey salt (C.I. = 5 ft).*

MAJOR SALTS

Devonian

Prairie Formation

The thickest single salt present within the North Dakota portion of the Williston Basin is within the Prairie Formation. This formation extends south from Canada into North Dakota and is present over approximately half of the study area. The Prairie Formation has been subdivided into four members, the Ratner, Esterhazy, Belle Plaine, and Mountrail each of which is separated by halite beds (Anderson and Swinehart, 1979; Oglesby, 1988; Fig. 9a). The entire sequence is capped by the "Second Red Bed." It attains a maximum thickness of 638 ft (194.5 m) in North Dakota (Figs. 9b, c).

The basal member, the Ratner, transitionally overlies the deep water argillaceous laminites of the Winnipegosis Formation in the central portion of the basin and abruptly overlies Winnipegosis carbonates along the margin of the basin. It grades upward from a laminated anhydrite into enterolithic and rosette-patterned anhydrite, and into a massive anhydrite. The Ratner has been included in the Prairie because the initial saline conditions suggested by these lithologies are more consistent with Prairie deposition than with those of the underlying Winnipegosis Formation (Holter, 1969; Oglesby, 1988). The lower portion of the Prairie, between the Ratner and Esterhazy members, consists predominantly of milky halite. Also present are thin, laterally persistent interbeds of anhydrite that probably resulted from a brief influx of more normal marine waters. This is capped by the potash beds of the Esterhazy Member (Anderson and Swinehart, 1979). The next two members, Belle Plaine and Mountrail, represent repeated depositional sequences of clear, inclusion-free halite and potash. These cycles of interbedded halite and potash are regionally correlative, asymmetric, with a mineralogy indicative of an overall increase in salinity. The potash represents the highest salinity and the shallowest brine depth and consists of halite, sylvite, and carnallite with other minor hypersaline minerals. Another partial cycle overlies the potash of the Mountrail Member; however the potash is absent, possibly due to dissolution or erosion.

Red to green non-fossiliferous dolomites and calcareous shales of the Second Red Bed cap the entire Prairie sequence. These lithologies may represent an influx of clastics over the salt sequence or may be a residual product of weathering and solution (Holter, 1969; Williams, 1984; Oglesby, 1988). The Second Red has been included in the Prairie or the overlying Dawson Bay Formation by different workers. Regardless of placement, the Second Red appears to have prevented the dissolution of the Prairie salt during the Dawson Bay transgression.

Beyond the limits of the salt, the Prairie Formation changes into an interbedded anhydritic dolostone, dolomitic shale, and siltstone with inclusions of halite (Sandberg and Hammond, 1958).

Mississippian

Charles Formation

The major and associated minor Charles salts, F through A, occur in the central portion of the basin (Figs.10). The F salt, also commonly referred to as the "Last Salt", has the greatest areal extent, and higher salts occur over less area than does the F Salt (Fig. 11).The F through C salts extend into southern Saskatchewan, and all of the major salts and some of the minor ones extend into Montana. Unlike the lower Charles salts, the upper salts were deposited in the central basin, probably as a result of a combination of sea-level changes, some type of restrictive shoals or uplift, and perhaps a change in subsidence rate (Andrichuk, 1955; Fish and Kinard, 1958; Sandberg, 1973; Peterson, 1987).

Permian

Opeche Formation

The Opeche Formation consists of evaporites and fine-grained detrital sediments. In the central portion of the basin, these are predominantly halite and red claystones. Towards the margin of the basin anhydrite, gypsum, and dolomite predominate (Maughan, 1966; Bluemle et al., 1986).

Two massive salts can be identified and mapped within the Opeche, and are referred to as

A.

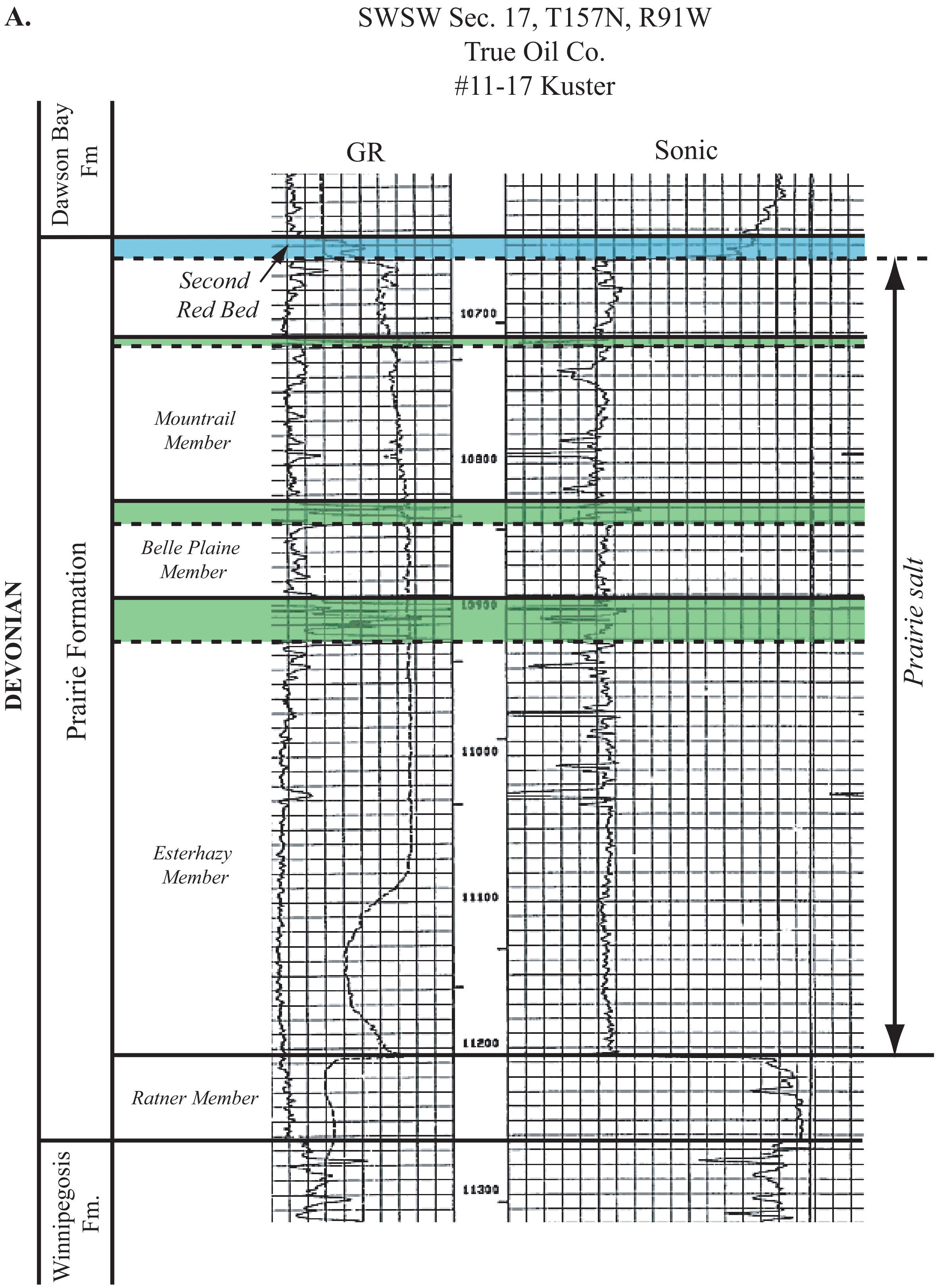


Figure 9. *A.) Typical log characteristics of the Prairie Formation showing the salt and four members. Potash beds are shaded green.*

B. C.

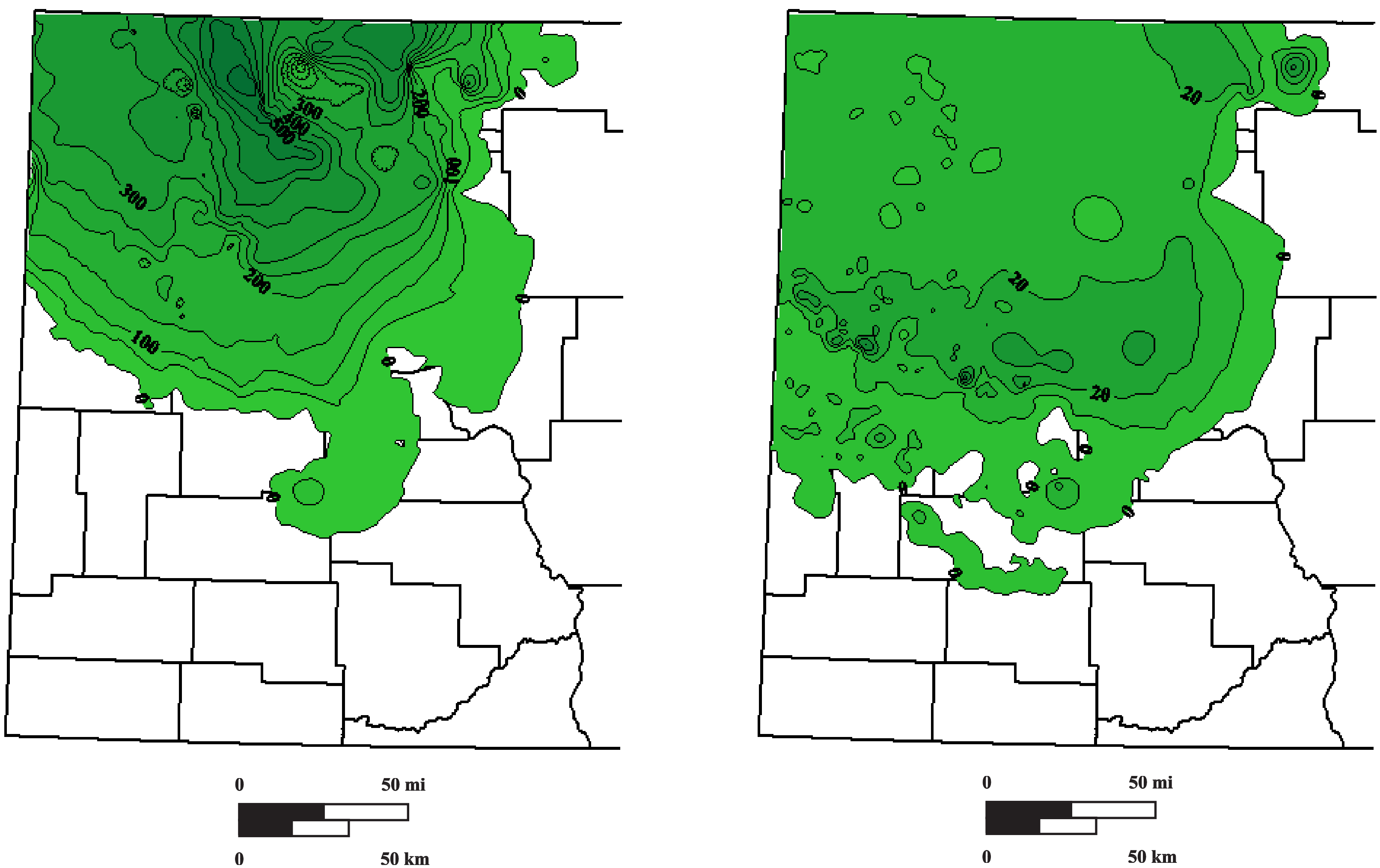


Figure 9 (con't). B.) Isopach map of the Prairie salt (C.I. = 50 ft). C.) Isopach map of the Second Red Bed (C.I. = 10 ft).

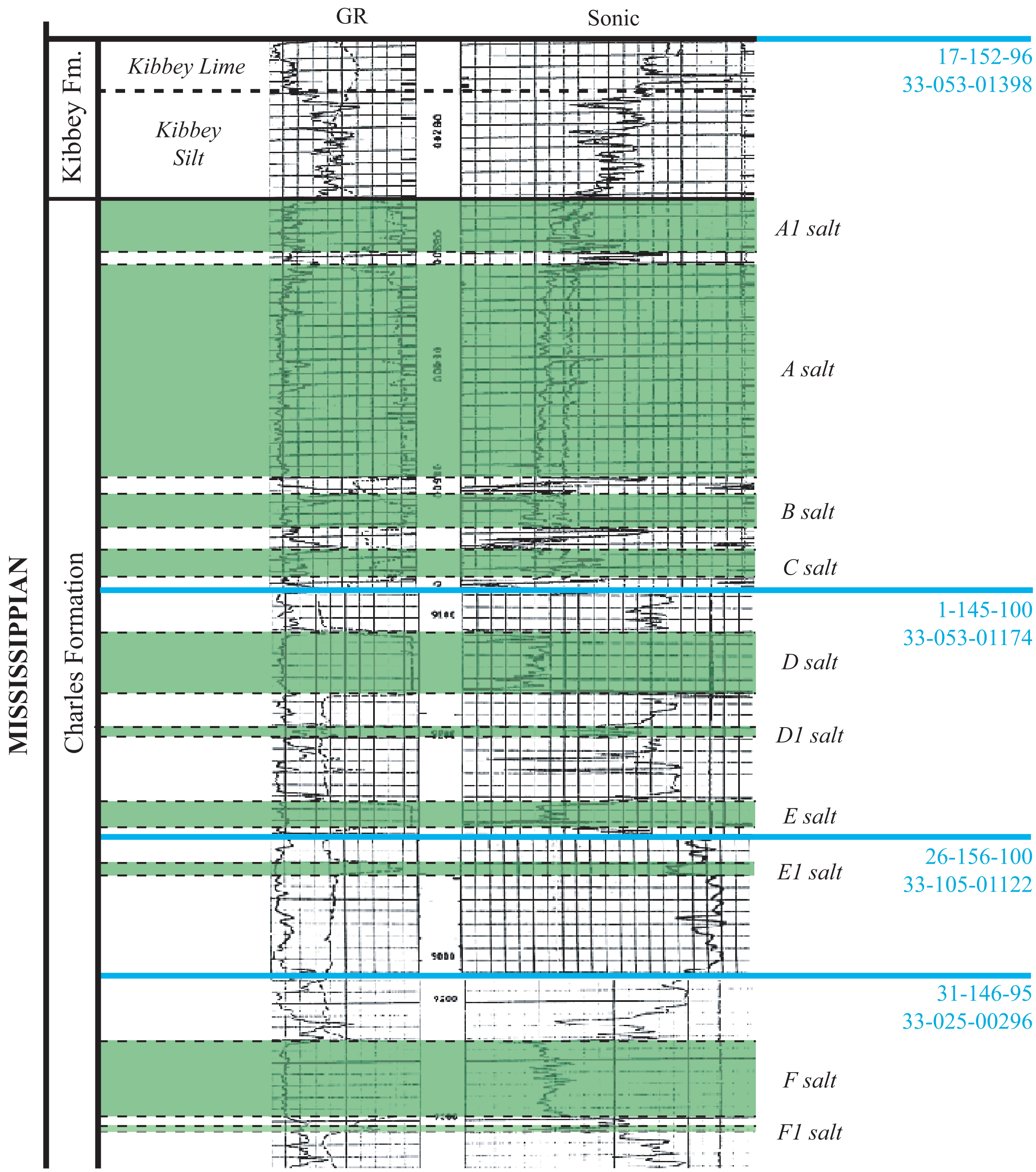


Figure 10. *A.) Composite well log showing the typical log characteristics of the Charles salts, F1 through A1.*

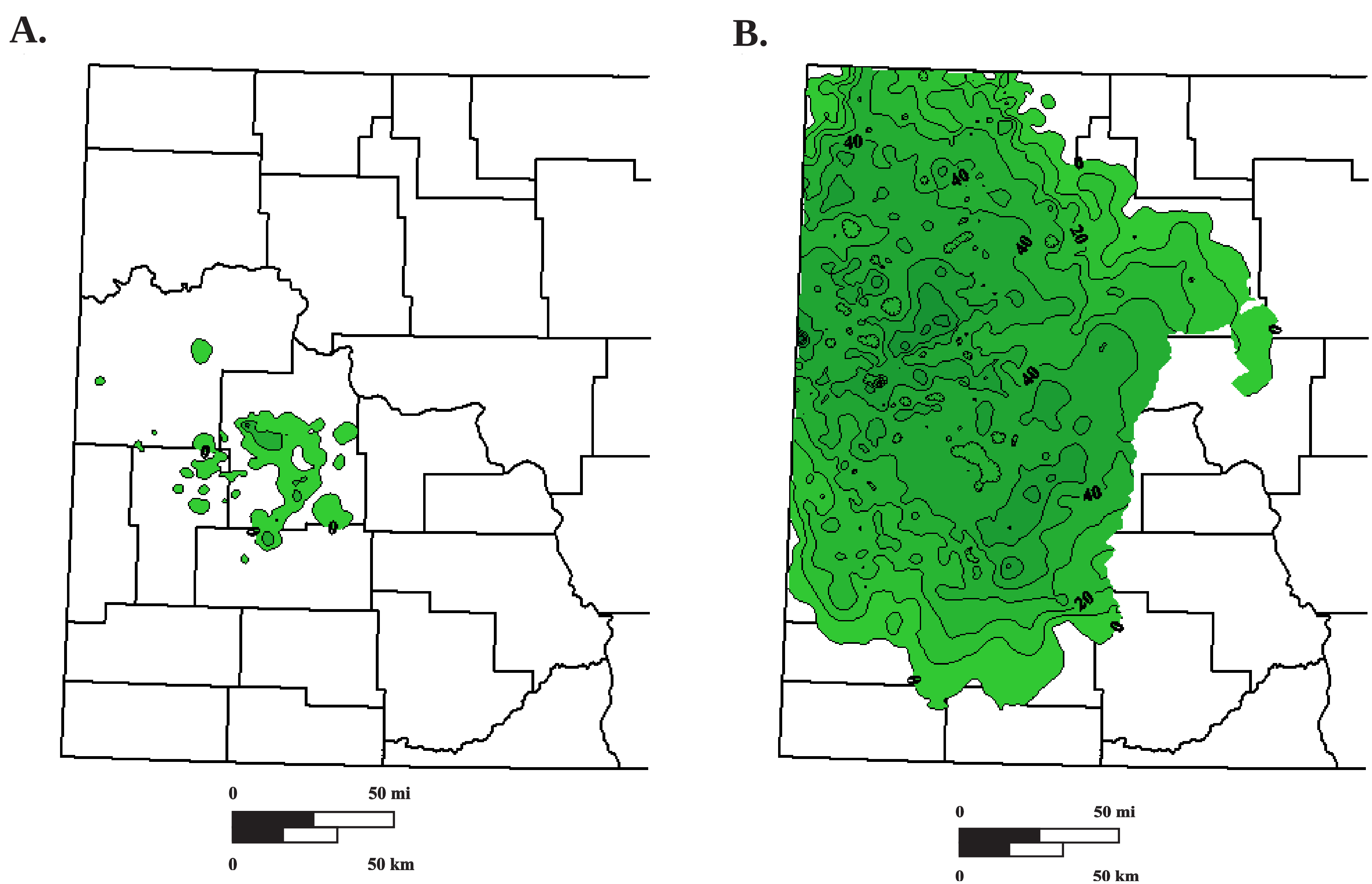


Figure 11. A.) Isopach map of the F1 salt (C.I. = 5 ft). B.) Isopach map of the F salt(C.I. = 10 ft).

C.

D.

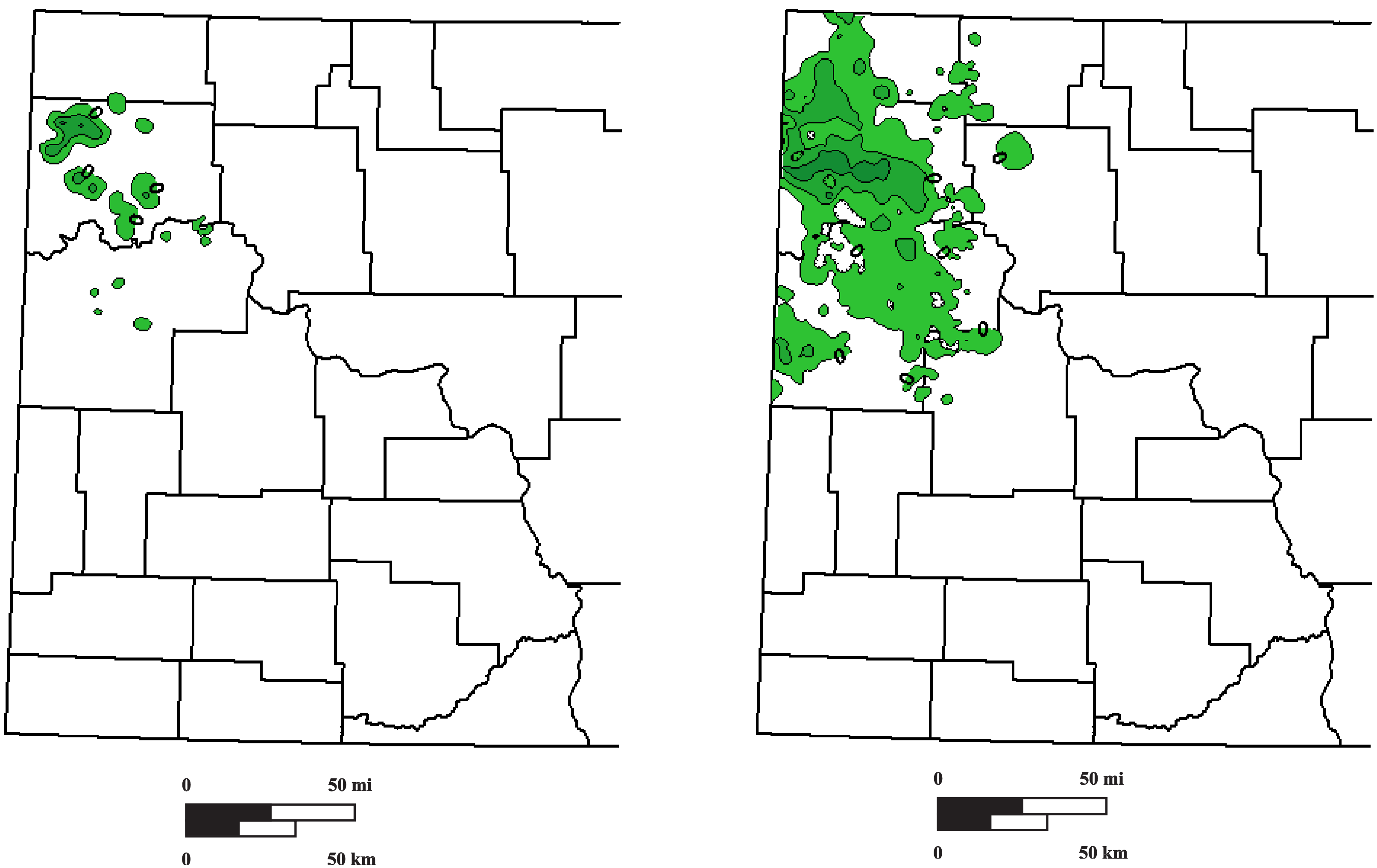


__Figure 11 (con't).__ C.) Isopach map of the E2 salt (C.I. = 5 ft). D.) Isopach map of the E1 salt (C.I. = 5 ft).

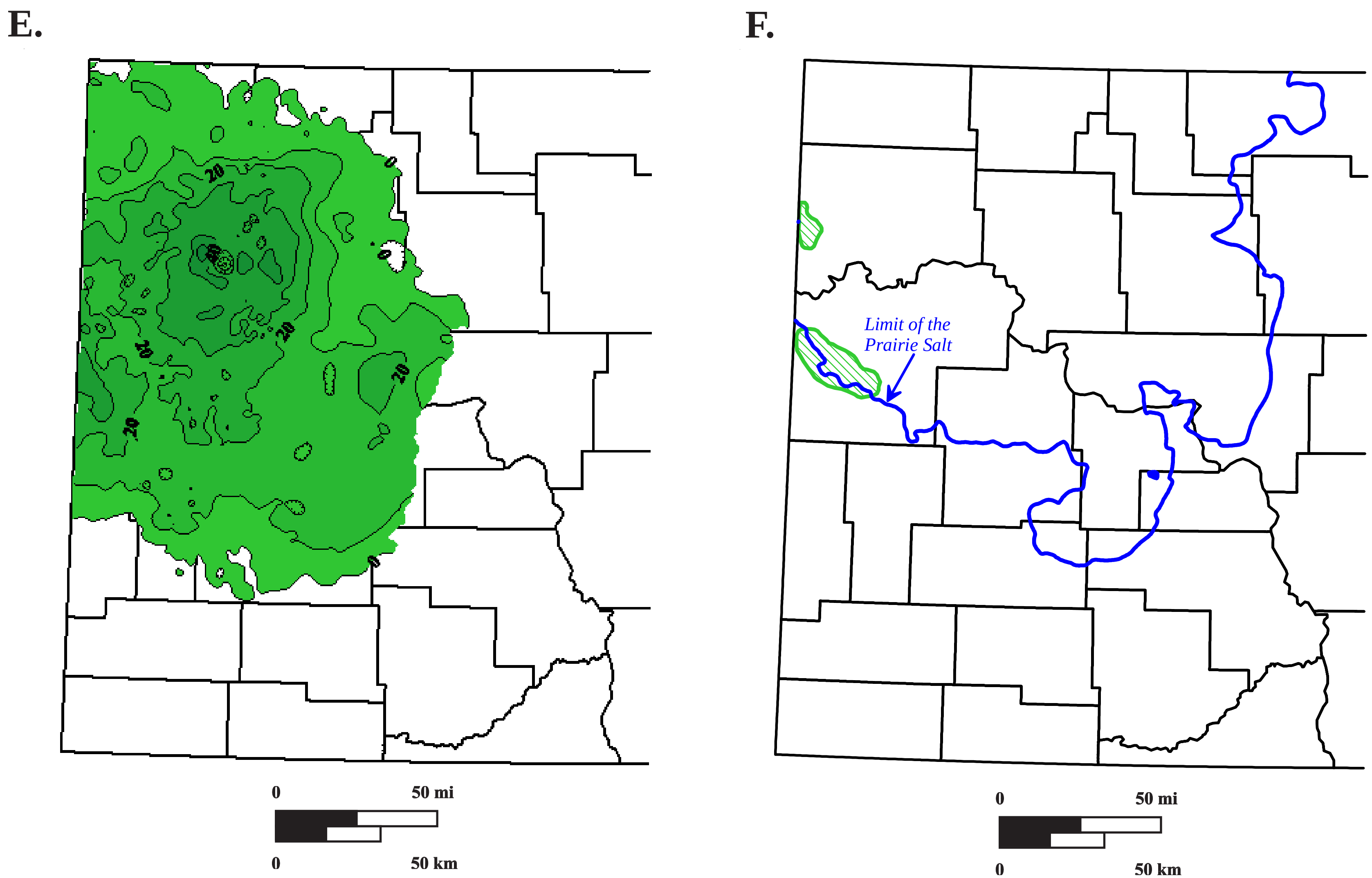
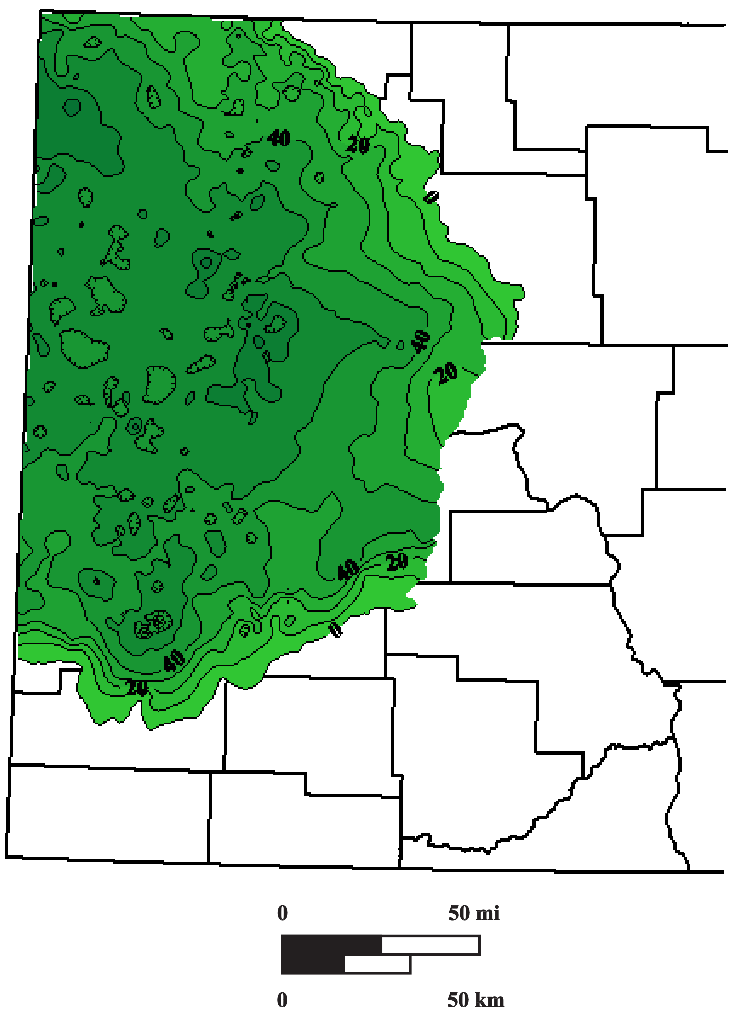


Figure 11 (con't) E.) Isopach map of the E salt (C.I. = 10 ft). F.) Areal distribution of the D1 salt.

G.



H.

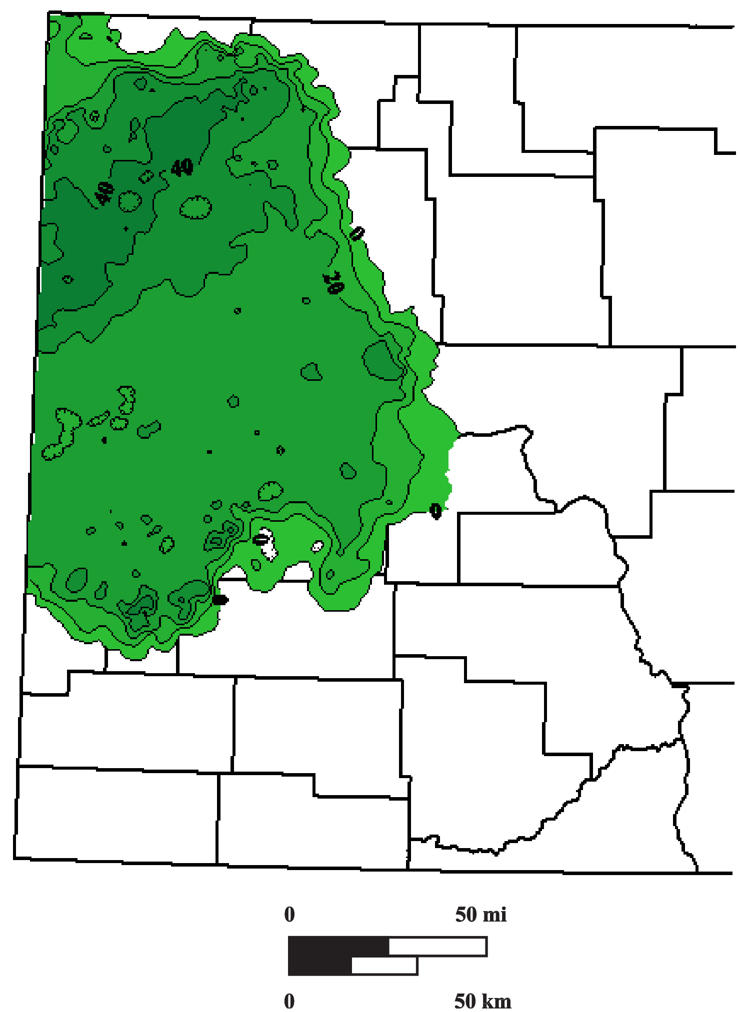


Figure 11 (con't) *G.) Isopach map of the D salt (C.I. = 10 ft). H.) Isopach map of the C salt (C.I. = 10 ft).*

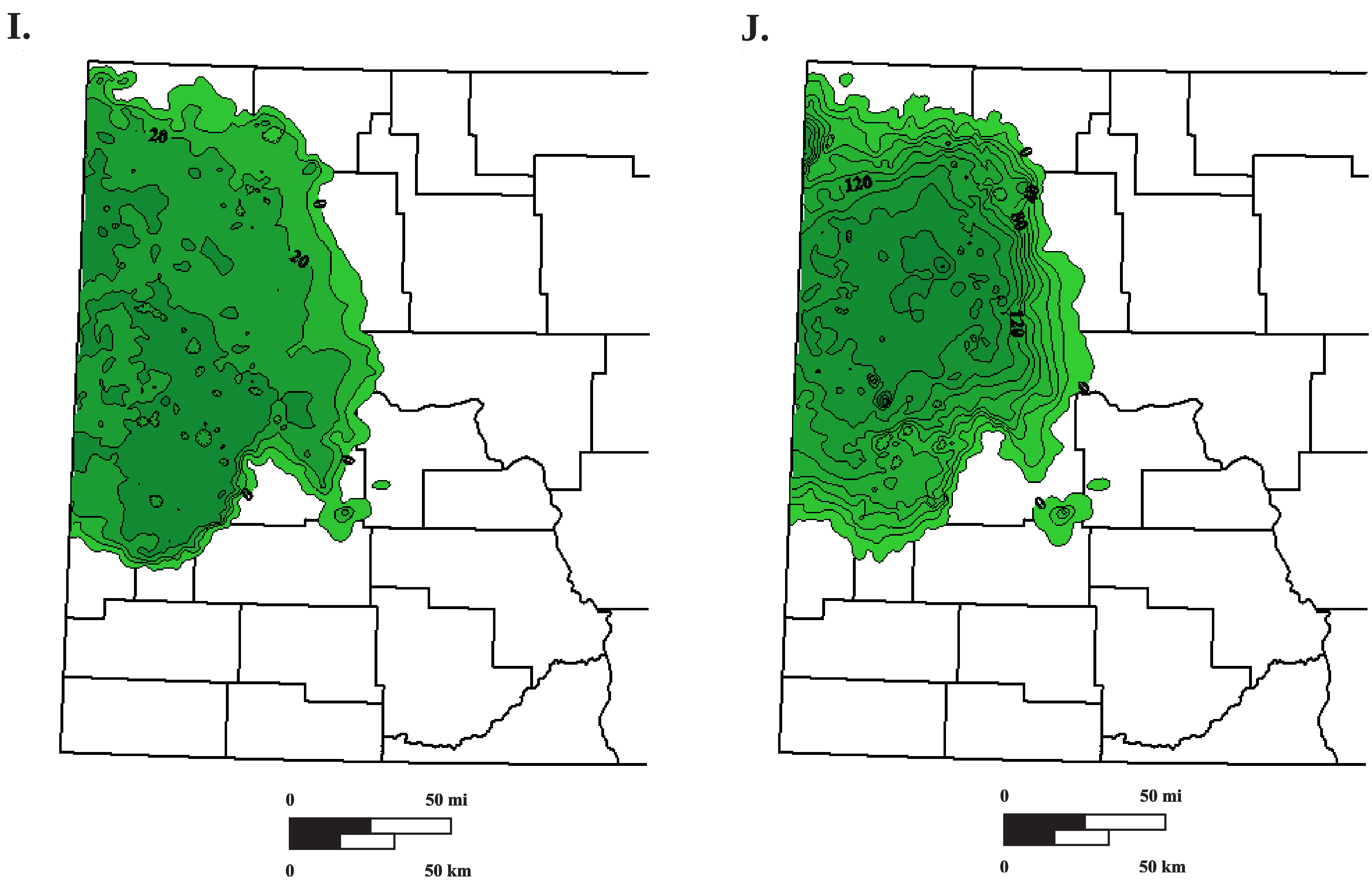


Figure 11 (con't). I.) Isopach map of the B salt (C.I. = 10 ft). J.) Isopach map of the A salt (C.I. = 20 ft).

K.

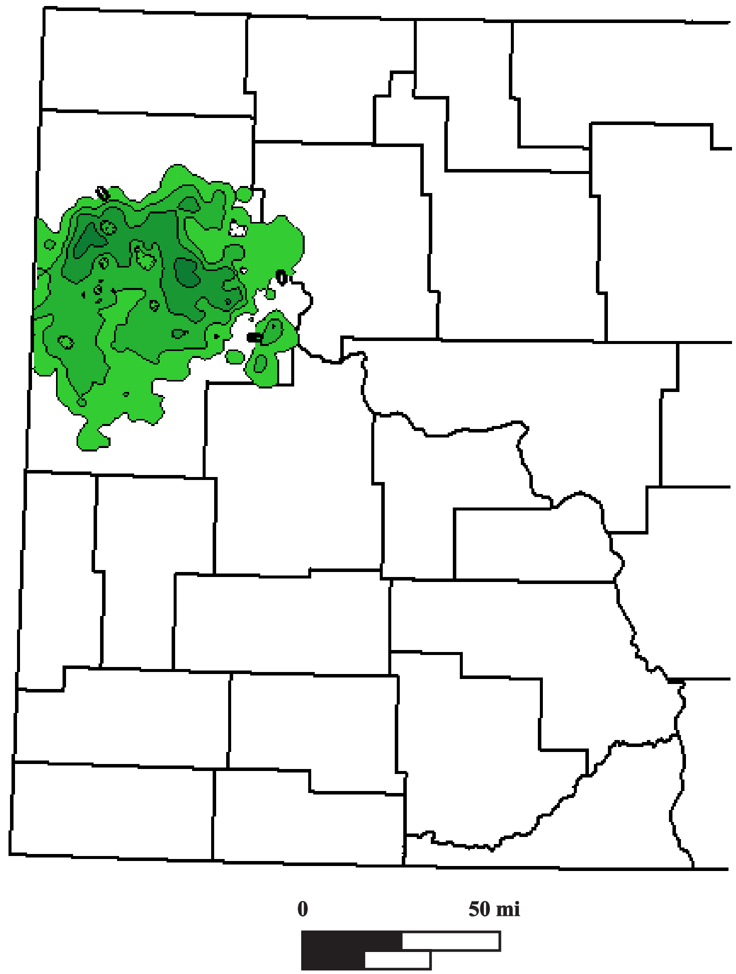


Figure 11 (con't). *K.) Isopach map of the A1 salt (C.I. = 20 ft).*

Opeche B and A (Anderson and Hansen, 1957; Fig. 12a). The upper salt, Opeche A, has a slightly greater areal extent than the lower Opeche B salt. There is a significant difference in thickness; the maximum thickness of the Opeche B is 57 ft (17.4 m) and the Opeche A is 229 ft (69.8 m)(Figs. 12b, c).

Benison and Goldstein (2000) argued for a nonmarine origin for the evaporites of the Opeche Formation throughout the Williston Basin, and attributed the salts to deposition in an inland playa-type saline-pan. The basin at the time of Opeche deposition was at the landward end of a long embayment of the Permian sea (Sandberg, 1973). It became more isolated with time, possibly as a result of uplift along the Cedar Creek anticline. This uplift continued to restrict flow from the open sea and increase the salinity within the basin. Salts and clastics were laid down as the seas dried up and streams brought muds in from surrounding areas.

Triassic (?)

Spearfish Formation

There are three members of the Spearfish Formation, the lower Belfield, middle Pine Salt, and upper Saude (Dow, 1967; Fig. 13a). The lower two members are restricted to the central basin area, Montana, South Dakota, and Wyoming. The uppermost member, the Saude, extends northward into Canada. In addition to the middle Pine Salt Member, the Spearfish has two other minor salts present within the Saude Member.

The Pine Salt is the thickest of the three salts and has the greatest areal extent (Figs. 13b, c, d). The Pine reaches a maximum thickness of 249 ft (75.9 m). A persistent marker bed lies approximately 20 ft (6 m) above the Pine salt in Bowman, Slope, and portions of Golden Valley, Billings, Stark, and Hettinger Counties. It is generally an anhydrite and is referred to informally as the G marker bed. Isolated lenses of the G salt occur northeast of the main concentration. The G salt is thinner than the rest of the Spearfish salts, with a maximum thickness of 205 ft (62.5 m). An unnamed salt overlies the G salt in a very limited area in Slope County, and reaches a maximum thickness of 130 ft (38.6 m; Fig. 13d).

The Spearfish was deposited in an arid to semi-arid climate, in a marginal marine-tidal flat environment. The salts represent a slight regression or restriction in an overall transgressive system, not unlike the conditions present during Opeche sedimentation.

Jurassic

Piper Formation

The Piper Formation consists of an interbedded sequence of marine limestones and shales. Piper deposition started with a thin, 10 ft (3 m) thick, bed of shale, informally referred to as the Poe marker. This shale horizon is overlain by the Dunham salt. The Dunham extends over most of western North Dakota with a few isolated lenses outside of the main salt body (Fig. 14). It reaches a maximum thickness of 189 ft (57.6 m).

The Dunham salt consists predominantly of halite with some interbeds of reddish brown mudstone and anhydrite. The Dunham also followed patterns similar to the Spearfish and was probably deposited during a minor restrictive phase in a transgression.

SALT DISSOLUTION

Recognition

Several methods can be used to help identify areas of possible salt dissolution in theWilliston Basin. Methods commonly used include geophysical surveys, isopach and structure maps. Care must be taken in the correlations on wireline logs when the data are used for recognition of salt dissolution and subsidence structures. The following discussion is based upon isopach and structure maps for the various salts within the study area. Geophysical data were not available.

Data from isopach and structure maps can be substantiated further by the examination of available cores. Cores can display characteristics common to salt collapse, such as a collapse-fill facies consisting of a basal zone of fine, insoluble material (mostly clays) overlain by collapse breccia (Holter, 1969). This information can then be carried into areas where the only data source is wireline logs.

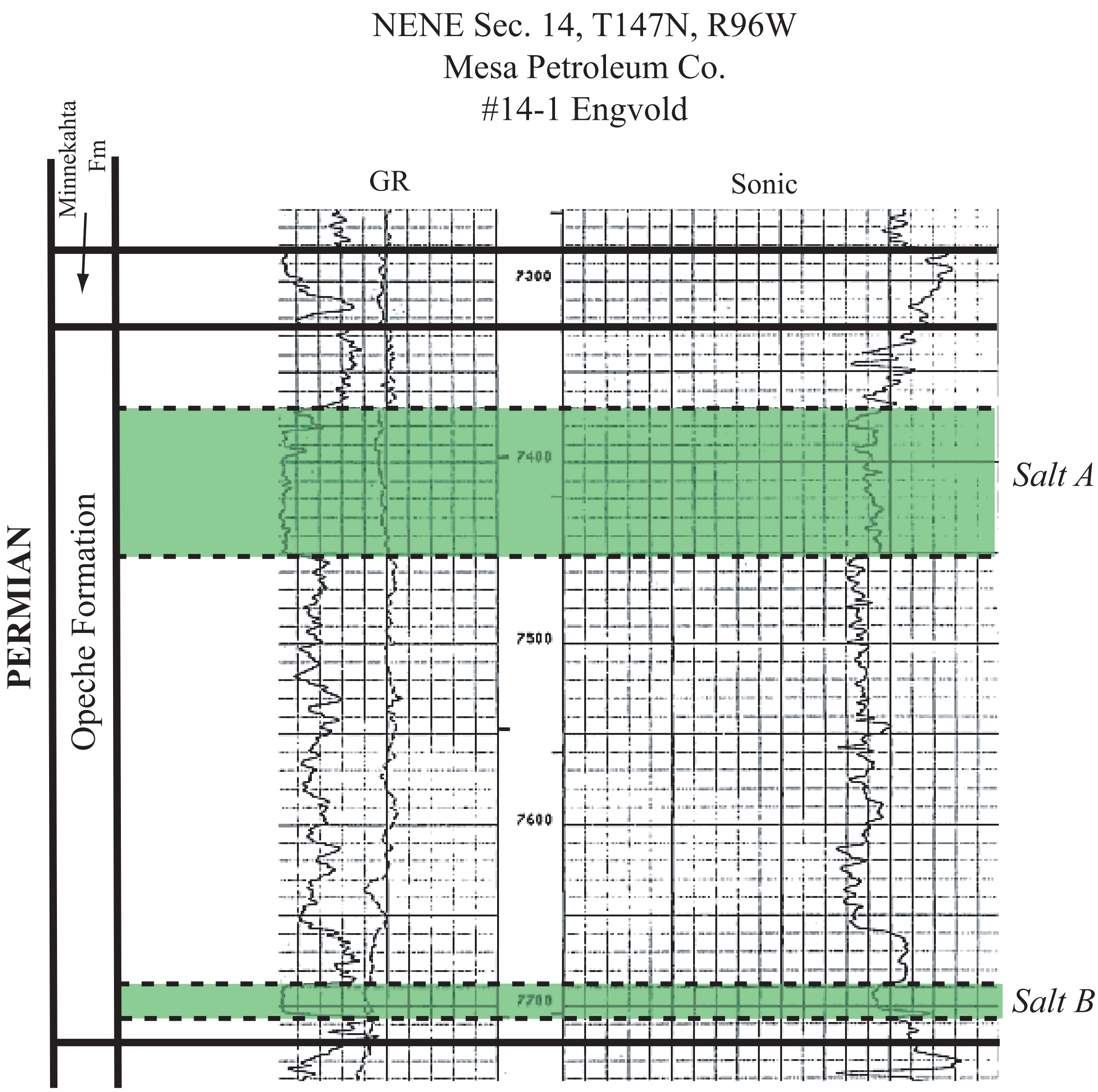


Figure 12. *A.) Typical log characteristics of the two massive Opeche salts, B and A.*

A.

B.

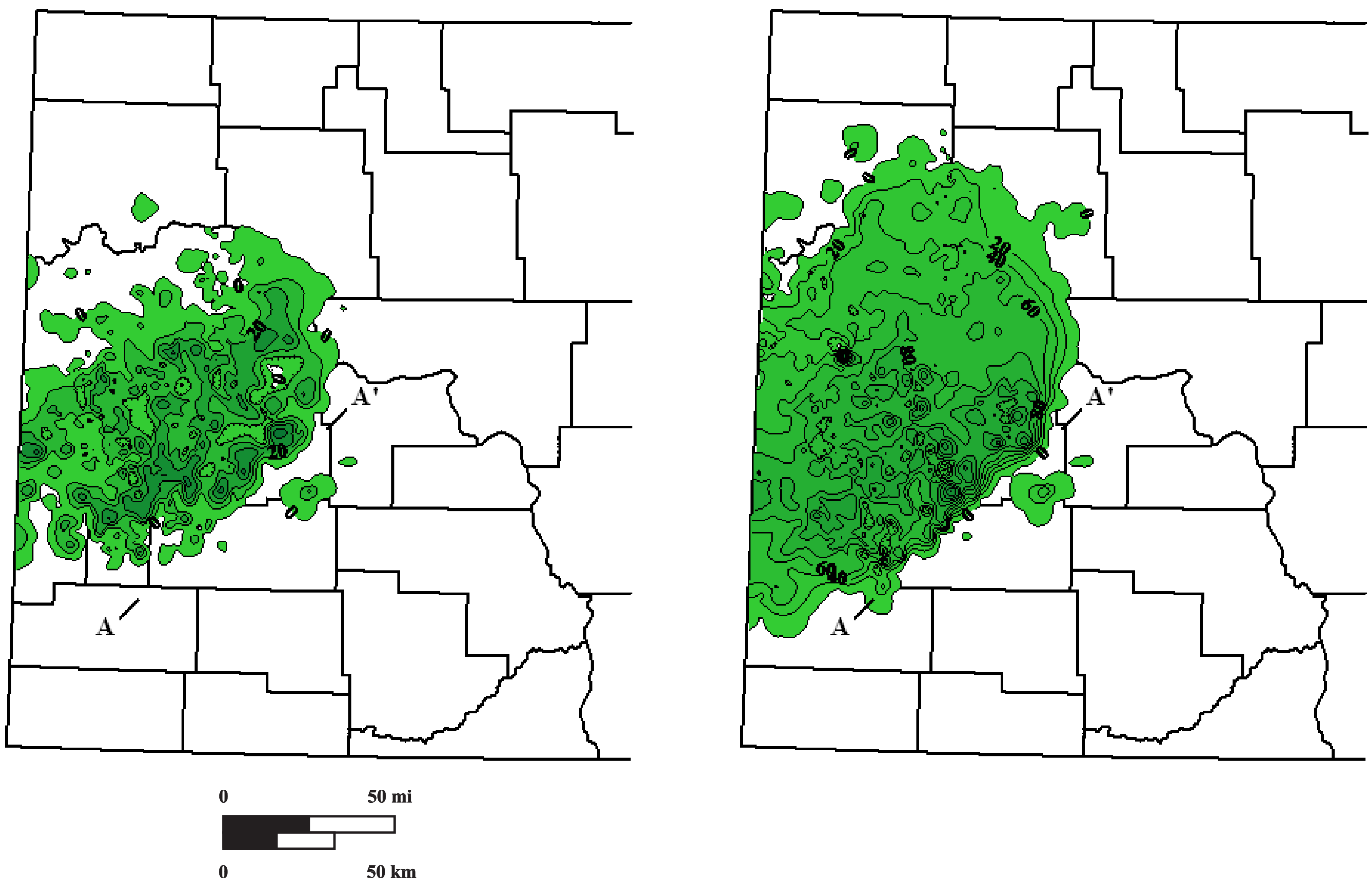
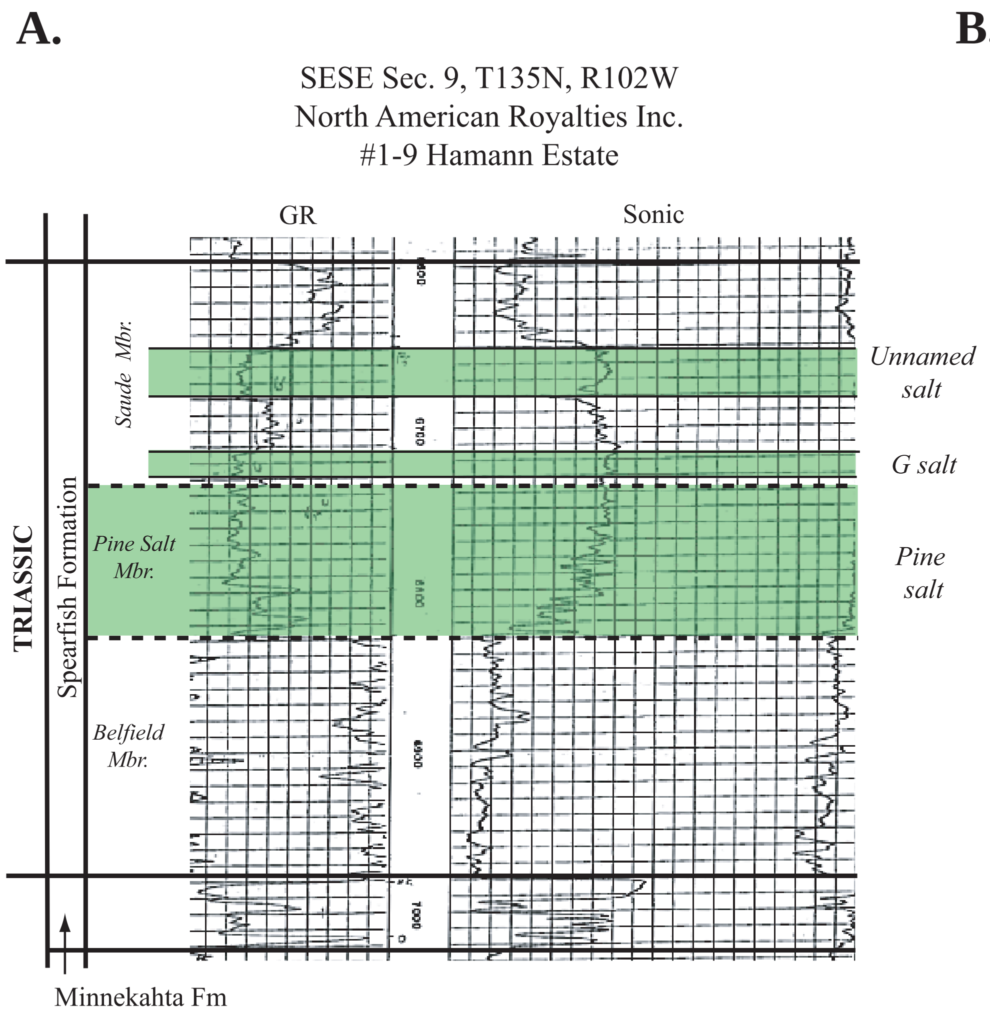


Figure 12 (con't) B.) Isopach map of the Opeche B salt (C.I. = 10 ft). C.) Isopach map of the Opeche A salt (C.I. = 20 ft). Dissolution edge is marked by trend from A to A'.



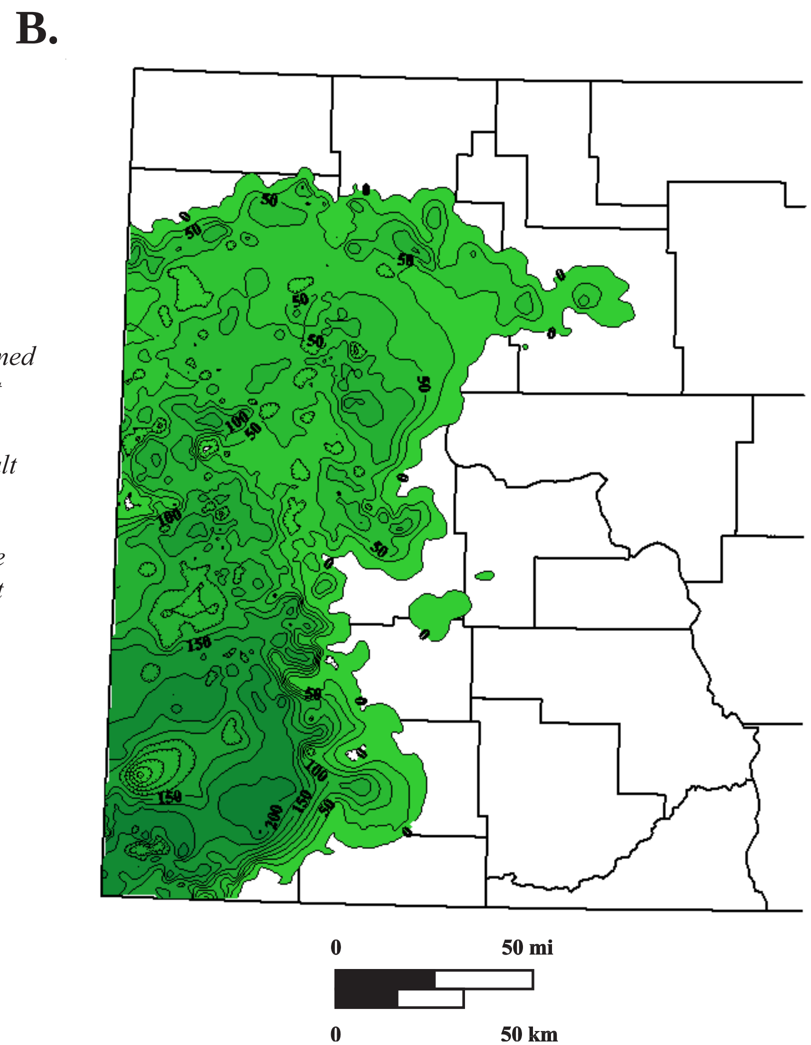
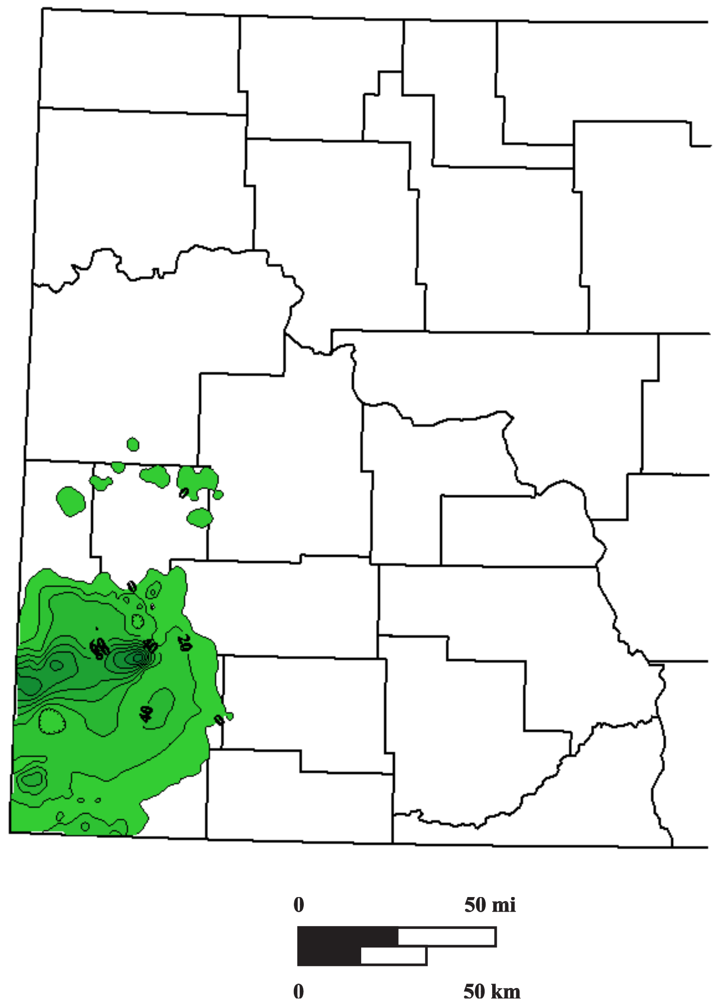


Figure 13. *A.) Typical log characteristics of the salts of the Spearfish Formation. B.) Isopach of the Pine Salt Member (C.I. = 25 ft).*

C.



D.

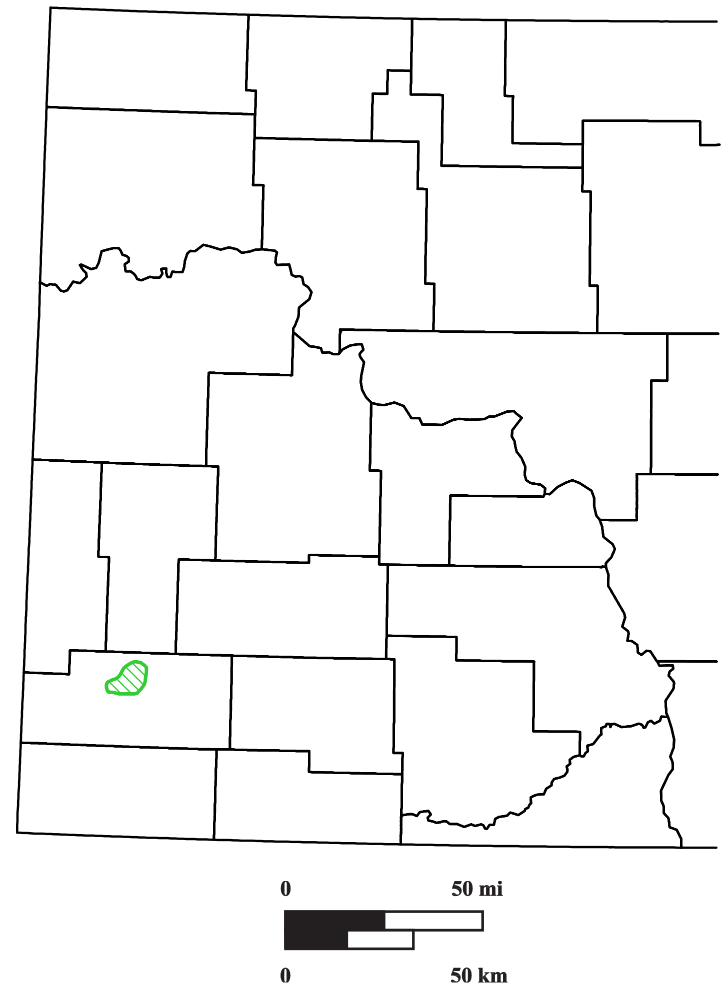


Figure 13 (con't). *C.) Isopach of the G salt (C.I. = 20 ft). D.) Areal distribution of the unnamed Spearfish salt.*

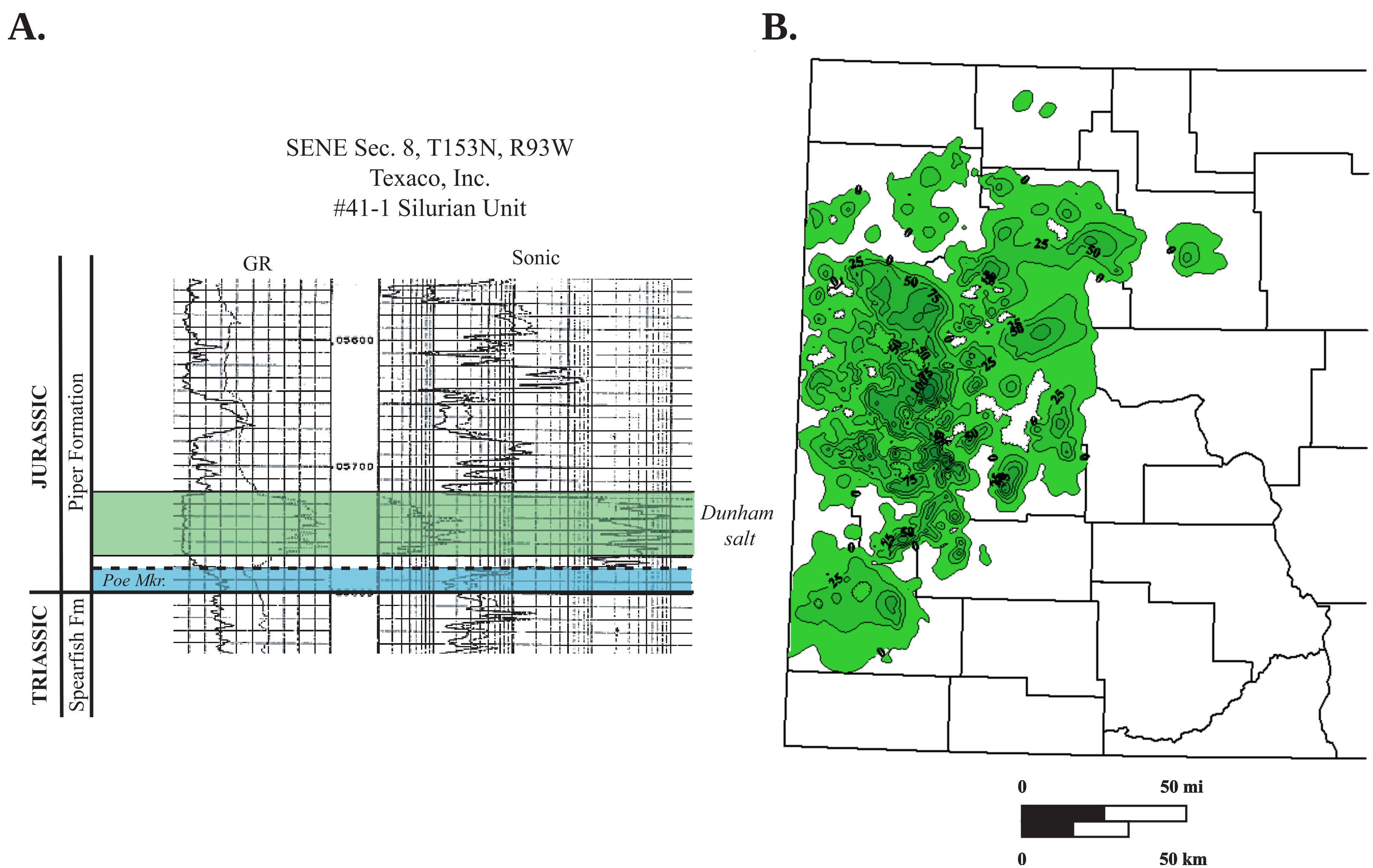


Figure 14. *A.) Typical log characteristics of the Dunham salt of the Piper Formation. B.) Isopach map of the Dunham salt (C.I. = 25 ft).*

Mechanisms

Salt dissolution can occur as localized isolated features, a series of dissolution lenses, a channel-like structure, or as a slow moving front (dissolutional edge). The shape of the dissolution feature and the shape of the resulting collapse feature, considered in a regional context, may provide insight about the mechanism that caused dissolution. Holter (1969) reported a correlation between many of the areas exhibiting salt dissolution with the existence of Precambrian highs and reactivation of pre-existing structures. The feature common to most of the areas was the presence of fractures or faults. Fractures or faults allow fluid to move up and down or in and out of the salt bed. Salt removal is also intermittent, generally with long periods of no evidence of dissolution.

Several models have been suggested for salt dissolution (Fig. 15; Holter, 1969; Gendzwill, 1978; Oglesby, 1988): 1) depositional facies control - dissolving fluids move through permeable beds adjacent to the salt horizon; 2) compaction and dewatering of surrounding sediments supplies the fluid necessary for salt dissolution; 3) surface water recharge at the outcrop and resulting basinward flow, perhaps assisted by fractures, dissolves salts.

Dissolution

Several areas of demonstrated or probable salt dissolution have been identified in the North Dakota Williston Basin (Fig. 16). All were identified through a combination of salt isopach and structure maps, and the recognition of overlying compensating section.

Areas of known salt dissolution include the Hummingbird trough, the South Heart syncline, the Newburg syncline and the Glenburn anticline. The Hummingbird trough is a 100 mi (160 km) long depression that extends along a northwesterly trend in southern Saskatchewan (DeMille et al., 1964; Holter, 1969). Subsidence in the Canadian part of the trough began as early as Late Devonian and has recurred repeatedly into Tertiary time. The extension of the Hummingbird trough into North Dakota occurred during deposition of the Midale carbonates and again during the deposition of the E salts.

Dissolution along the South Heart syncline was first recognized by Anderson (1966), who reported dissolution of the Opeche salt around Dickinson field (T139-140N, R96-97W) and locally in T138N, R100-101W. The syncline was first described as an extensive solution feature by LeFever and Crashell (1991). Subsidence along the syncline was apparently Late Cenozoic, as the Oligocene surface strata are affected by the collapse.

The Newburg syncline and the Glenburn anticline were described by LeFever and Anderson (1986) and LeFever and LeFever (1991). These structures overlie what was previously thought to be the boundary between two Precambrian provinces. Recent data has enhanced the interpretation and subdivided the Churchill province into smaller fault-bounded terranes (Trans-Hudson orogenic belt; Green et al., 1985; Klasner and King, 1986). Periodic movement has resulted in the dissolution of the Prairie salt and subsequent collapse of the overlying sediments. Limited deep control suggests that dissolution may have begun during the deposition of the Dawson Bay Formation (Devonian). The dissolution front is documented in this area by anomalous thicknesses in the overlying strata of Devonian and Mississippian age (Anderson and Hunt, 1964).

There are numerous structural features within the North Dakota part of the basin which might influence dissolution of salts (Fig. 17). In some cases, as with the Dunham salt, they have apparently done so (Fig. 18). The Nesson anticline and the Billings anticline have been shown to consist of individual structural elements or blocks, which have moved independently of the basin subsidence (LeFever et al., 1987; LeFever and Crashell, 1991). All of the structural blocks are presumably bounded by faults, although few faults have been described in the literature. The boundaries of the blocks are thus locations where fluid movement might produce salt dissolution.

Three extensive fault systems have been described within North Dakota (Fig. 19): 1) the Nesson anticline boundary fault (Gerhard et al., 1982); 2) the Antelope fault (Folsom et al., 1959; Murray, 1968); and 3) the Heart River fault system (Chimney et al., 1992). All three are possible pathways for fluid migration, although little salt solution is evident along their extents.

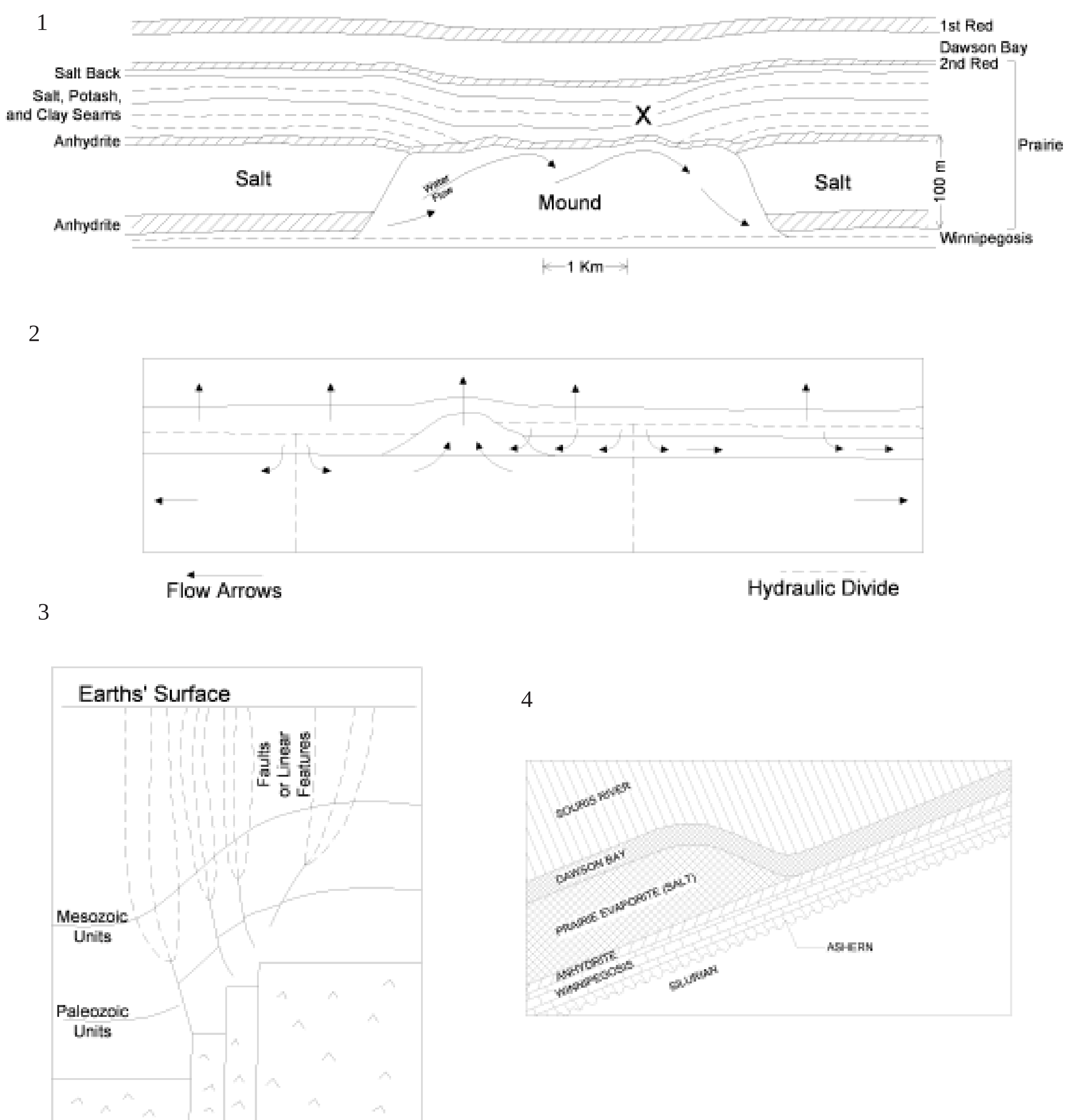


Figure 15. *Proposed models for salt dissolution. 1) Model showing dissolving fluid moving through permeable beds. This diagram is a model proposed by for Winnipegosis mounds in Montana (after Gendzwill, 1978). Model shows suggested water circulation through the mound, slumping as result of salt removal directly above the mound, accumulation of insoluble materials on top of the mound, local intense solution-collapse "X," thickening of "salt back" over potash beds , and thinning of the Dawson Bay Formation. 2) Compaction and dewatering of surrounding sediments supplying dissolving fluids. The diagram shows a hypothetical model for groundwater flow related to the Leduc reefs and surrounding Ireton shales (after Hugo, 1985). 3) Model of surface water recharge at the outcrop resulting in basinward flow, assisted by fractures to deliver dissolving fluids to salt horizon. Faults or linear features that are possibly rooted in basement rocks act as a conduit for fluid movement to the salts (after Shurr, 1982). 4) Model for salt dissolution and development of a compensating section along the depositional limit of the Prairie salt (Gorrell and Alderman, 1968).*

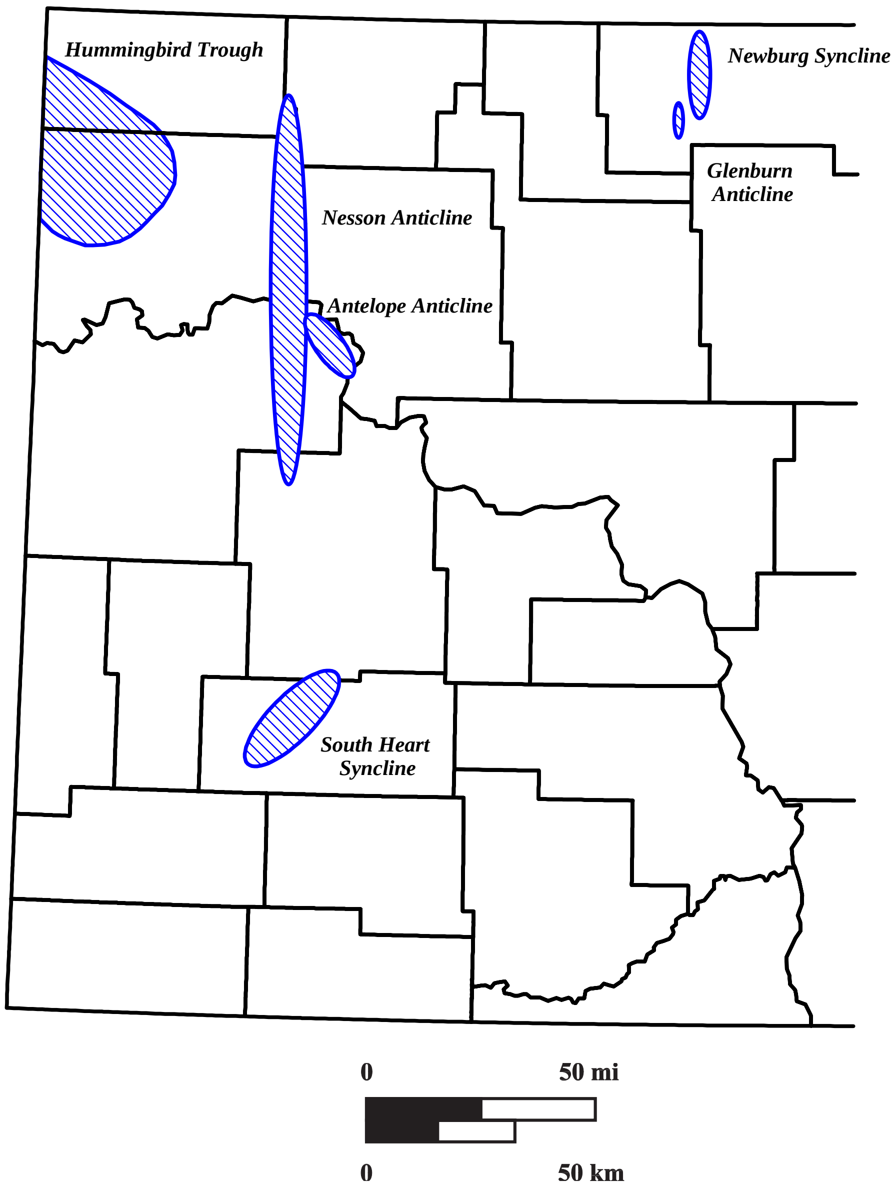


Figure 16. Areas of known salt dissolution and related features.

Many of the salts show no evidence of dissolution. However, knowledge of their existence becomes important when drilling and exploring inanew region. The following discussion concerns salts that may have relevance to trapping and reservoir development.

Prairie Formation

Numerous studies have described various aspects of the Prairie salt on both a regional and local scale, from its relationship to the underlying Winnipegosis Formation to the dissolution of the salt and resulting tectonics and reservoir development (i.e. Anderson and Hunt, 1964; DeMille et al., 1964; Holter, 1969; Gendzwill, 1978; McTavish and Vigrass, 1987; Oglesby, 1988). The Prairie salt has had and continues to have a profound influence on the overlying sediments.

The isopach pattern of the Prairie salt reflects the Devonian connection with the Elk Point Basin (Fig. 9b, c). There is a gradual increase in thickness to the north away from the zero edge. This increase is reversed in Burke County, where the Prairie was deposited around the pre-existing topography of the Devonian Winnipegosis pinnacle reefs. The Nesson anticline was also a positive feature, and the Prairie salt thins over the structure. Contours change abruptly along the eastern margin of the basin in Bottineau County. The abrupt change in contours and the presence of a small outlier of Devonian salt reflect dissolution along this edge. Although the remaining edge of the Prairie appears gradational, there is evidence that suggests that the entire limit of the Prairie salt results from dissolution.

Deposition of the Prairie salt is thought to have occurred in a "deep basin" setting (Gendzwill, 1978; Oglesby, 1988). Since evaporites accumulate rapidly, a basin with a suitable topography or water depth would be necessary in order to accommodate the Prairie salt. Salts of the Prairie would fill in, around and eventually over the pre-existing Winnipegosis topography (pinnacle reefs). This appears to have been the case in Burke County. However, the total thickness of the salt plus the pinnacle reef is slightly less than the thickness of the salt away from the pinnacle, which suggests loss of salt (dissolution) over the pinnacle. Additional evidence for this dissolution event includes localized collapse structures with folds and fractures. It was suggested by Gendzwill (1978) that only partial dissolution occurred over these reefs. Fresher water is thought to have moved horizontally into the porous carbonate zone where it dissolved the surrounding salt. The brines thus generated sank, were replaced by fresher water, and dissolution continued along the salt-carbonate interface. Eventually insoluble material plugged the porosity in the upper portion of the reef and prevented further dissolution. Diagenetic changes within the potential reservoir rock, in addition to the impermeable cap rock, could provide a suitable trap for hydrocarbons in the underlying Winnipegosis rocks. Diagenetic changes would have to be limited, since halite plugging, incomplete anhydrite or residue seals, and over-dolomitization may affect or destroy potential reservoirs (Ehrets and Kissling, 1987).

The present limit of the Prairie salt in north-central North Dakota apparently results from dissolution, not deposition. There are several lines of evidence that suggest this has occurred: 1) The isopach map of the Prairie in this area shows an abrupt change in the contours, rapidly increasing in thickness towards the center of the basin. 2) There is a small outlier of salt present in the Amerada Petroleum Corp. #1 Lila Stark (SESE Sec. 20, T162N, R78W) well. The salt is 68 ft (20.7 m) thick in the #1 Stark and is beyond the current limit of the Prairie salt. 3) There is an east to west progression of isopach thicks for the Devonian formations overlying the Prairie. Each successively higher unit has a band of isopach thicks that step basinward. Available well control demonstrates that in Mississippian time compensating section was deposited through the Bakken, Lodgepole, Tilston, and Frobisher-Alida beds (Anderson and Hunt, 1964; Parker, 1967; LeFever et al., 1991). This zone of compensating section also stepped basinward through time. 4) One well, California Company - #1 Blanche Thompson (SWSE Sec. 31, T161N, R81W), that cored the Prairie in this area has collapse breccia over the interval. Major structures resulting from the dissolution of the Prairie in this area are the Newburg syncline and the Glenburn anticline (LeFever and Anderson, 1986; LeFever and LeFever, 1991).

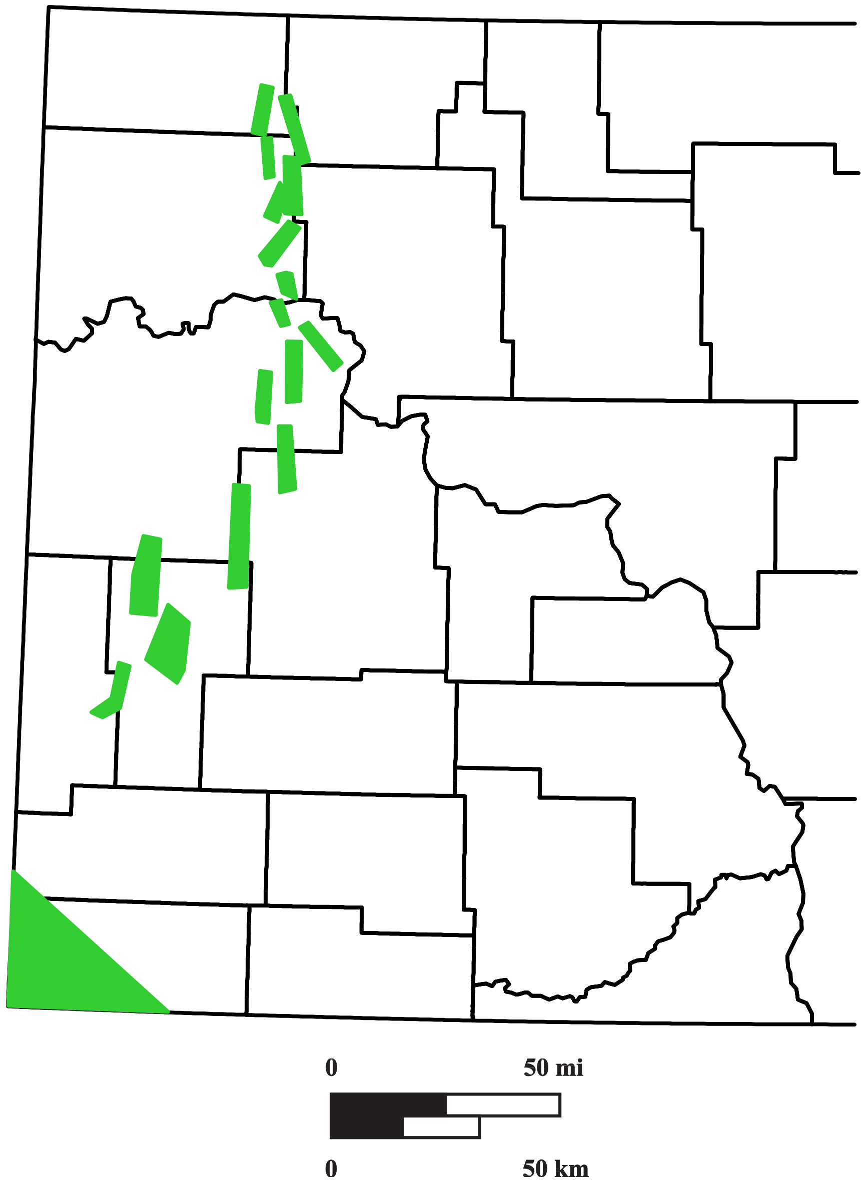


Figure 17. Known structural blocks in western North Dakota.

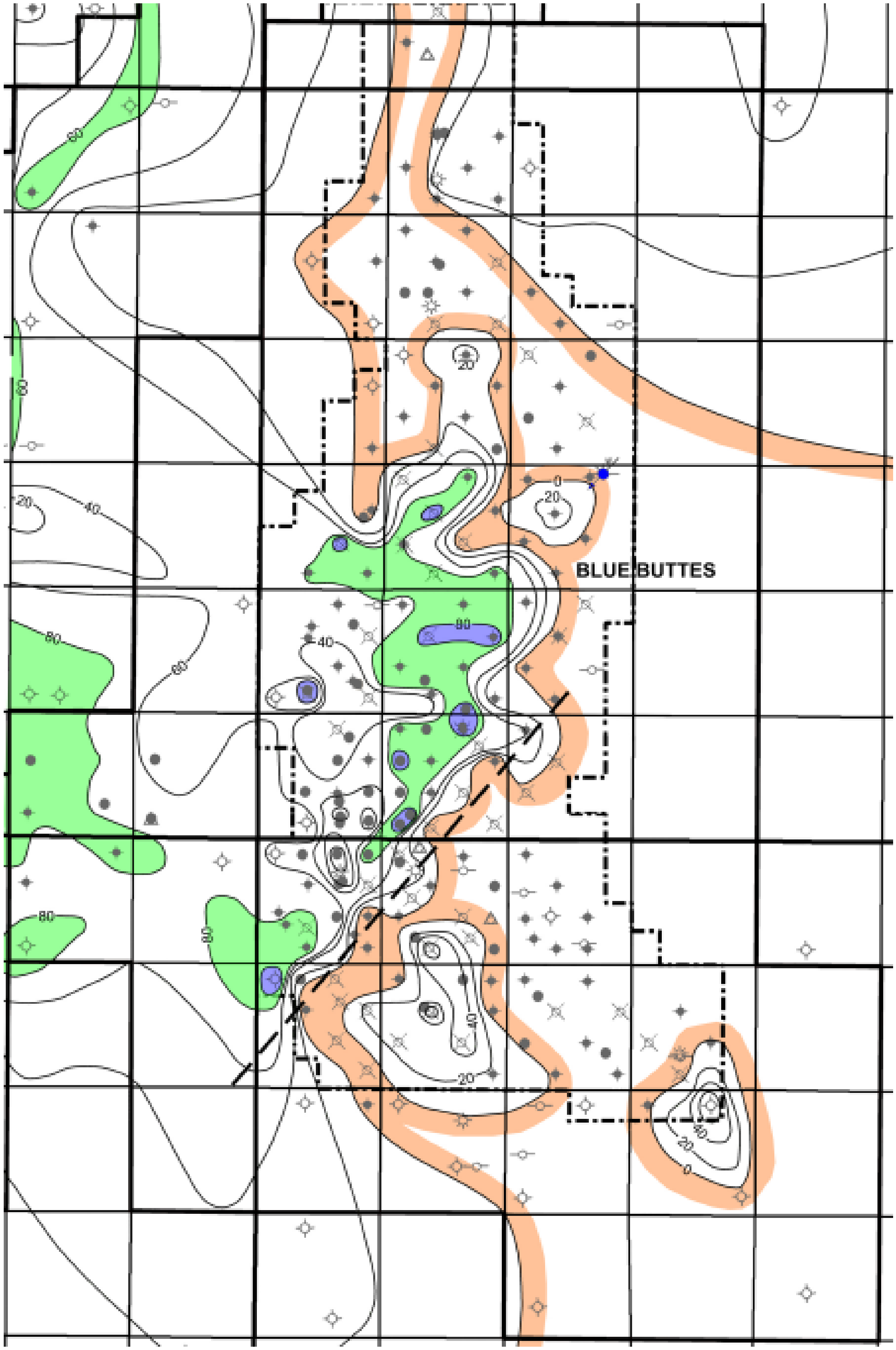


Figure 18. Isopach map of the the Dunham salt (Jurassic) in Blue Buttes Field, Nesson anticline (C.I. = 20 ft). Timing of dissolution of the salt along the northeast-trending fault is Late

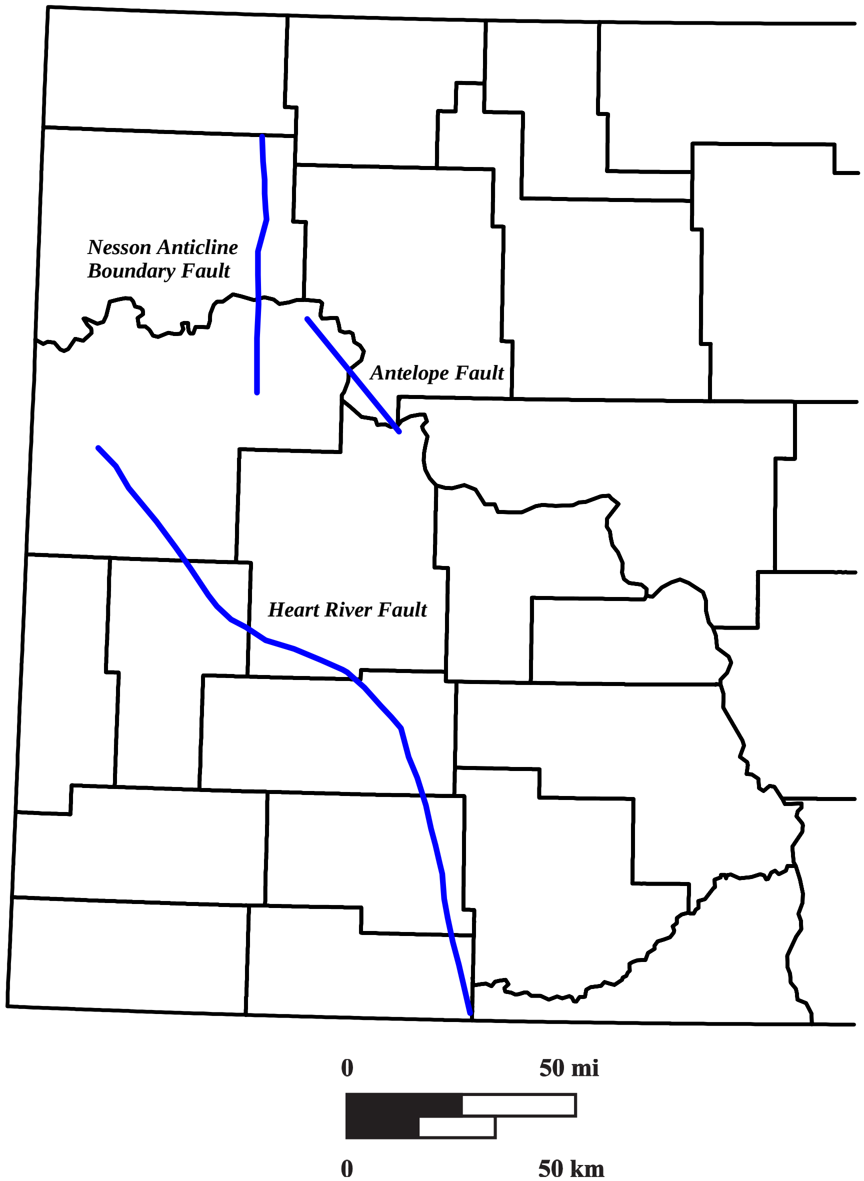


Figure 19. Known fault systems in western North Dakota.

The limit of the Prairie salt in north-central North Dakota appears to be a dissolution edge that moved basinward through time. Dissolution is probably related to periodic movement of faults rooted in the Precambrian basement. This area overlies the junction between the Trans-Hudson Orogen and the Superior Craton. Fracturing along the juxtaposition of the two terranes would allow fluid to migrate into the salt. Initiation of dissolution was during the deposition of the Dawson Bay Formation.

The southern limit of the Prairie Formation has been considered to be depositional rather than a dissolution edge. Examination of the isopach maps and additional core data indicates that this limit may also result from dissolution of the Prairie salt. Immediately overlying the Prairie Formation is a thin bed referred to as the Second Red. This unit consists of red to green non-fossiliferous dolomites and calcareous shales that maintain a constant thickness of about 15 ft (4.6 m) over the study area. Where the Second Red is anomalously thick, it consists of the original lithology plus a collapse-fill facies of insoluble residual fines and breccia. All dissolution wells in the basin show thickened Second Red (Oglesby, 1988). The isopach map of the Second Red exhibits a series of isolated thicks along the southern margin of the Prairie salt (Fig. 9c). When this map is overlain on the Prairie salt isopach, this zone overlies the zero to 50 ft (15.2 m) salt interval. This strongly suggests that in this area partial dissolution has occurred, resulting in a thin remnant of salt that is overlain by a collapse-fill facies and the Second Red. Extensions of thickened Second Red occur farther south in Billings and Golden Valley Counties and southern Dunn and Stark Counties.

The occurrence of dissolution in an area previously thought to be depositional leads to a change in ideas on the way to explore for hydrocarbons in the area. Compensatory section, fractures, and lithofacies changes all need to be taken into account when examining an area for a potential prospect. Moreover, dissolution may have occurred several times in any given area.

Charles Formation

The Sherwood and Bluell salts occur in a discontinuous band along the eastern margin of the basin, from Bottineau County into portions of Sioux and Dunn Counties (Fig.7). Distribution of the salts in the Bluell and Sherwood beds essentially mirror each other. Differences are minor; the Bluell extends farther south and the Sherwood extends slightly farther west. Both salts occur slightly east of the dissolution edge of the Prairie salt. They represent sabkha or salt pan deposits, are probably directly related to the dissolution of the Prairie salt and, like the Devonian and Mississippian isopachous thicks and compensatory sections, are another line of evidence of the basinward migration of the Prairie salt edge. The thin, localized occurrence of the F^1 salt immediately south of the Prairie limit in Dunn, Billings and McKenzie Counties is also probably a function of Prairie salt dissolution (Fig. 11a).

The F salt ("Last Charles Salt") was deposited over most of western North Dakota (Fig. 11b). Minor thickness differences occur in the central portion of the salt area. The convoluted zero contour is probably the result of an irregular shoreline at the time of deposition. Isopach patterns do not reflect any of the present structures in the basin, which indicates that they were not positive elements at the time of deposition. The F salt appears not to be significantly affected by dissolution.

Three separate salt beds can be recognized above the F salt. They occur immediately above the Ratcliffe marker (Greenpoint anhydrite) and are relatively thin, reaching a maximum thickness of 82 ft (25 m). Although the marine connection with the basin was westward through the central Montana trough, the isopachs show a marked northwesterly trend. This trend is apparent on the isopach of the main E salt bed to some degree, but is more pronounced on the E_1 and E_2 isopachs (Fig. 11c, d, e). These salts show the extension of the Hummingbird trough of Saskatchewan into North Dakota.

The D salt is more widely distributed than the E salt, and the D is thicker, reaching a maximum of 96 ft (29.3 m; Fig. 11g). The four uppermost Charles salts are less widely distributed than the D salt (Figs. 11h through k), and the final Charles salt, A1, is restricted to two counties, McKenzie and Williams. All of the salts A through D have probably been affected by dissolution along their southeastern limits, where the edges of the salts abut the South Heart syncline, a known dissolution feature.

Opeche Formation

Isopach maps were generated for the two massive Opeche salts (Fig. 12).

The Opeche salts gradually thicken towards the south. The irregular pattern of the isopachs may be a function of impure salt sections or may result from partial dissolution of the salt. Dissolution of both salts has occurred along the southeastern limits, along the South Heart syncline. This is reflected by the linear pattern of the Opeche salt limit that trends northeast across Stark and Dunn counties (A to A', Fig. 12c). Along this edge the contours also change abruptly.

Spearfish Formation

Three Spearfish salts are shown on Figure 13. The lowermost (Pine Salt) has the greatest areal distribution and is thickest in the southwestern corner of the state, in the direction of the marine connection to the Phosphoria sea (Maughan, 1966). Changes in the Pine Salt are more gradational in the northern portion of the isopach. Irregularities in the southern half of the map are related to later dissolution. Isolated isopach thins, areas devoid of salt, and the current eastern limit of the Pine were previously reported by Anderson (1966). Based on compensatory section, timing of the dissolution appears to be Late Jurassic.

Deposition of the G salt was much more limited than that of the Pine (Fig. 13c). Isolated occurrences of the salt occur to the northeast of the main deposit and are probably a function of the depositional environment.

Piper Formation

The irregular thickness distribution of the Dunham is largely due to dissolution (Fig. 14). Notable dissolution has occurred along the Nesson anticline. The dissolution edge crosses the anticline through Clear Creek, Hawkeye, Blue Buttes, and Antelope fields. Faulting in the area of Blue Buttes Field is readily apparent as the salt is removed abruptly between wells in a 40 acre spacing unit (Fig. 18). Timing of this movement was Late Jurassic, prior to deposition of the Cretaceous Inyan Kara Formation. Additional compensating section has been documented along a lens of Dunham salt immediately west of the anticline and along the northern portion of the anticline. Timing of the dissolution in this area was Late Jurassic-Early Cretaceous. The presence of the Dunham salt in isolated lenses with compensatory section suggests that the current limit of the Dunham is a dissolution edge.

HYDROCARBON TRAPS

Salts provide a variety of different types of hydrocarbon traps that can form or enhance a reservoir. The easiest type of trap to identify is related to porosity and permeability pinchouts. This is apparent where salt drapes over or around a depositional or structural feature. Examples in the North Dakota portion of the Williston Basin are the Winnipegosis pinnacle reefs (Gendzwill, 1978; Oglesby, 1988). Draping and dissolution of the Prairie salt over the reefs has resulted in the formation of hydrocarbon traps. Salt plugging related to salt dissolution and/or reprecipitation in available porosity and permeability may also form an effective trapping mechanism, as in the Dolphin Field Duperow pool of Divide County. Mapping the available well control in Dolphin Field indicates no apparent structural closure in the field. However, the structure has been enhanced by dissolution of the Prairie salt. Dissolution has also resulted in a reduction of porosity in the field due to salt plugging (Heck, 1988).

Structural features related to multiple stage salt collapse are common in the Williston Basin. Fields with hydrocarbon accumulations that are related to salt collapse include Hummingbird field and the Elbow structure of Saskatchewan, Outlook, Tule Creek, Volt, Benrud fields of Montana, and Dolphin field of North Dakota. Reservoirs may be enhanced by an increase in fracture porosity and by localized diagenetic changes. Early migration of oil into these reservoirs is not necessary.

Several areas within the North Dakota portion of the Williston Basin warrant additional examination. One of these areas follows the limit of the Prairie salt. Isopachous maps and compensatory section of successively higher formations indicate that the limit of the Prairie salt has moved basinward through time. The ability to accurately predict this movement increases the potential of encountering structural traps. Additionally, the ability to map this edge may also explain the local changes in depositional environments. Another area of interest concerning the Prairie salt occurs in the northwestern corner of the state. The extension of the Hummingbird trough into North Dakota provides an additional exploration target. Two-stage salt dissolution has been currently documented to have occurred in the area and further mapping may reveal potential traps.

Since the majority of salt dissolution is related to faulting, dissolution of salts not associated with hydrocarbon production can provide evidence for subtle structural features. Dissolution features related to the Opeche, Pine and Dunham salts are indirect evidence of faulting. One of the best examples of this concerns the Dunham salt in the southern portion of Blue Buttes Field. The absence or presence of these salts may indicate local areas of re-occuring activity, as in the Medora-Fryburg-Dickinson areas.

SUMMARY

Numerous salts exist throughout the subsurface of the North Dakota Williston Basin. Although not all of the salts have tectonic significance, many of the salts can be directly or indirectly related to basin structure. Detailed correlation and mapping of these salts can identify areas of possible salt collapse structures that may entrap hydrocarbons.

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