Montana Bakken Hybrid and Unconventional Plays*

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Abstract

Mature Bakken shales in northeastern Montana including all or parts of Daniels, Sheridan, Roosevelt and Richland counties are being developed at a slow pace. There are two reasons for this: 1) a hypothesis that the Brockton-Froid Lineament ("BFL") divides the Bakken into an eastern unconventional play and a western conventional play, and 2) high water cuts have been reported from wells completed to date on both sides of the BFL in northeastern Montana.

The Brockton-Froid Lineament is one of six major lineaments that cut across the mature area of the Bakken shales. It is considered by many operators and authors to influence the Bakken even though the Nesson and Cedar Creek lineaments are documented to be related locally to significant vertical faults. For the BFL to be a barrier, migration within the Bakken is required. Contradictory evidence supports and invalidates migration. However, if migration within the Bakken did ensue, only the southern third of the Cedar Creek Lineament is a barrier to migration for all Williston Basin reservoirs, not just the Bakken.

Porosity and permeability of the Bakken middle member are not sufficient to explain high water production reported to date in northeastern Montana. High water yields are attributed to erroneously selecting the Bakken middle member as the target in areas that have not reached the peak generation window and are compounded by aggressive fracs that may communicate the well bore with the Nisku Formation and, on some occasions, the Dawson Bay Formation, which are effective aquifers.

Targets for laterals in northeastern Montana must be selected on the basis of maturity stage. If maturity is in the peak generation window, expulsion into the Bakken middle member is likely and it should be evaluated in a pilot hole as the target. In mature areas that have not reached this window, expulsion is limited or non-existent and the target should be the Bakken upper shale.

Northeastern Montana sweet spots most likely will be associated with solution of salt in the Prairie Evaporite. Timing of the solution may produce abnormal facies or fracturing. Although salt solution has resulted in more than 60 miles west-to-east migration of the present-day solution edge, most of the solution occurred during Devonian and Early Mississippian time. To form a Bakken Oil System (BOS) sweet spot, solution must be coeval to BOS deposition or peak generation.

Introduction

Northeastern Montana lies on the western margin of the Williston Basin. Where the Bakken shales are mature, the basin is dissected by six major lineaments (Figure 1.). Unlike the Brockton-Froid Lineament, the Cedar Creek and Nesson lineaments are locally defined by major near vertical faults with significant displacement.

All or parts of three formations (Three Forks, Bakken and Lodgepole) make up the Bakken Oil System (Figure 2). The Devonian-Mississippian unconformity occurs at the base of the Bakken upper shale. The unconformity surface is onlapped by progressively younger strata to the west and south in NE Montana.

Initial commercial development of the Bakken Oil System (BOS) occurred in the 1953 discovery of Antelope Field in which the Sanish Sandstone (at the top of the Three Forks) and Bakken are host rocks. It was not until a 1978 publication by Meissner that the reason for the prolific production was a intense fracture fairway along the flexure of the Antelope structure. This sparked active drilling along the depositional edge of the Bakken upper shale in the 1980's and 1990s.

Technology changed the economics of the play when Meridian re-entered their Elk Horn Ranch 33-11 (143N-102W, Sec. 11) and drilled a 2600 foot lateral in an eight-foot Bakken upper shale (BUS) that is in unconformable contact with the Three Forks Formation. Although IP was only 263 BOPD, decline was low and the well has produced nearly 400,000 BO. Operators took notice and began drilling horizontal Bakken wells in the BUS along the fractured flanks of known structures during this time period.

Several unsuccessful Red River tests were recompleted in the Bakken middle member ("BMM") in northeastern Richland County. Few of the BMM "bail outs" paid out on a full cycle economic model because of low oil prices and the burden of supporting the extra cost of drilling and evaluating the approximate 3000-foot of section between the Bakken and Red River D. In 2000, LYCO Energy drilled the first horizontal well in the BMM that led to the discovery of Elm Coulee Field. The well was significant because it was the first in which a lateral purposely targeted the BMM. Maturity of the upper shale was sufficient to expel oil into the BMM which contained higher than normal porosity and permeability in a dolomitic rich facies within the limits of Elm Coulee Field. Discovery of Elm Coulee changed the Bakken play from a shale unconventional play to a hybrid BMM one.

There are nearly 675 producing wells in Elm Coulee to date, but there are only 79 producing Bakken wells in the rest of Montana compared to nearly 4400 producing Bakken wells in North Dakota. This is attributed to two factors; namely, to date high-water yields have discouraged many companies from developing their leases in Montana and many operators and authors believe the Brockton-Froid Lineament ("BFL") is the western boundary of the Bakken Oil System unconventional play (Sonnenberg, 2012, Slide 10).

It is the purpose of the paper to present evidence that: 1) where mature, Bakken shales are continuous oil-bearing source rocks in NE Montana; 2) the BFL has no effect on the Bakken; 3) limited drilling indicates the Bakken middle member has similar development potential as the east side of the BFL and 4) the Bakken Oil System in northeastern Montana affords similar development opportunities as the Bakken Oil System in North Dakota.

Stratigraphy and Reservoir Characteristics

The Bakken Formation and its Alberta equivalent, Exshaw and Banff formations, were deposited in an elongated extension of the Devonian sea (Figure 3). Over 7000 wells have penetrated the Bakken section in the U.S. portion of the embayment and thus the stratigraphy of the Bakken is well documented (Meissner, 1978 ; Webster, 1984, to name a few authors).

The Bakken, from base to top, is composed of three members, a homogeneous lower mudrock (shale) member, a heterogeneous middle member, and an organic rich upper mudrock (shale) member. The lower two members are Devonian in age and the upper one is Mississippian. In northeastern Montana the lower shale varies from 0 to 24 feet thick (Figure 4). It is dark colored due to its high organic content that ranges up to about 25%. Disseminated pyrite is common and clay minerals make up less than 20% of its composition. Locally thin limestone and green-shaded clay-rich shale beds occur in the lower part of the member. Organic matter is typically Type II kerogen (LeFever, 2007). It was most likely deposited in a subtidal environment.

In northeastern Montana the Bakken middle member ("BMM") represents subtidal to tidal deposits and varies from 0 to a maximum thickness of about 60 feet. The BMM is a heterogeneous interbedded sequence composed of silica-rich sands and silt- and mud-sized lithologies that log data depict as a coarsening-upward sequence that in many cases is actually an increase in carbonate (Figure 5). Intergranular porosity ranges from less than 6% to 10%, and the higher range is typically more dolomitic. Permeability is normally 0.01 md, but up to 0.05 md has been reported.

The Mississippian Bakken upper shale is typically a black, thinly laminated, fissile organic rich mudstone. Total organic carbon ranges up to more than 25%. Disseminated pyrite is scattered throughout the member. Clay content is normally less than 20%. Porosity is about 2%.

Thickness of the shale is rather uniform but ranges up to 25 feet (red area on Figure 6). Seismic data indicates the local thickness anomalies are due to Early Mississippian solution of salt in the Prairie Formation east of its regional solution edge.

Overlying the Bakken are the Lodgepole, Mission Canyon, and Charles formations of the Mississippian Madison Group. The Three Forks, Nisku (Birdbear), and Duperow formations are Upper Devonian units that underlie, in succession, the Bakken.

Maturity of Bakken Shales in Northeastern Montana

Generation

Temperature at which organic matter ("OM") begins to mature is well documented (Figure 7). It is known that for every 18^{o}F the temperature increases, generation reaction time is halved (Philp and Galvez-Sinbaldi, 1991). Not much data has been published on the thermal history of the Williston Basin. However, lineaments exist in the basin and it has been speculated they are deep-seated and perhaps a source of heat that produced a significantly higher thermal gradient than the present gradient depicted in Figure 8. Recent cooling is attributed to the melting of the various continental ice sheets that covered the area during the Pleistocene and erosion.

Timing of Peak Generation

A time vs. temperature Index plot ("TTI") for northeastern Montana (Figure 8) is based on the present thermal gradient (Figure 9) and Bakken burial history. The TTI plot depicts initial generation of Bakken oil as having begun in Early Cretaceous and peaked in mid- to Late Cretaceous time. The peak generation curve on the TTI plot was obtained from Figure 7. In the event the current temperature is in fact less than it was during the Jurassic, peak generation might have initiated in Late Jurassic or Early Cretaceous time.

Maturity and Source Rocks

Based on 101 wells, Demicki and Pirkle (1985) published a Vitrinite Reflectance (Ro in %) map (Figure 10) before the more the recent Bakken penetrations. For example, Ro in excess of 1.0 has been recorded in the Samson Gretel II (22: SWSE, 28N-53E). Ro ranges from 0.82 to 1.14 with a medium of 0.96. This places it in the middle range of peak generation (Samson Oil and Gas, 2012, slides 21 and 26). Based on Figure 10, Ro in the Gretel II should be about 0.85.

The southerly trending Ro low through Sheridan County is supported by a similar trending lower pore pressure area (Figure 11). The dashed contour lines are after Meissner (1978). Data to support solid contours was generated for this article. For the most part, pore pressure in northeastern Montana is above 0.5 psi/ft which is thought to be the threshold between mature and immature source material.

Meissner (1978) noted that where Ro is less than about 0.6, resistivity ("Rt") of the Bakken shale in eastern Montana and North Dakota is less than 100 Ω m^2/m (. Where Ro is greater than 0.6, Rt is more than 100 Ω. Because there are more control points for resistivity, this map of resistivity (Figure 12) may be more accurate than either the pore pressure or the Vitrinite Reflectance map. This assumes that there is a direct relationship between Ro and Rt.

Source rock maturity is also indicated by determining hydrocarbon index ("HI"). HI value below 650 is the defining value for hydrocarbon generation (Figure 13). In eastern Montana HI ranges from 0 to about 500. This supports the interpretation that the Bakken shales are mature in NE Montana. A HI of 400 or lower indicates peak generation. During peak generation kerogen is converted to oil causing a 30% increase in volume. A HI of 400 or lower is typically sufficient to stimulate expulsion. If the source rock is bounded by strata that contain sufficient pore-throat size, expulsion occurs. However, regardless of maturity, if the source rock is encapsulated in impermeable strata, expulsion is limited and pore pressure rises.

It is apparent that the four maturity indicator maps present similar but not identical representations of maturity stages. This is primarily due to the expense and time of conducting Vitrinite Reflectance and hydrocarbon index analysis, thus limiting the number of control points. Few control points, of course, affords more leeway in contouring. Further, only a few, if any, common wells were analyzed for both Ro and HI. It is also possible that the various measurements are not direct analogs of one another.

Migration

Fundamental to migration is a regional carrier bed directly or indirectly in contact with a source rock and a driving force. A carrier bed must contain sufficiently large pore throats to permit expulsion and later movement of oil from pore to pore. The driving force is a combination of buoyancy, high pore pressure in the source rock, and hydrology. The main restraining force is capillary pressure.

Basic to the argument against lateral migration within the Bakken is the fact that the Bakken middle member ("BMM") does not contain sufficient porosity and permeability to meet the standards of a regional carrier bed. As stated above, it is heterogenous, typically contains less than 6% porosity and 0.01 to 0.05 md of permeability. Normally a carrier bed is characterized by more than 12% porosity and millidarcies of permeability. However, it has been documented that migration paths often occur along unconformable surfaces, and the Mississippian-Devonian unconformity occurs at the base of the Bakken upper shale.

"Migrators" argue that most of the Bakken oil has been expelled into the Bakken middle member (Pitman et.al., 2001) despite the fact the shales are overpressured and shale-only completions have produced up to about 400,000 BO. LeFever et al. (1991) report that there has been significant lateral migration of Bakken oil. Hindle (1997) proposed a three-dimensional technique to predict pathways of Bakken migration within the Williston Basin. Theloy. and Sonnenberg (2012) consider migration as a fundamental variable in Bakken production. Short-distance lateral migration (a few miles) may have occurred in the upper and lower Bakken shales along bedding planes (Sarg et al., 2011).

On the other hand, Pollastro et al. (2010) report there are no proven conventional Bakken reservoirs in the U.S. portion of the Williston Basin. Bachu and Hitchon (1996) report the Bakken is an aquitard and as such restricts groundwater movement.

“Non-migrators” think migration within the Bakken is not probable, and they use Antelope Field as an example. There is no structural closure; there is no evidence of a stratigraphic trap at Antelope (Figure 14), and thus migration did not occur. “Migrators” point out that low EUR of off-structure wells supports migration because oil has been “depleted” from the area by migration.

Contradictorily, arguments are also made to explain the origin of the prolific Elm Coulee Field. Non-migrators maintain that if migration occurred, a systematic increase in oil cuts would be controlled by structure within the field. Figure 15 depicts the ninth month of oil-cut percentage at Elm Coulee for 651 wells. From northwest to southeast, there is over 2500 feet of structural relief across Elm Coulee. Lowest oil cuts occur on the highest structural position in the field. Migrators argue low oil cuts updip are expected because a facies change within the BMM reduced reservoir quality which is normal for stratigraphic traps. Theloy and Sonnenberg (2010) advise lower recoveries occur downdip from major accumulations; they attribute this feature to migration into the field.

Perhaps the most compelling evidence non-migrators present is there is no systematic relationship between depth and GOR within the U.S. portion of the Williston Basin (Figure 16). In the heterogeneous Bakken middle member, low porosity and permeability should favor gas migration over oil. Therefore, GOR should be related to structure and should increase around the preserved limits of the Bakken. Undoubtedly, limited lateral migration (probably less than a few 10’s of miles) has occurred along the unconformity surface at the base of the upper shale. However, migration is limited to areas where expulsion ensued.

The strongest evidence that migration within the BMM occurred is the Parshall Field area. Despite lower Ro and HI values than required for expulsion to ensue, the BMM is productive; therefore, migration is required to explain the production. Johnson (2009) suggests that early stages of generation produces an increase in acidity of formation waters. The acid-etching water creates secondary porosity and thus forms migration pathways. Distance of lateral migration would have to be measured in tens of miles.

Reasons for Slow Pace of Bakken Development in Northeastern Montana

Evidence including but not necessarily limited to Ro, Rt, HI, and pore pressure is more than adequate to demonstrate that Bakken shales are mature in northeastern Montana and maturity that favorably compares to North Dakota. Yet, the pace of development has been extremely slow. There are two main reasons; namely, oil cuts have been low, thus dissuading operators to develop their leases, and two, the hypothesis that the

Brockton-Froid Lineament ("BFL") is a boundary between a continuous hydrocarbon-bearing Bakken unconventional play on the east and a discontinuous conventional reservoir on the west (Sonnenberg, 2012, slide 10). This has caused many operators to ignore northeastern Montana.

Lineaments as Barriers to Migration

Of the six Williston Basin lineaments (Figure 1) that cross mature Bakken shales, only the Bakken-Froid Lineament has been used to separate the Bakken into unconventional and conventional play categories (Sonnenberg, 2012, slide 10). Yet, both the Nesson and Cedar Creek lineaments are significantly more distinct in the subsurface, and locally they are delineated by major vertical faults with significant displacement.

The Brockton-Froid Lineament ("BFL") has been described by the USGS Earthquake Hazards group (Wheeler, 1999) "as striking northeast across the glacial plains of northeastern Montana and northwestern North Dakota into Saskatchewan." Wheeler reports there is no surface evidence the BFL is deep-seated because nine Fort Union lignites (late Paleocene) do not show vertical offset across the 1500-foot-wide surface lineament and isopach maps of the lignites do not indicate lateral movement.

The BFL barrier hypothesis requires three corollaries: 1) BFL leaks and deflects oil into Canada along its trace, 2) oil migrates within the Bakken and 3) BFL affects facies within the Bakken.

Brockton-Froid Lineament Leaks: This corollary holds that the 1500-foot-wide BFL zone provides a pathway of migration into Canada. This requires the eastern fault or faults to leak and the western system to seal. Samson Oil and Gas (2012) reported that the lateral of their Gretel II drilled through the BFL (Figure 17). Surface location was about 4000 feet west of the three faults comprising the BFL. The lateral cut two-down-to-the-east faults (6- and 11-foot displacement, respectively) and one down-to-the-west fault (19-foot displacement). Significantly, total recorded gas dropped to near zero in the vicinity of the first fault and was consistently low through the fault zone (Samson Oil and Gas, 2012,). If the BFL leaks and deflects oil into Canada, gas shows should have increased rather than decreased within the fault zone. Displacement was not enough to offset the Bakken middle member.

Bakken Oil Migrates: Assuming migration is a significant process within the Bakken, Hindle's model (Figure 18) demonstrates that with the exception of the southern third of the Cedar Creek Lineament, none of the six lineaments affected interpreted migration pathways within the Bakken. Evidence to support his conclusion includes: 1) both older reservoirs (Ordovician Red River through Devonian Nisku) and younger reservoirs (Mission Canyon through Charles) than the Bakken are productive on both sides of the BFL; thus there is no geological reason for it only to serve as a barrier to the Bakken Oil System; 2) there is no evidence that the lineaments affected Vo, Ro, Rt. HI, pore pressure or present-day temperature; and 3) there is no discernible difference in GOR across the lineaments.

Finally, it is inconsistent to use the BFL as a boundary between an unconventional and conventional Bakken play. In the event migration is the reason for the prolific production at Elm Coulee and Parshall fields, as Migrators argue, it follows that the fields are conventional stratigraphic traps and that they are located on the east side of the BFL. Yet, Migrators allege the BFL is the western boundary of the Bakken unconventional play.

BFL Influence on Bakken Facies: This corollary maintains that the BFL influenced facies within the Bakken, and that west of the lineament, the Bakken middle member ("BMM") contains sufficient porosity and permeability to permit migration and entrapment on structures or stratigraphic traps. Regional isopach maps of the BMM depict a maximum thickness of more than 67 feet along the Nesson Lineament (NL) (Figure 19). It trends northwest through Mountrail, Divide, and Burke counties, North Dakota. The thick is not related to the NL, BFL or Poplar Lineament (PL). In the event migration within the BMM was significant, Mountrail County would not be so prolific if the concept that low EUR is due to depletion caused by migration. If migration is a significant process within the Bakken, the thick probably is the most likely pathway of migration into Canada (not northeast Montana) and should be an area of conventional traps; yet it is not.

High Water Production

To date, high water cuts and disposal costs have significantly contributed to the reluctance of operators to offset the few wells that have been drilled in northeastern Montana on both sides of the BFL. Figure 20 is a scatter chart of all horizontal Bakken wells (excluding Elm Coulee) as of December 31, 2012, drilled in northeastern Montana **east** of the BFL. Only ten of thirty-one wells that have been on production for at least three months have yielded oil cuts above 50%. The Bakken middle member was the target in each well and multi-stage fracs were aggressive.

There are geological and operational reasons for the low oil cut. Wells drilled east of the BFL are located in southeastern Sheridan and eastern Roosevelt counties. Ro and HI maps depict a lower maturity window trending southerly through this area. Although Bakken shales are mature, expulsion into the middle member probably has not occurred or it is limited; thus, the upper shale should be the target for Bakken development rather than the middle member.

Adding to the problem of high water production is that aggressive fracs are applied to each lateral regardless of geological parameters. Although no consensus has been reached to date on frac height within the Bakken, published data suggests the range is between 300 to 500 feet and proppant reaching out 50 to 150 feet (Brigham, 2011; Heading et. al., 2008). Thickness of the Three Forks Formation in northeastern Montana is typically less than 150 feet (Figure 21). Therefore, frac fluid reaches the Nisku Formation and perhaps, on occasions, the Middle Devonian Dawson Bay Formation. Both formations contain regional porosity zones that act as carrier beds and salt-water aquifers.

It could be argued that low oil cuts in the area are due to migration and thus depletion (Thelo and Sonnenberg, 2012). Figure 22 is a structure map on the Last Charles Salt covering parts of the Ratcliffe Flat Lake Field located in northeast Sheridan County near the Canadian border. TAQA has drilled eleven horizontal Bakken wells to date, and migration is not supported by production. The structurally highest well, located in Section16, produced 5559 BO and 24,133 BSW (19% O.C.) during its third month on line, and in seven months the well yielded 144,349 BSW. In contrast, the well located in Section 8 and about 30 feet low to the Section 16 well yielded 9787 BO and 1101 BSW (90% O.C.) during its third month of production.

Application of the concept that depletion is a result of migration requires migration to be a faster and more efficient process than expulsion and that generation has ceased. It is thought that generation has not ceased, as demonstrated by current temperature of the Bakken (Figure 9), and it is unlikely that migration within the BMM is a faster process than explusion because the latter is in part the driving force.

Comparison of oil cuts from both sides of the BFL in eastern Montana yields surprising results. Figure 23 is a scatter chart of all Bakken wells drilled west of the BFL that have been on production at least three months as of December 31, 2012. All of the wells, except one are located in T37N-56E and 57E. The exception is the Whiting Oil and Gas 31-25TFH located in T31N-55E, Sec. 25. Production from this well during its third month was 3,603 BO and 8,018 BSW. On the third month of production, average oil cut for wells on the west side of the BFL was 37% compared to 39% for wells completed on the east side of the BFL (Figure 17). A difference of 2% oil cut does not support the collary that the BFL leaks and deflects oil migration into Canada along its trace.

Selection of Targets for Future Bakken Development in Northeastern Montana

The Bakken is not as simple a play as many may preceive. Although the first commercial development of the Bakken Oil System occurred in the Sanish at Antelope Field, operators did not focus their attention on the Sanish but rather the Bakken upper shale. However, after the discovery of Elm Coulee operators have frequently made the mistake drilling all laterals targeting the Bakken middle member regardless of facies and/or stage of maturity of the shales. For the Bakken middle member to be the target, explusion (or migration) is required.

An excellent example is a comparison of the Samson Oil and Gas log of the Gretel II (22-28N-53E) and Australia II (29-28N-55E) laterals. Both wells targeted the middle zone. The Gretel II log recorded significantly higher total gas than was recorded in the Australia II (Figure 24). The reason is that, although the Bakken is over 700 feet deeper at the Australia II (9441 vs. 8724 feet) than the Gretel II, it is not as mature in this well as it is in the Gretel II. Mean Ro for the Gretel II is 0.96 and ranges from 0.82 to 1.14. Mean Ro for the Australia II is 0.86 and ranges from 0.83-0.94 (Samson, 2012, slides 21 and 26). Thus expulsion occurred from the shales into the Bakken middle member in Gretel II area, whereas it was a limited process in the Australia II.

Figure 25 is a target map for northeastern Montana. The Bakken upper shale member is the preferred target for development in the gray area. Both Bakken shales are mature in this area, which is typified by an Ro of greater than 0.6, HI between 200 and 400 and resistvity above 100 Ω.

Although the shales are mature, expulsion of oil into the Bakken middle member is limited. In this area the oil phase is continuous and thus it is an unconventional shale play

The Bakken middle member should be considered as the target in the green colored area in Figure 25. Pore pressure is above 0.5, Ro is greater than 0.9 and HI is less than 200. Although these paramenters typcially signify explusion, low prorosity and permeability within the BMM may be insufficient to permit expulsion. Prior to selecting this zone as the target, reservoir analysis should be completed in a cored pilot hole prior to selecting a target. If the BMM is selected, careful monitoring of gas should be conducted while drilling the lateral. If total gas recording drops it is probably best to steer the bit into the Bakken upper shale. Development of this area is a hybrid unconventional play.

There is a rather wide transition zone as depicted by the yellow area (Figure 25). Ro ranges from 0.8 to 0.9 and HI 400 to 200. Source rock analysis as well as reservoir parameters should be determined in a pilot hole prior to selecting a target in the transition area. It is possible the Bakken upper shale will be the target of choice in this area.

Possible Sweet Spots

Potential sweet spots in northeastern Montana most likely will be associated with solution of salt within the Prairie Formation. The Prairie Formation is about 1100 to 1200 ft. below the Bakken Oil System (Figure 26). Solution of Prairie Formation salt is well documented in the literature and numerous fields (e.g., Tule Creek, Volt, and Hummingbird, Canada) were formed by multistage salt solution. The solution edge has migrated from west to east more than 60 miles (Figure 27). Unfortunately, most of the solution occurred during Devonian time. Note there are several large solution voids within the preserved limits of the Prairie, most notably the Humming Bird Trough in Saskatchewan and northeastern Roosevelt County, Montana. Numerous other voids, that are a section or two in size, are too small to be depicted on the map.

Facies

Timing of solution will control whether the sweet spot is due to enhanced facies or fracturing within the Bakken Oil System. At Elm Coulee Field, Sonnenberg and Palmuto (2009) attributed the increase thickness and facies change within the Bakken middle member to solution of Praire salt. Abnormal thickness and porous facies could occur within all or part of any one of the formations that represent the Bakken Oil System. However, subsurface control is sufficient to speculate that the sweet spots related to facies, if any, will not approach the size of Elm Coulee Field.

Fractures

The concept for fractures produced in the Bakken Oil System is simple; open, nearly vertical fractures formed in the strata as they collapsed into a void caused by solution of Prairie salt (Figure 28). Note as the solution front migrated from west to east, maximum flexure occurred at the base and top of the salt edge and that the strata at the base of the salt edge was subjected to two stages of maximum flexure.

Unfortunately there is one more variable that controls the formation of a fractured sweet spot in the BOS; namely, timing. If the solution occurred prior to generation of oil, the fractures will most likely be healed by cementation and/or compaction. Thus, solution and fracturing must be coeval. As indicated by TTI plots for northeastern Montana, peak generation began during Early Cretaceous (Figure 8). As solution proceeded, the overlying strata would collapse into the salt void. The process results in a sag at the water-sediment interface, thus increasing accommodation of sediment, which in turn produces a sedimentary thick. Timing of solution can be determined by seismic data; the seismic signature is a “sag.” If the sag only occurred within the Late Paleozoic, solution pre-dated generation (Figure 29). If the sag affects Jurassic strata, initial generation had begun but probably maturity was insufficient to cause expulsion. The optimum condition was when solution was coeval to or post-dated Late Cretaceous.

Figure 30 is a west-to-east 12-fold, CDP, dynamite line that crosses the Prairie solution edge in northeastern Montana. The shallowest mappable reflector is the Cretaceous Greenhorn Formation. The line depicts minor thickening between the Jurassic Piper and Greenhorn, but most of the solution is post-Greenhorn in age. If the Cretaceous Frontier Formation (“Kf”) reflector is valid, some solution post-dates Frontier deposition.

Oil in Place

In parts of northeastern Montana, oil in place (OIP) exceeds that in Elm Coulee. It is a general concenses that oil in place at Elm Coulee is about 4.9 million barrels per section. Nutech, using their NewLook software, determined that OIP in the Texaco 1-22 Assinbone well (32N-52E, Sec. 22) is 6.1 million barrels of oil per section. The well is located west of the Brockton-Froid Lineament whereas Elm Coulee Field is on the east side of the BFL. The higher reserves are attributed to the presence of both shales (lower shale is absent throughout most of Elm Coulee), and fractures identified by the software within the Bakken.

Conclusions

Bakken shales in northeastern Montana are mature. Ro ranges from 0.6 to 1.10; HI, 0 to 500, pore pressures greater than 0.5 and resistivity above 100 Ω. These maturity parameters are equal to those in North Dakota. There is no evidence the Brockton-Froid Lineament affected matuirity level on either side of the lineament.

Migration within the Bakken is a contested issue. There is evidence that supports the conclusion that migration has ensued, as well as invalidates the process. There are six lineaments that cut across the mature Bakken area. In the event migration has occurred, only the southern third of the Cedar Creek lineament, not the BFL, is a barrier to migration within the Bakken as well as all other Williston Basin reservoirs. There is no Ordovician through lower Mississippian production west of the southern third of the Cedar Creek lineament. In the event Elm Coulee and Parshall fields are stratigraphic traps caused by migration of oil within the Bakken, it is inconsistent to hold that the BFL is the western boundary of the Bakken Unconventional play.

Targets for horizontal Bakken wells are dependent upon stage of maturity. In northeastern Montana where explusion has occurred, the Bakken middle member should be considered the target. Areas where expulsion has not happened, the Bakken upper shale should be the target and developed as an unconventional play.

Explusion is not only controlled by stage of maturity, but also by the bounding strata. Insufficient permeabilty will inhibit explusion and increase pore pressure within the upper and lower shales.

In northeastern Montana (as well as western North Dakota) hyrdrofracs should be designed to limit vertical height to less than the thickness of the Three Forks Formation at each location in order to prevent communication with the underlying Nisku Formation, and locally the Duperow Formation..

Sweet spots within the BOS are speculated to be related to solution of the Prairie Evaporite. Potential facies and/or thickness change within the BOS related to solution are possible, but subsurface control is sufficient to conclude the sweet spots will not be in the order of magnitude as Elm Coulee Field. In contrast, fracturing of the BOS by collapse into a salt void that postdates peak generation during Early to Late Cretaceous may be more productive than Elm Coulee for two reasons. Oil in place in parts of northeastern Montana are more than a million barrels greater than Elm Coulee, and fracturing of the BOS could have created addition storage and significantly better permeability than that which exists at Elm Coulee Field.

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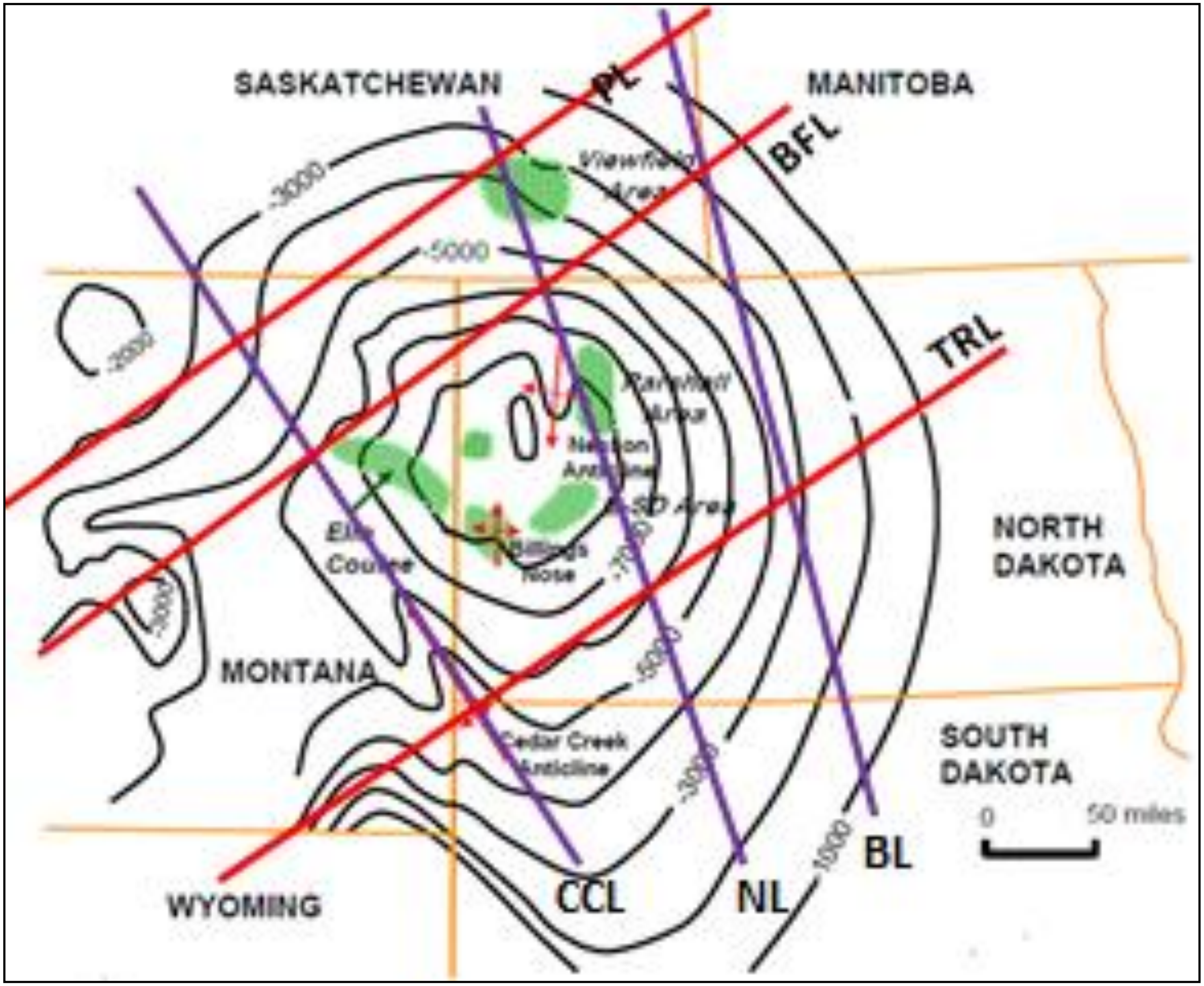

Figure 1. Base of Mississippian structure map depicts a symmetrical cratonic depositional basin. Major northwest-trending lineaments include Cedar Creek (CCL), Nesson (NL) and Bottineau (BL). Northeast-trending lineaments are Poplar (PL), Brockton-Froid (BFL), and Three River (TRL). (Map after Sonnenberg, 2012, slide 5; lineament overlay after Fischer et al., 2005.)

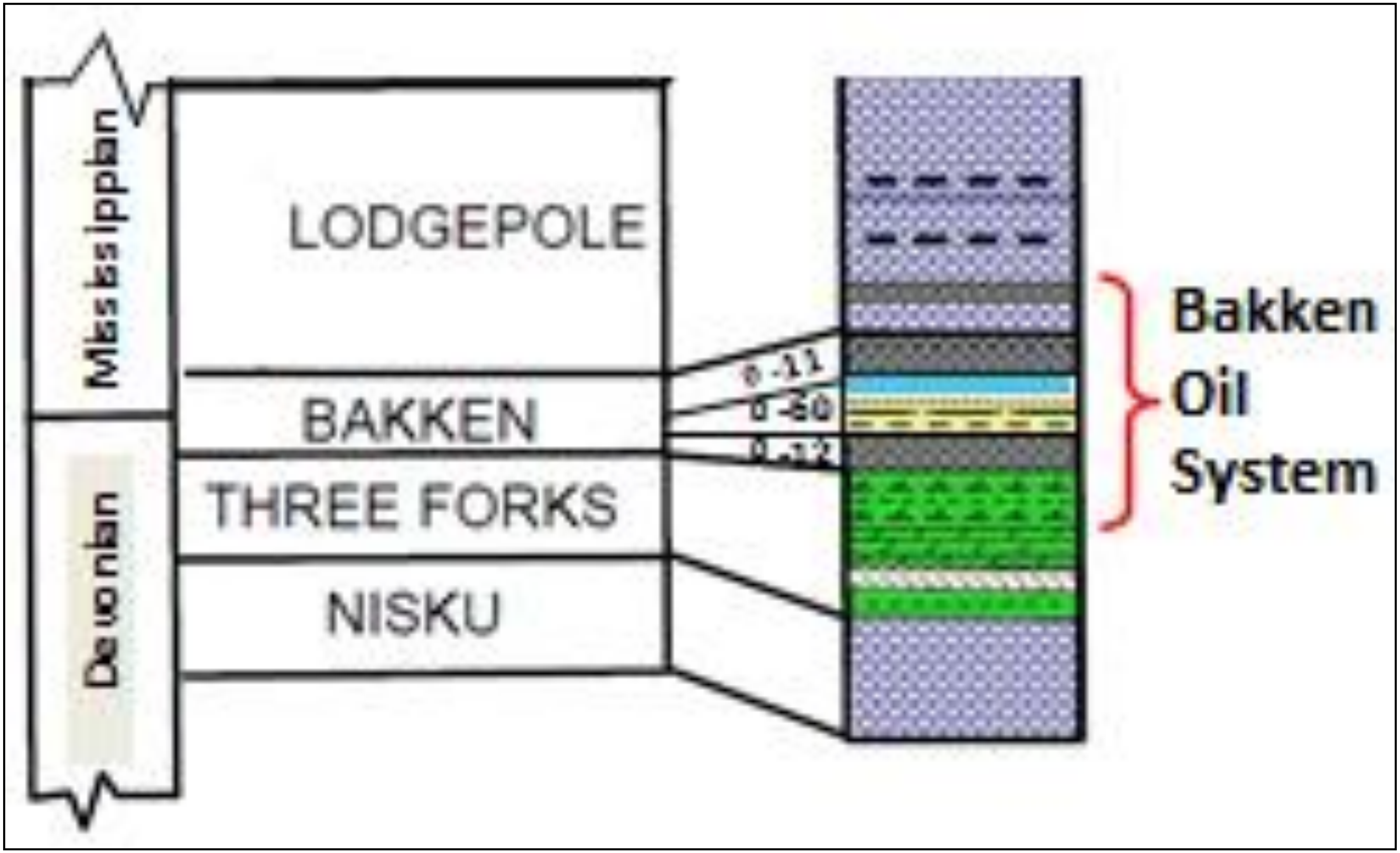

Figure 2. Bakken oil system includes upper Three Forks, Bakken and lower Lodgepole. The Bakken is informally divided into lower shale, middle carbonate-rich clastic, and upper shale members (modified after Webster, 1984).

Figure 3. The lower and middle members of the Bakken were deposited in a shallow embayment extending from the Devonian sea across northern British Columbia, Alberta, Saskatchewan, Montana and western North Dakota (modified from Blakey, 2007).

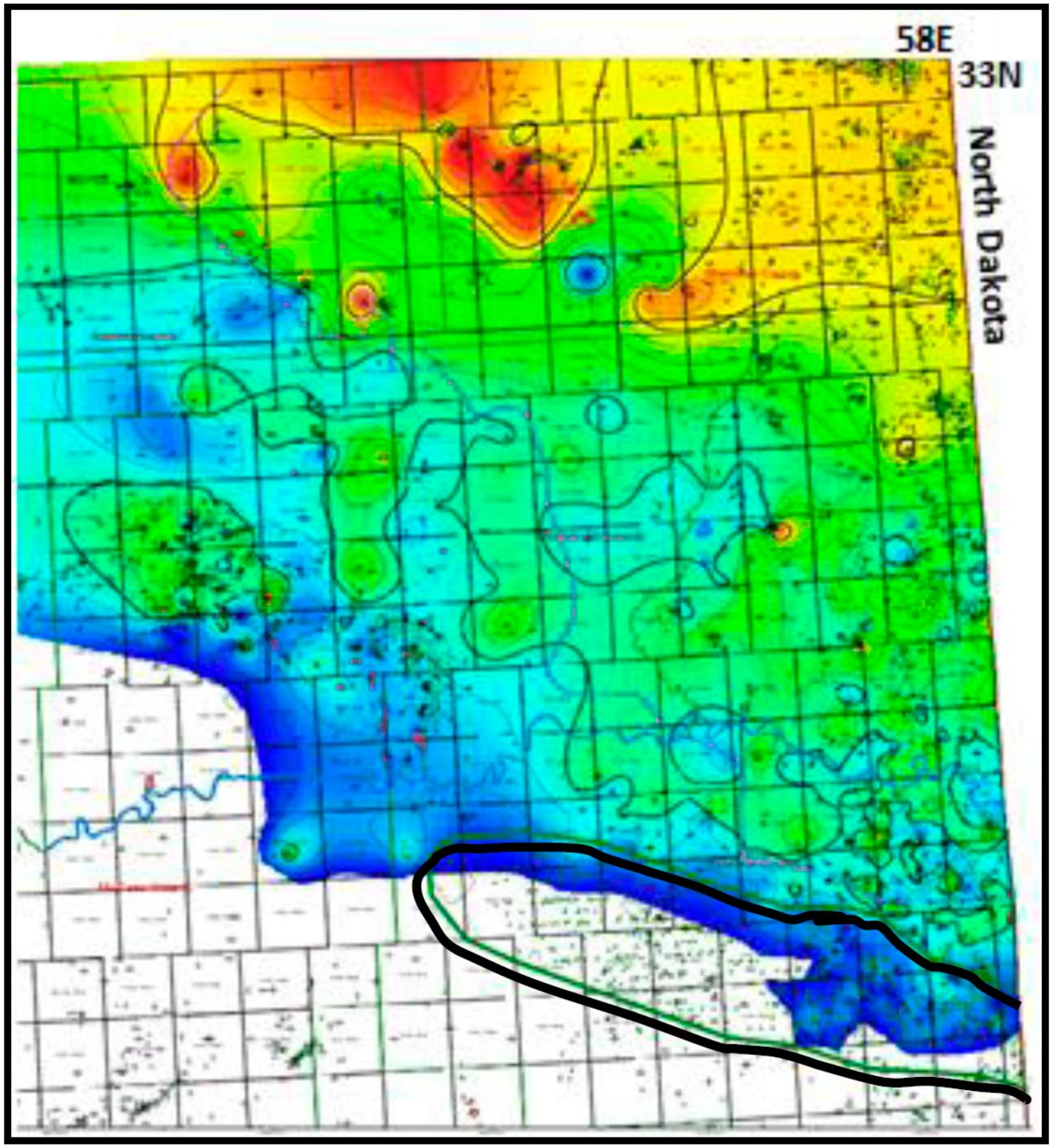

Figure 4. The Lower Bakken Shale member ranges in thickness from 0 to 24 feet (red area) in northeastern Montana. Green enclosure represents Elm Coulee Field approximate limits. CI: 2 Feet.

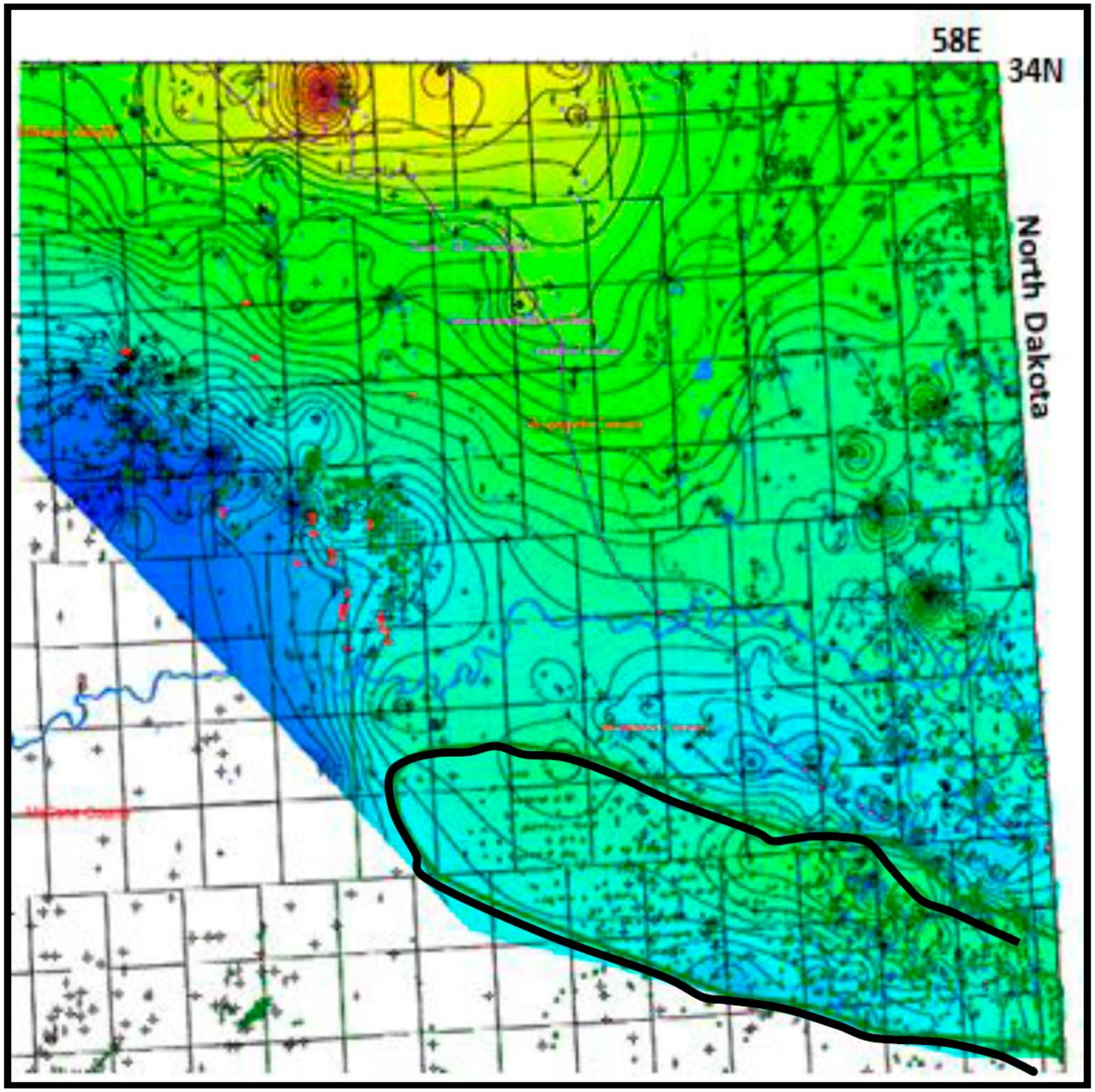

Figure 5. Isopach of Middle Bakken member varies from zero to nearly 60 feet thick (orange) in northeastern Montana. CI: 2 feet.

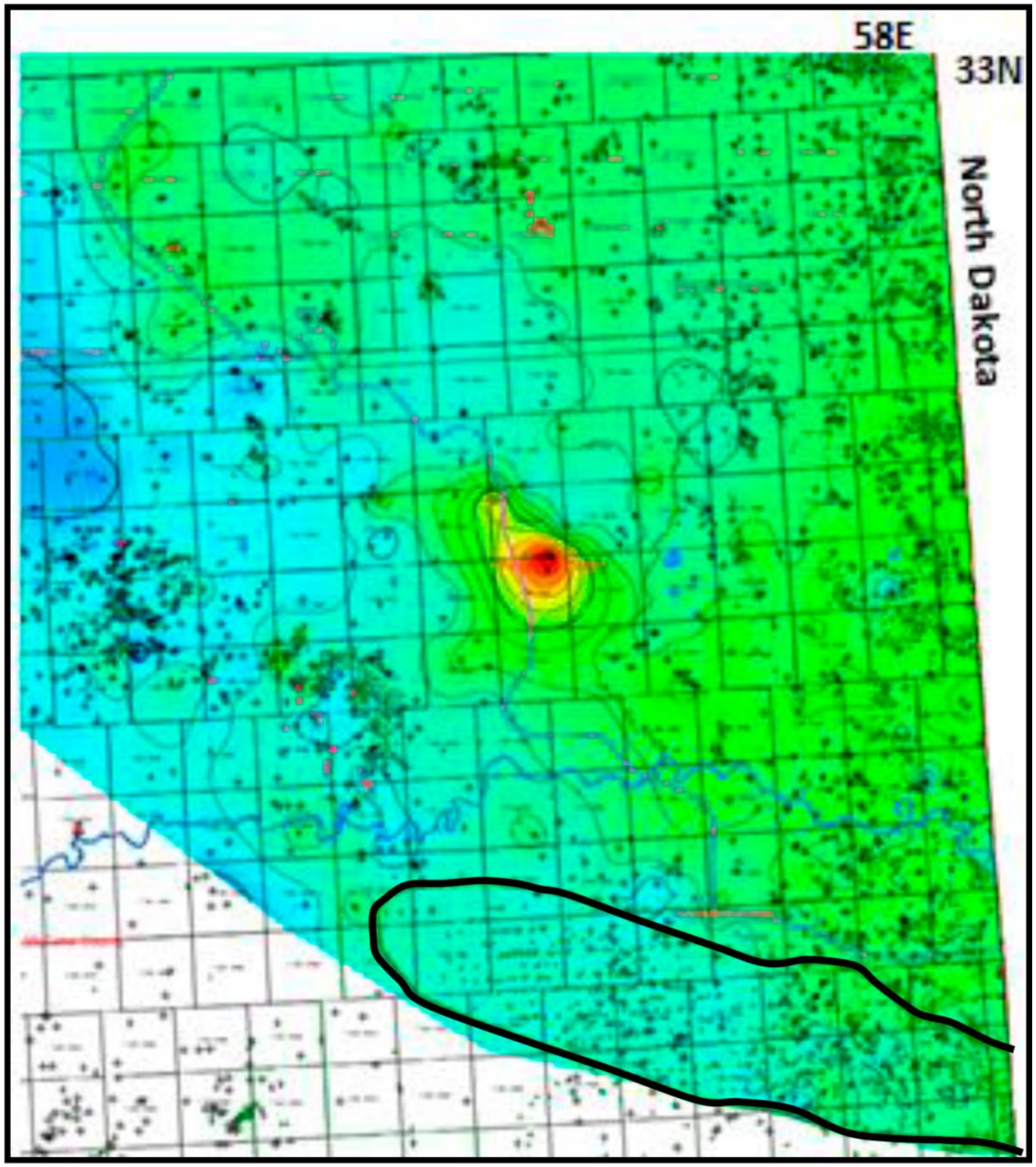

Figure 6. Isopach data depicts a range of 0 to 24 feet for upper Bakken Shale in northeastern Montana. CI: 2 feet.

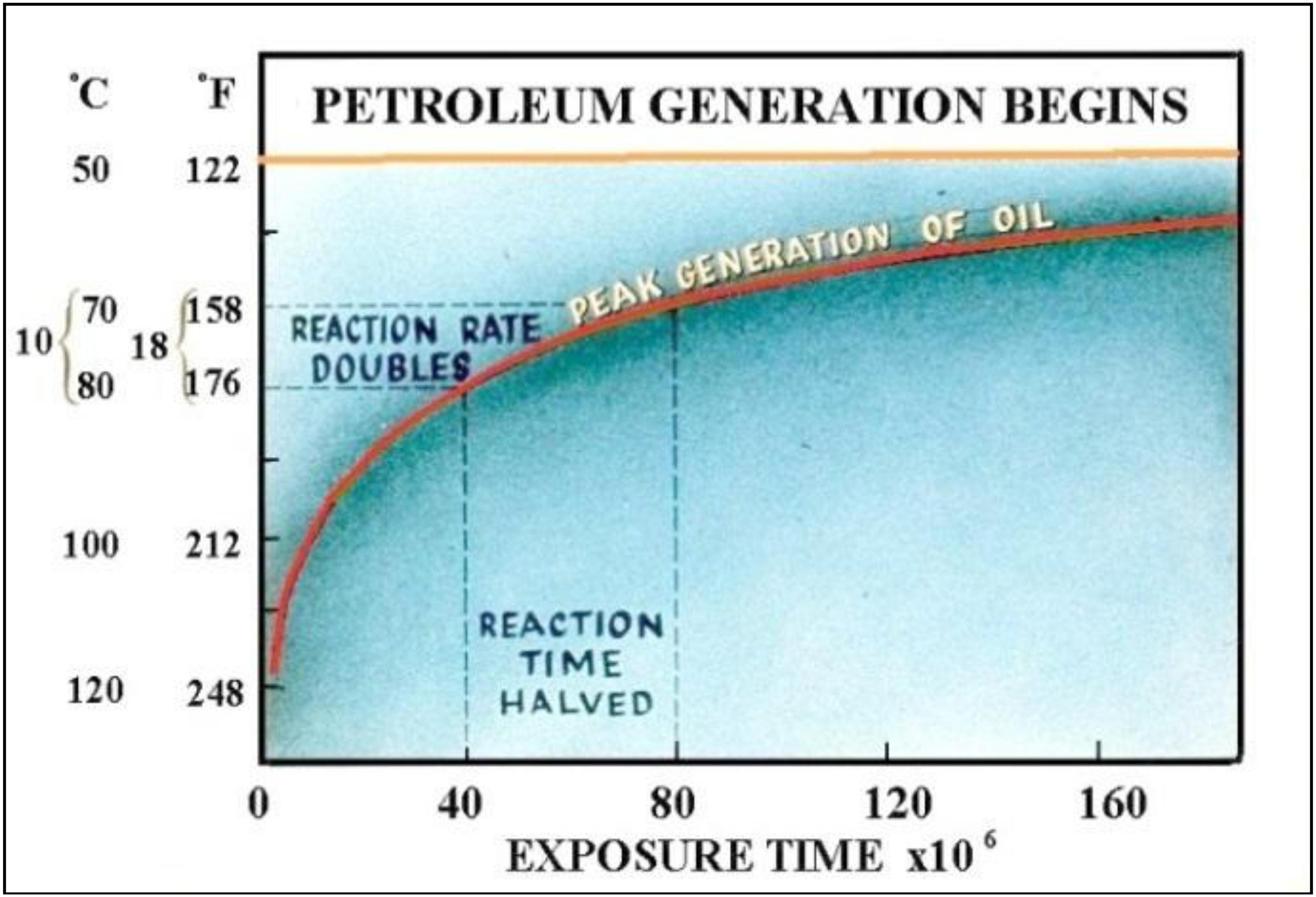

Figure 7. Generation is a function of time and temperature, and for every 18°F increase in temperature the reaction time is halved.

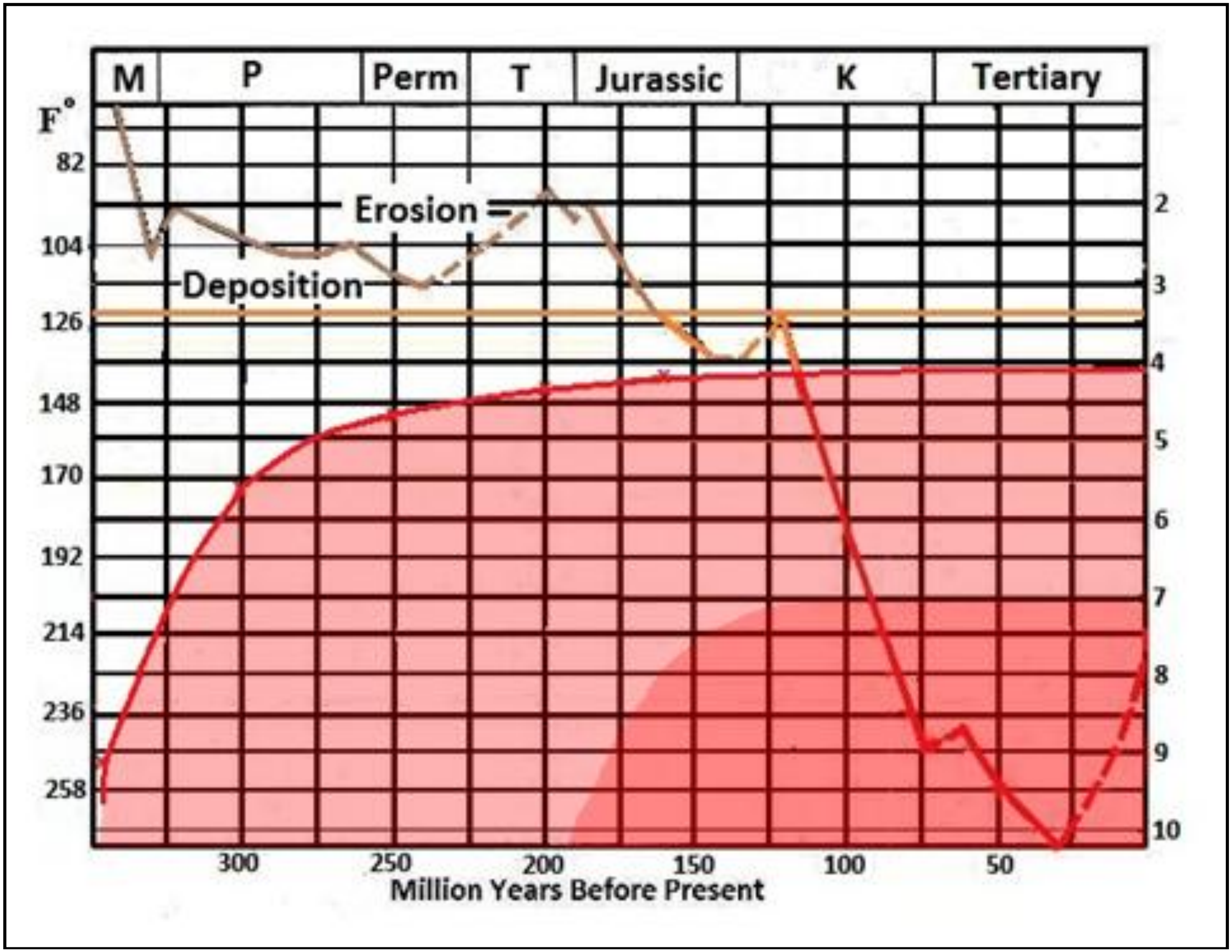

Figure 8. Time-temperature plot for northeastern Montana indicates Bakken peak generation began in Early Cretaceous time. Present-day depth of the Bakken in map area depicted on Figure 1 ranges from about 7600 to 10,100 feet.

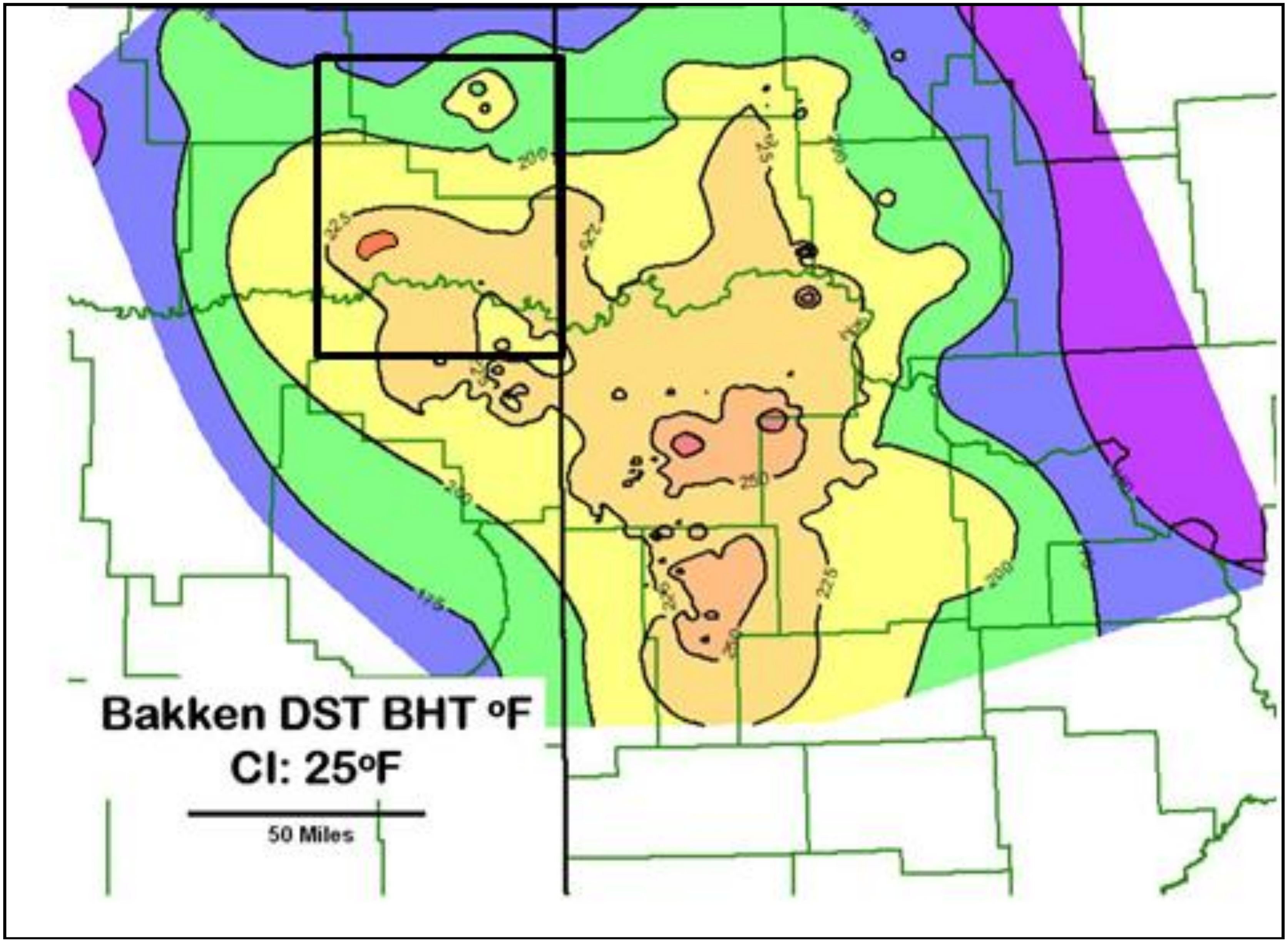

Figure 9. Present-day temperature of the Bakken. The black-bordered rectangle depicts the map area shown in Figures 2, 3, and 4. The temperatures were not corrected (modified from Sonnenberg, 2012).

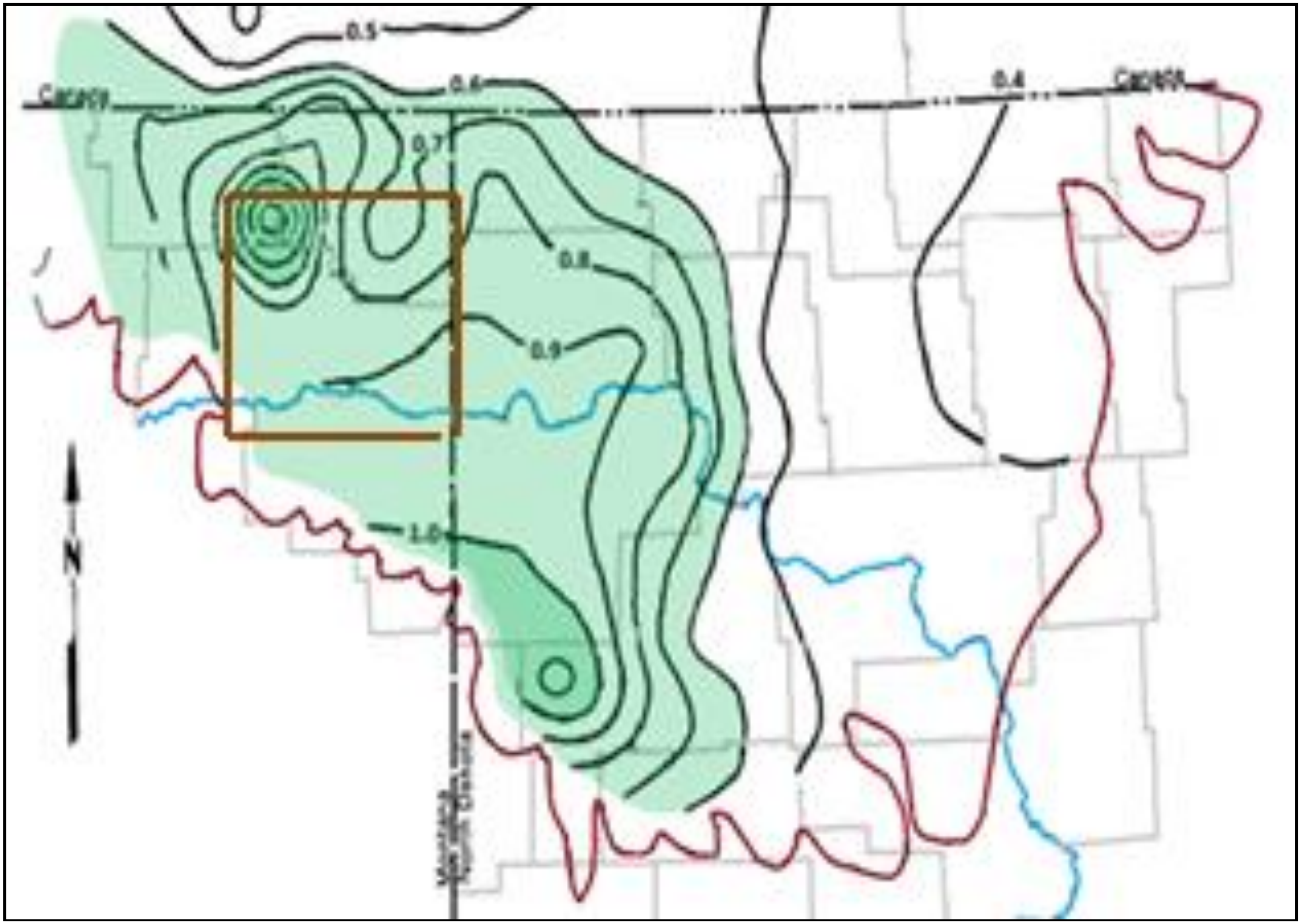

Figure 10. Contour map of Vitrinite Reflectance (Ro in %) within the Upper Bakken is based on only 101 sample points. Green shaded area, >0.6 Ro, is considered as mature area for the Bakken upper shale (adapted from Demicki and Pirkle, 1985).

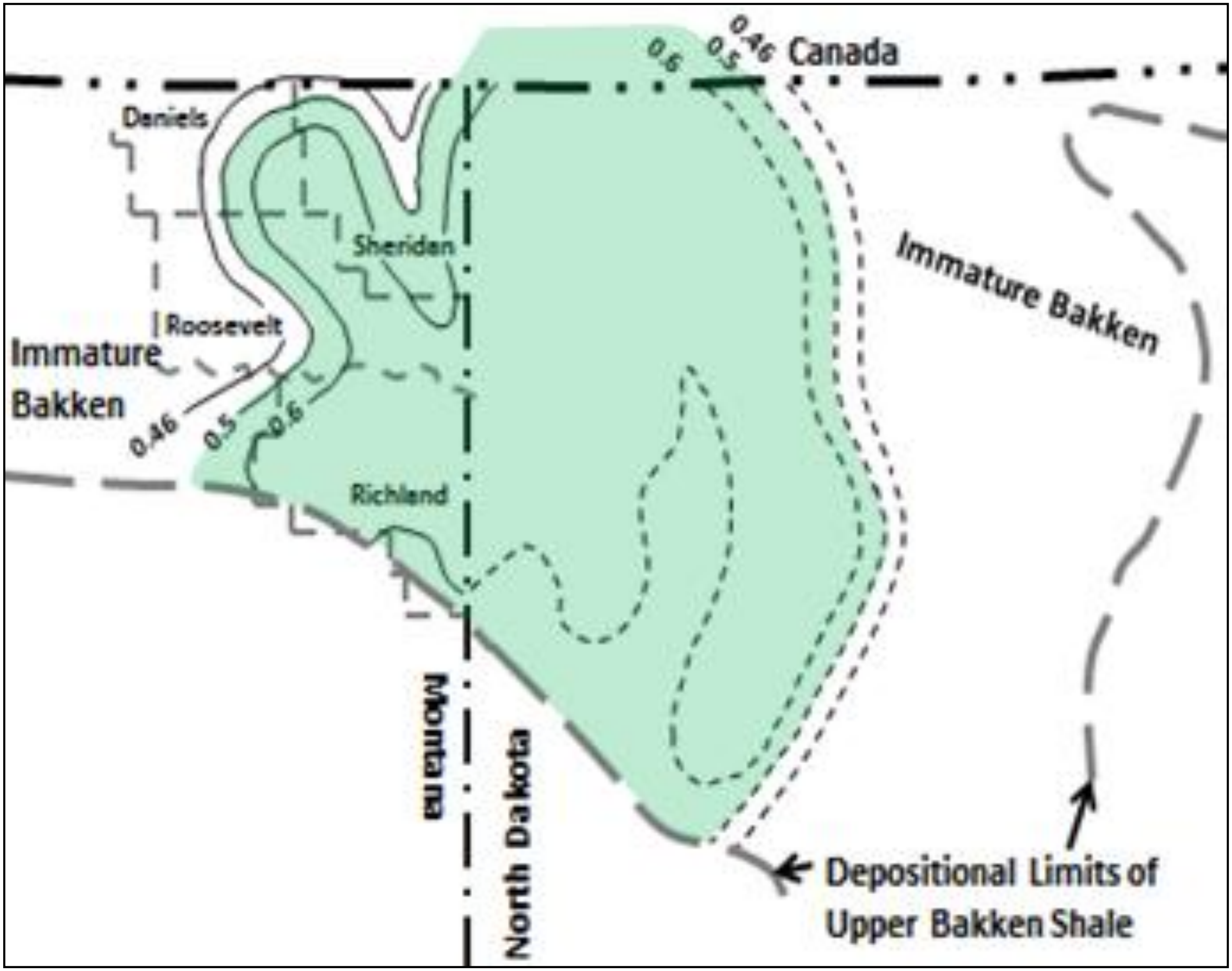

Figure 11. Normal pore pressure for the Bakken is 0.46 psi/ft. Pore pressure above 0.6 (shaded area) suggests the Upper Bakken Shale is mature (dashed contours after Meissner, 1978, solid lines generated for this study).

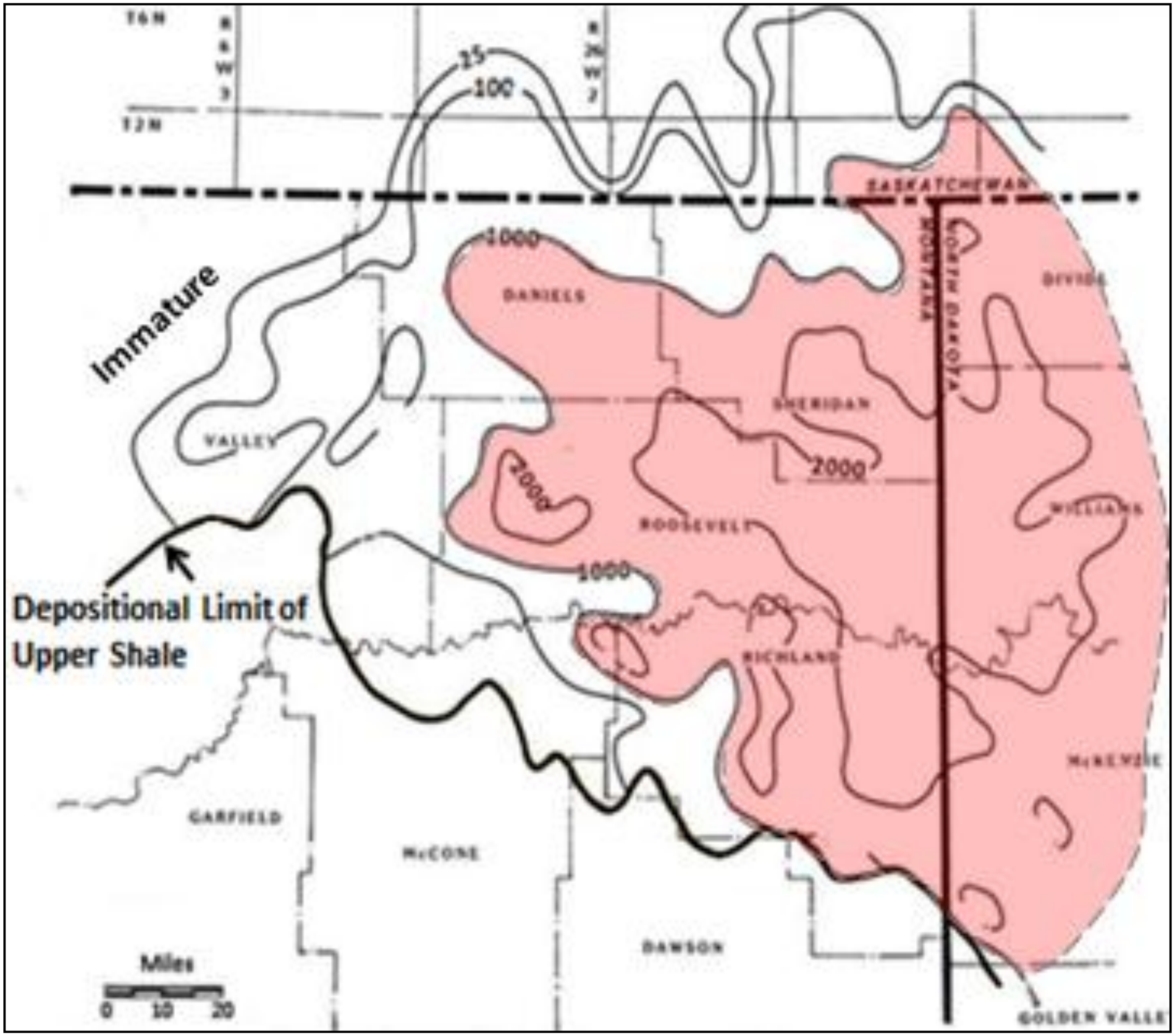

Figure 12. Resistivity of the Upper Bakken Shale defines similar Upper Bakken Shale mature area as the Ro map (Figure 8). Resistivity in red shaded area is 1000 Ω m^2/m or greater.

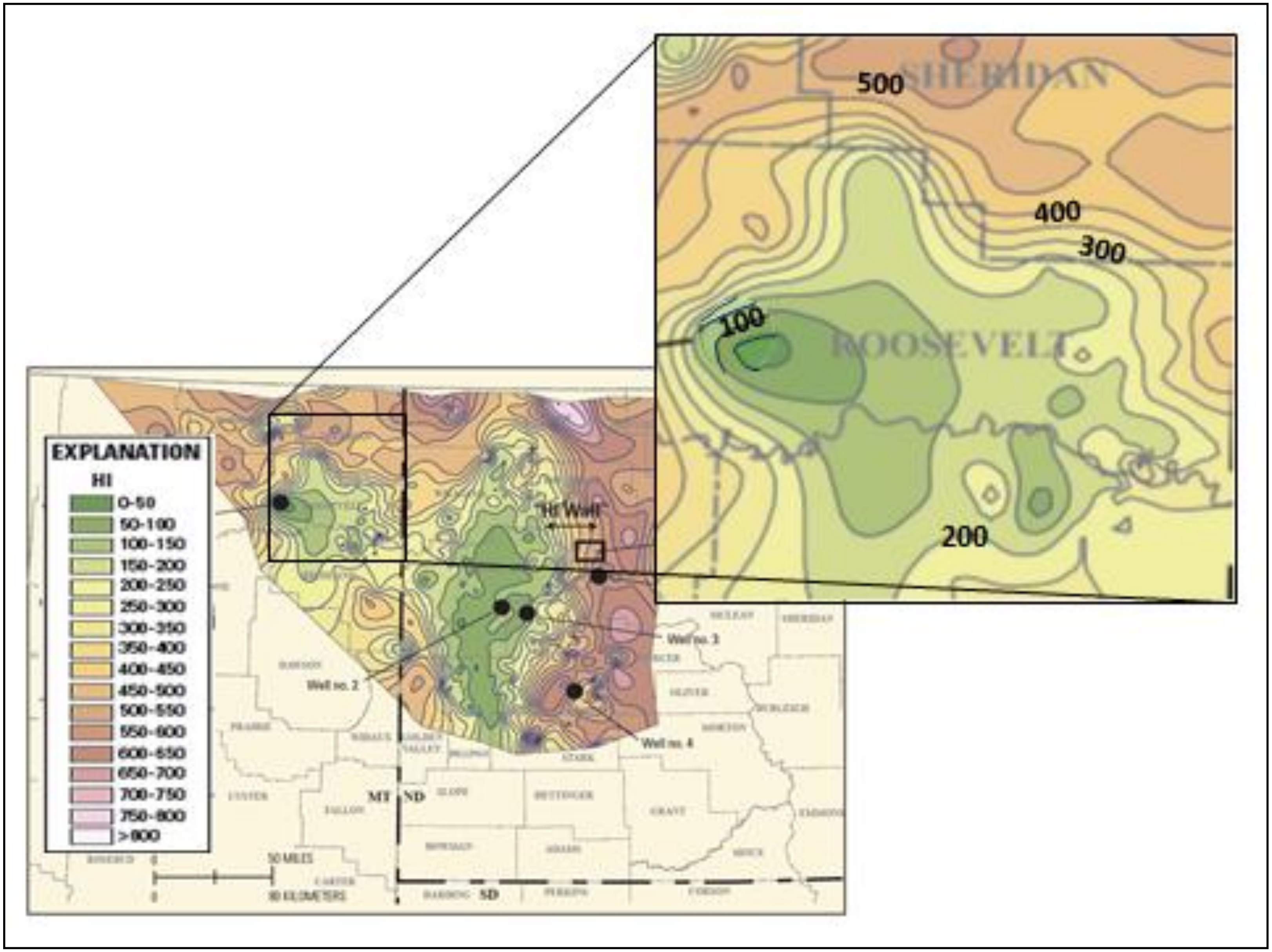

Figure 13. Upper Bakken Shale Hydrocarbon Index map of the U.S. portion of the Williston Basin demonstrates that the Upper Bakken Shale in eastern Montana is mature. A HI value of 200 or less signifies that the peak generation stage of maturation and expulsion is probable but dependent upon rock properties of the BMM (modified from Pollastro et.al., 2010).

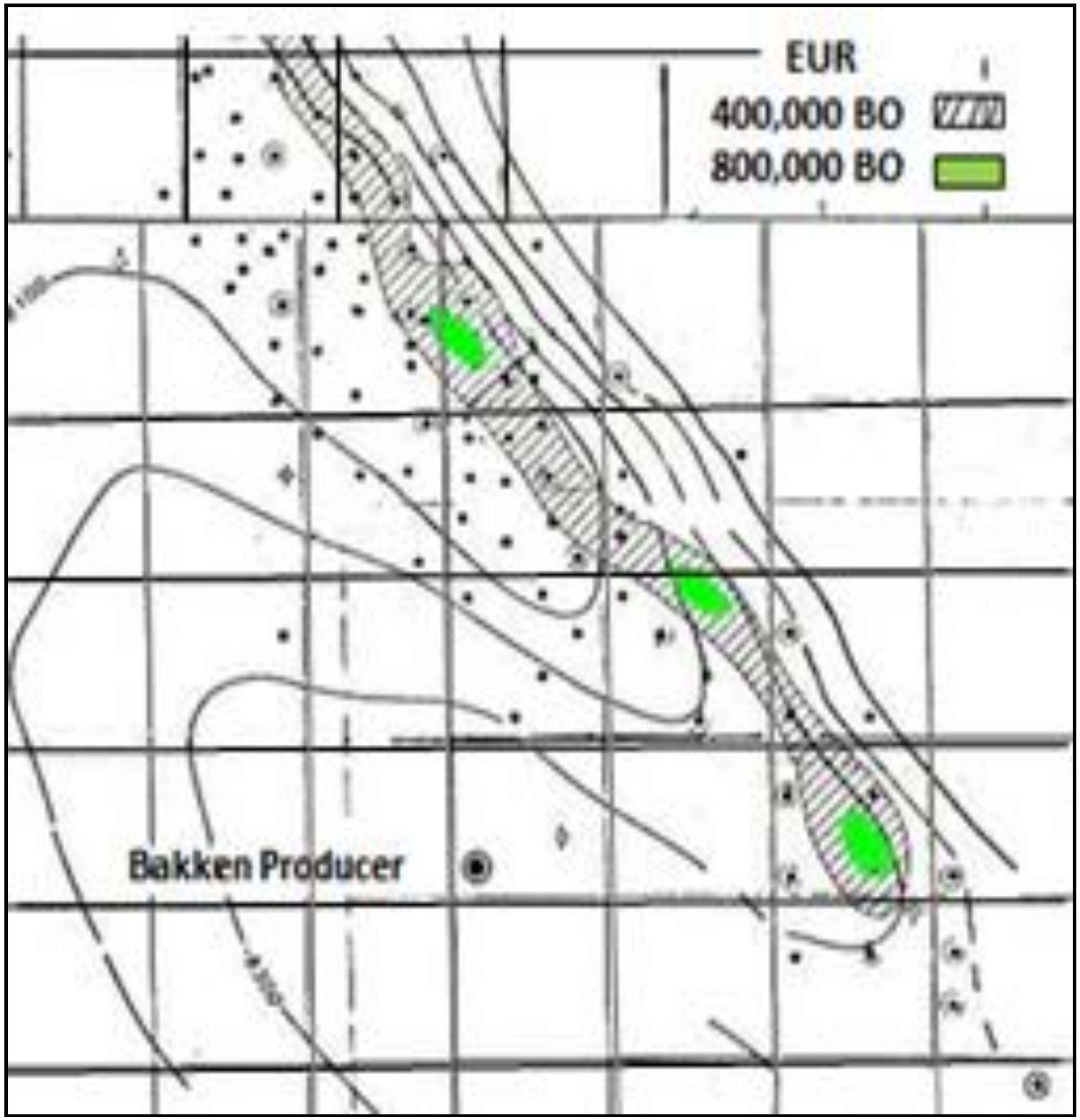

Figure 14. Highly fractured Sanish Sandstone (at the top of the Three Forks) occurs along flexure at Antelope Field, where EUR from several wells exceed 800,000 BO (green locations) from vertical completions (modified from Meissner, 1978).

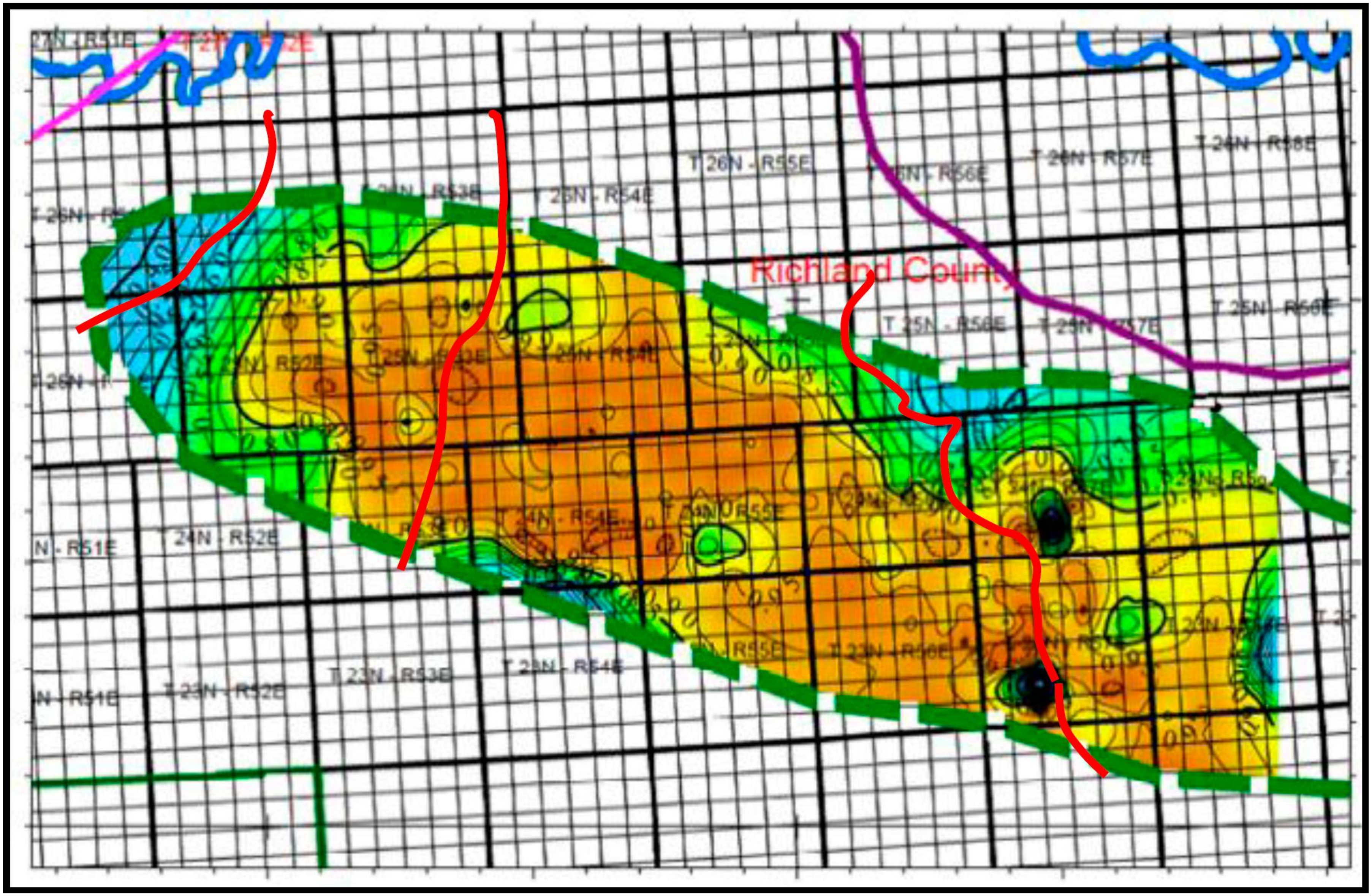

Figure 15. Oil cut on the ninth month of production of 651 wells at Elm Coulee. Blue >65%, green 65-85%, yellow 85-95%, orange <95%. Red line is -6,000-ft contour, with gentle dip to the southwest. There is no relationship between oil cut and structure. Purple line represents western edge of the Prairie salt.

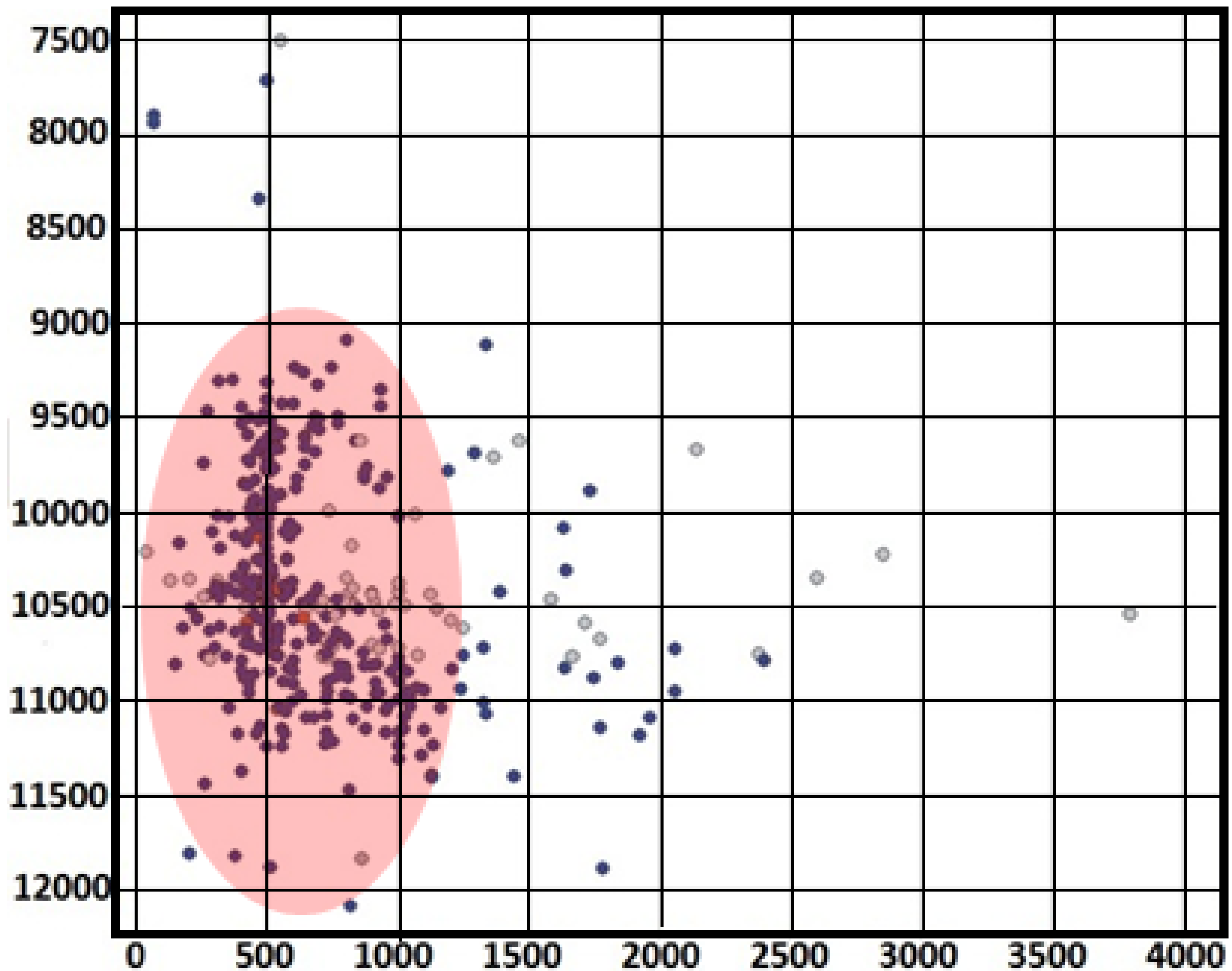

Figure 16. Scatter plot of GOR vs. depth indicates there is no direct relationship between depth and GOR (adapted from Flannery and Kraus, 2006).

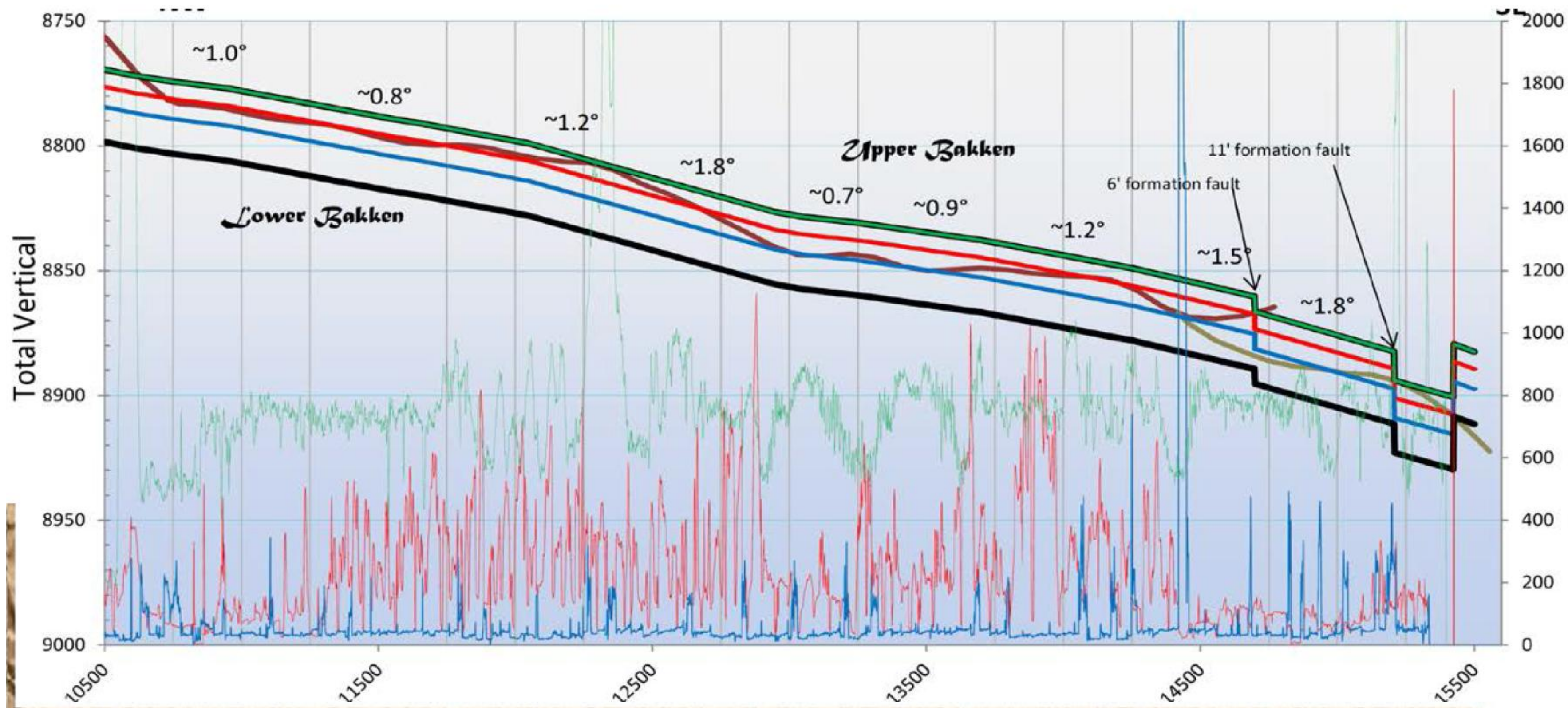

Figure 17. Log of Gretel II depicts rate of penetration, total gas, gamma ray and borehole path in the Samson II Gretel. Note major reduction in gas beginning at about 14,500 feet. Gas shows (red) were significantly reduced in the vincity of the faults (adapted from Samson Oil and Gas, 2012, slide 24).

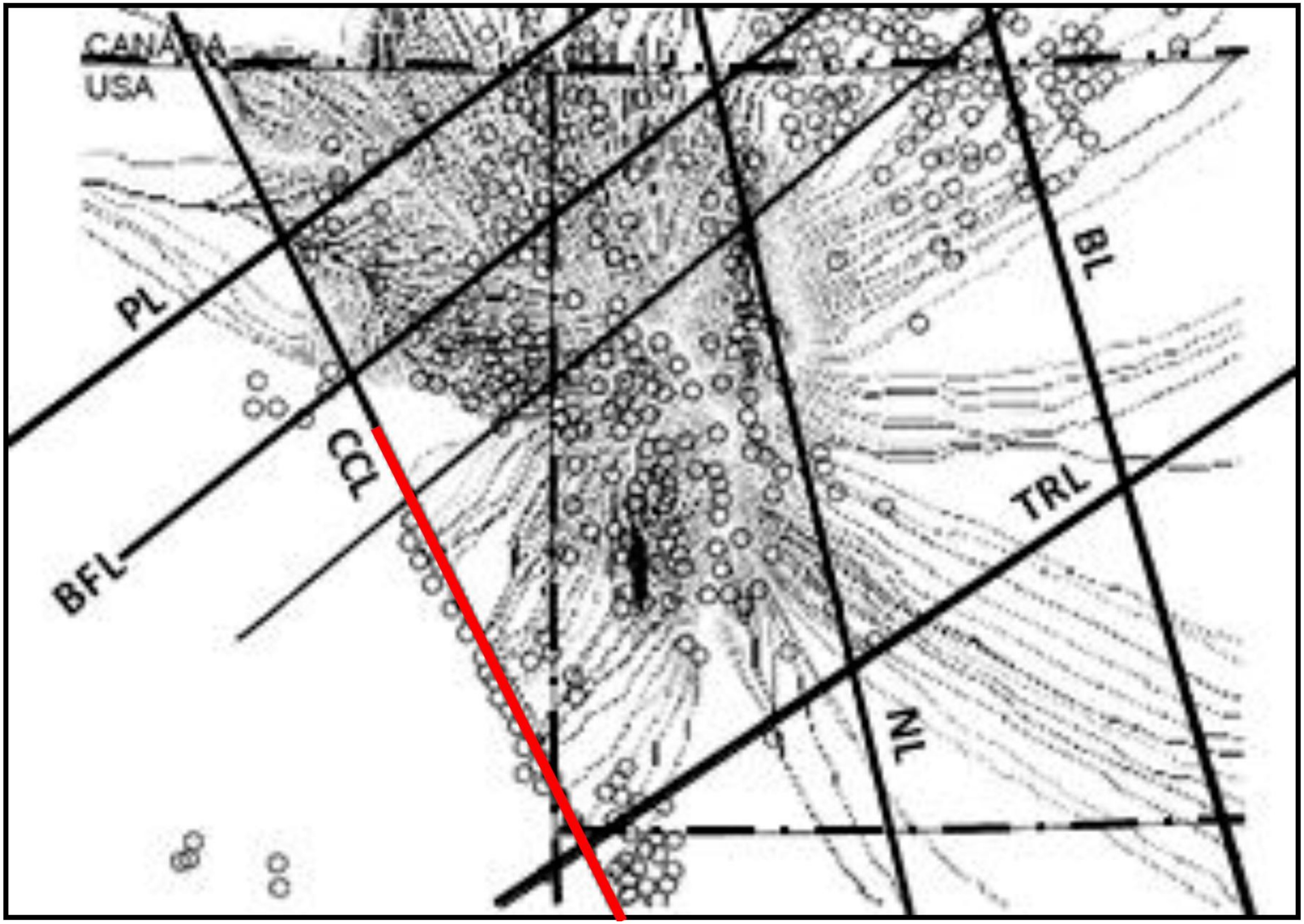

Figure 18. Map showing predicted migration paths within the Bakken, as modeled by Hindle (1997); they are not influenced by known lineaments within the Williston Basin. The lineaments are PL (Poplar), BFL (Brockton-Froid), TRL (Tongue River), BL (Bottineau), NL (Nesson), and CCL (Cedar Creek) (modified from Hindle, 1997; lineaments overlay after Fischer et.al., 2005).

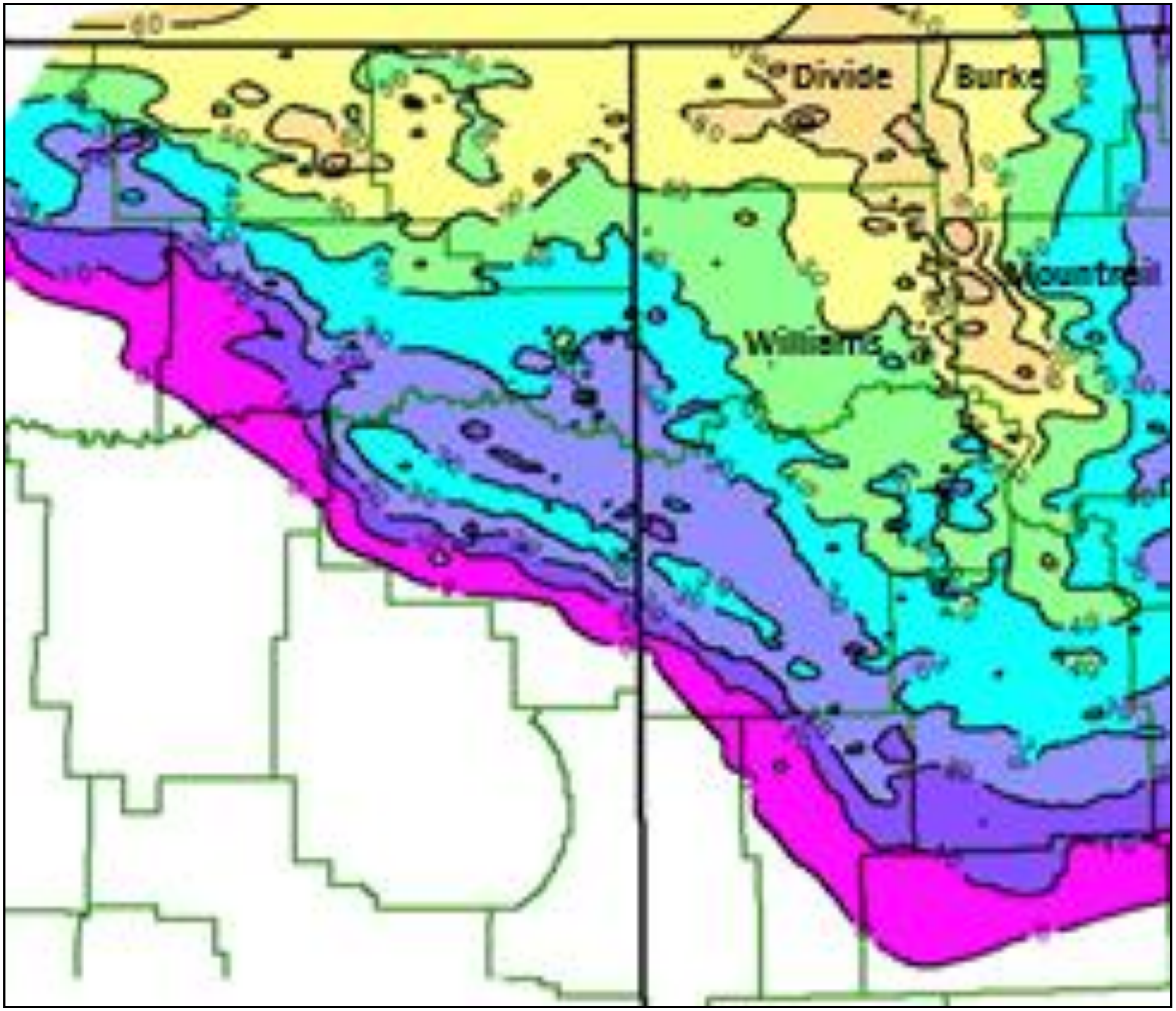

Figure 19. The thickest section of the Bakken middle member occurs in a northwest trend in Divide, Burke, and Mountrail counties. It trends northwest and crosses the Nesson Lineament (modified from Sonnenberg, 2011)

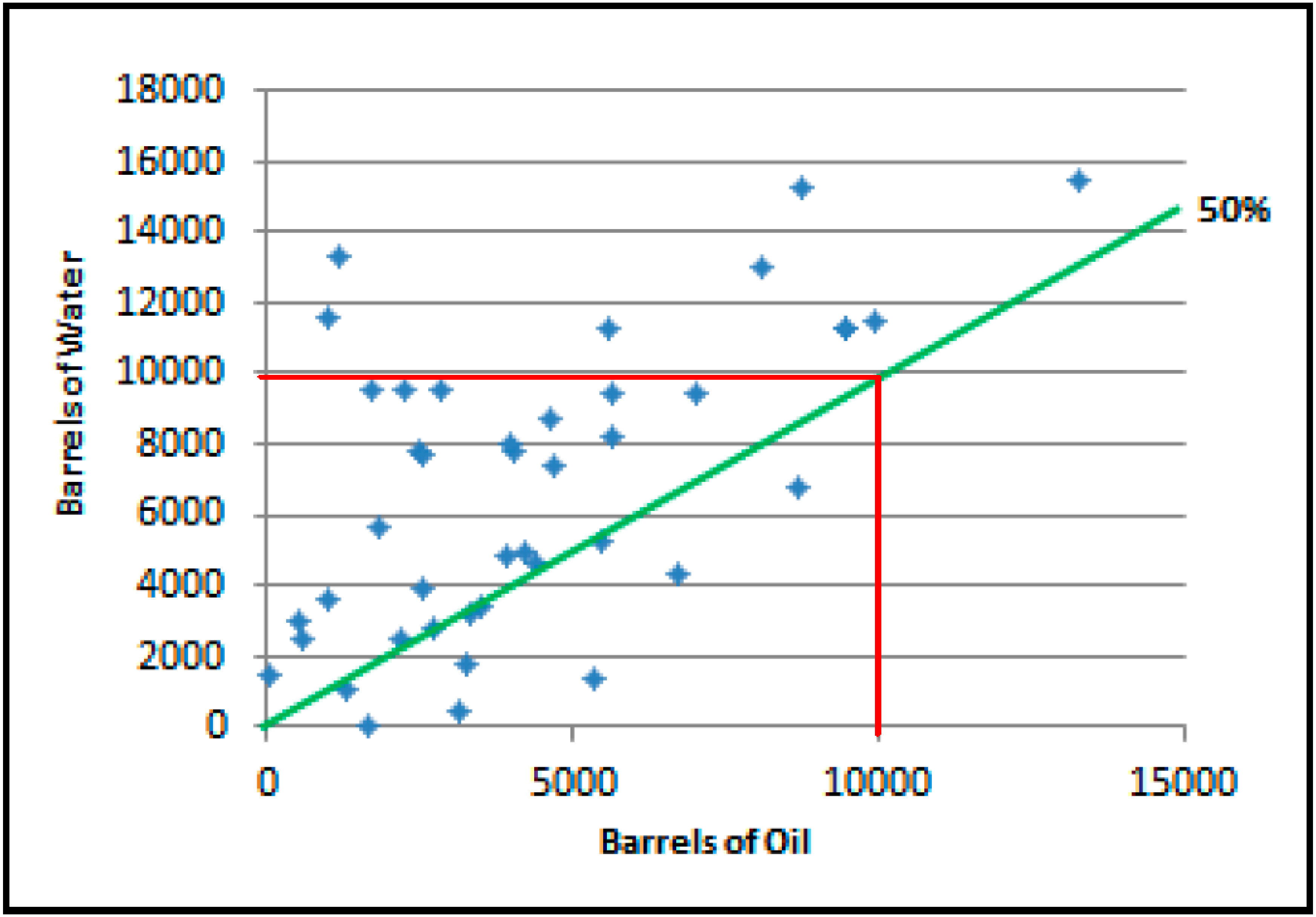

Figure 20. Scatter plot of all wells drilled east of the BFL in northeastern Montana that have been on production three or more months. Oil cut is based on the third month of production as of December 31, 2012.

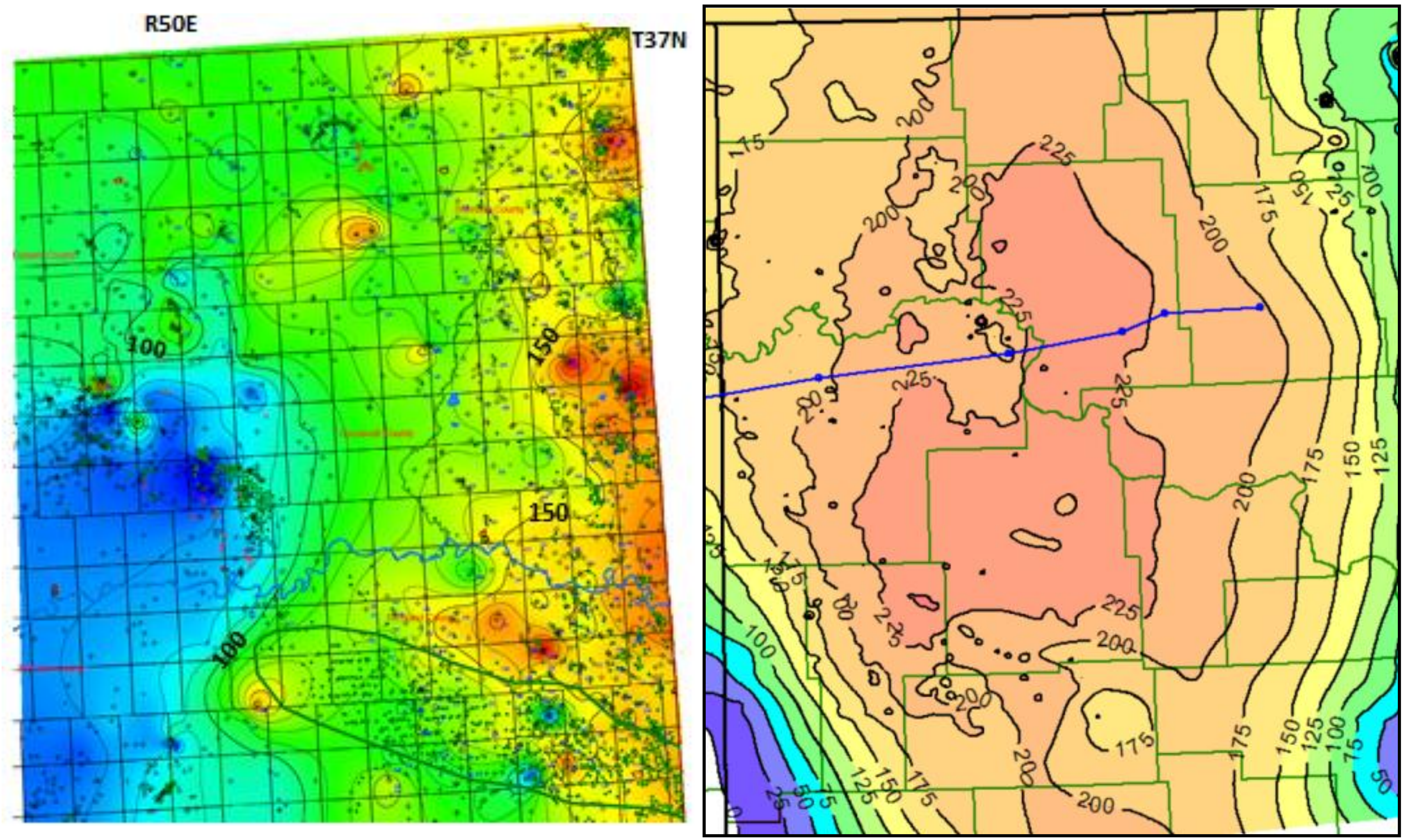

Figure 21. Isopach maps of the Three Forks Formation in northeastern Montana (Left) and North Dakota (Right). Maximum thickness in North Dakota is a little over 250 feet; in NE Montana it is about 160 feet (red area). (North Dakota map modified from Sonnenberg, 2011; left map generated for this article [CI = 10 ft.]).

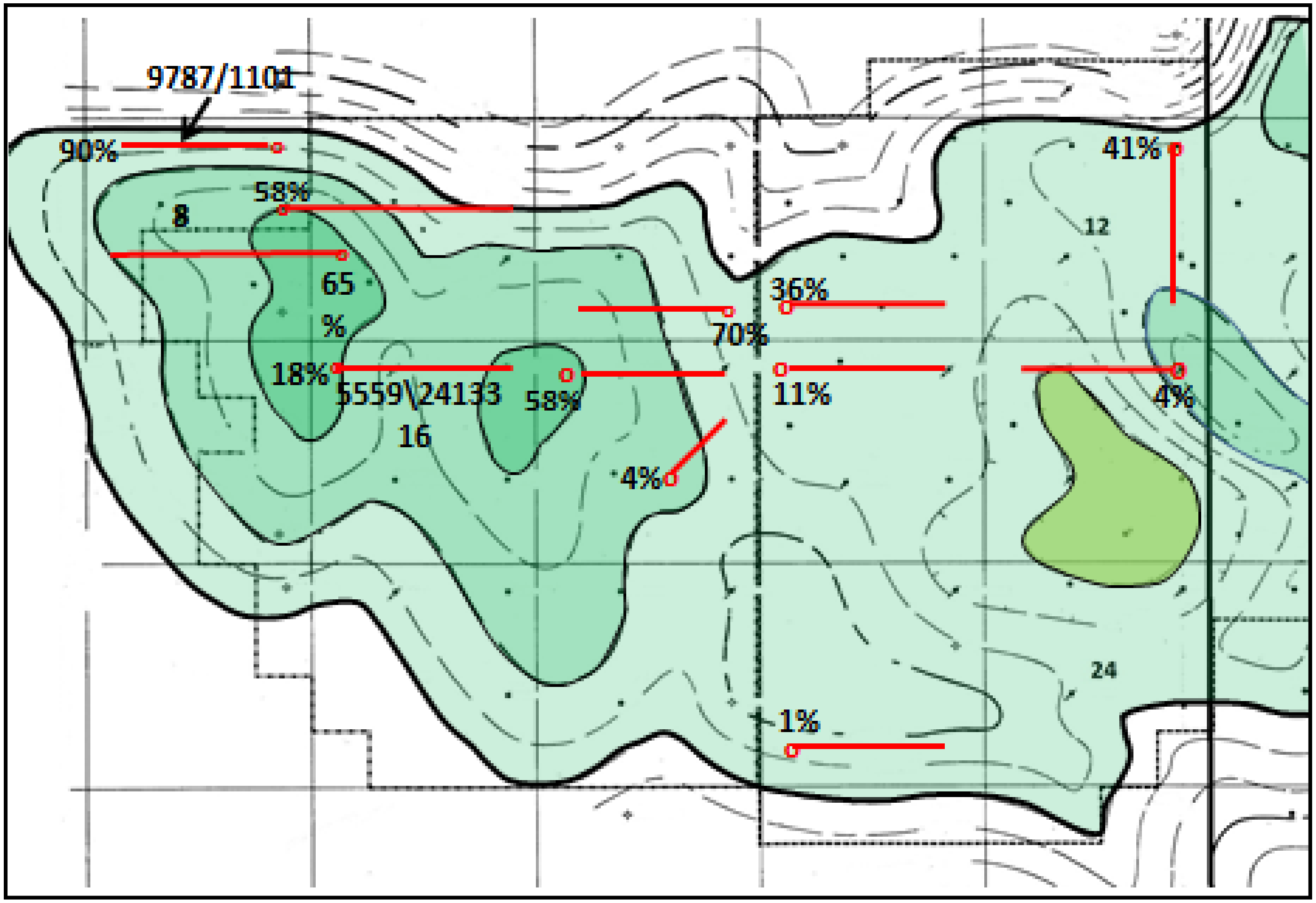

Figure 22. Structure map on top of the Last Charles Salt in parts of the Ratcliffe Flat Lake Field mirrors Bakken structure. Red lines are laterals of TAQA Bakken wells. Percentages are oil cut.

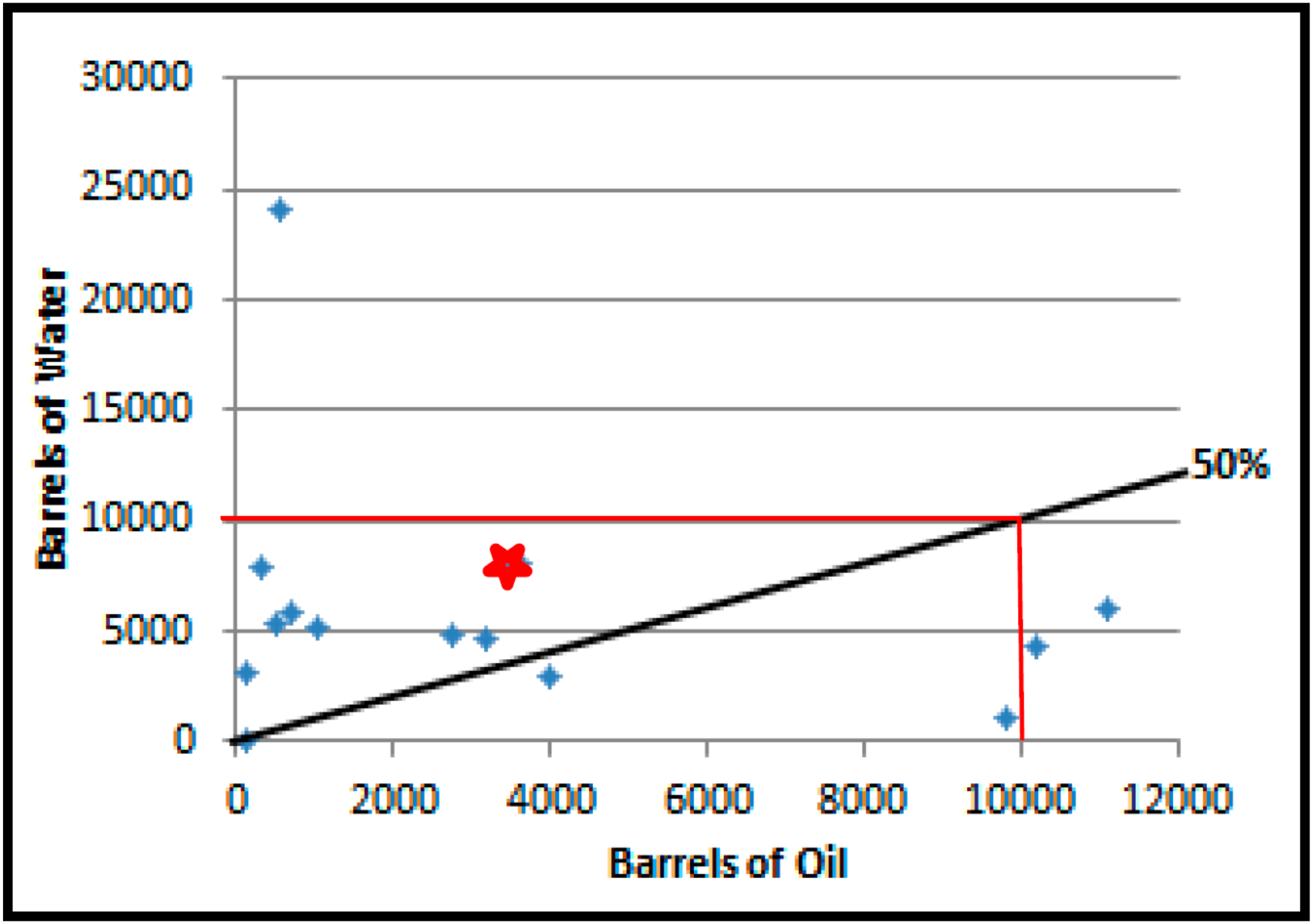

Figure 23. Scatter plot of the third month production of Bakken horizontal wells completed on the west side of the BFL.

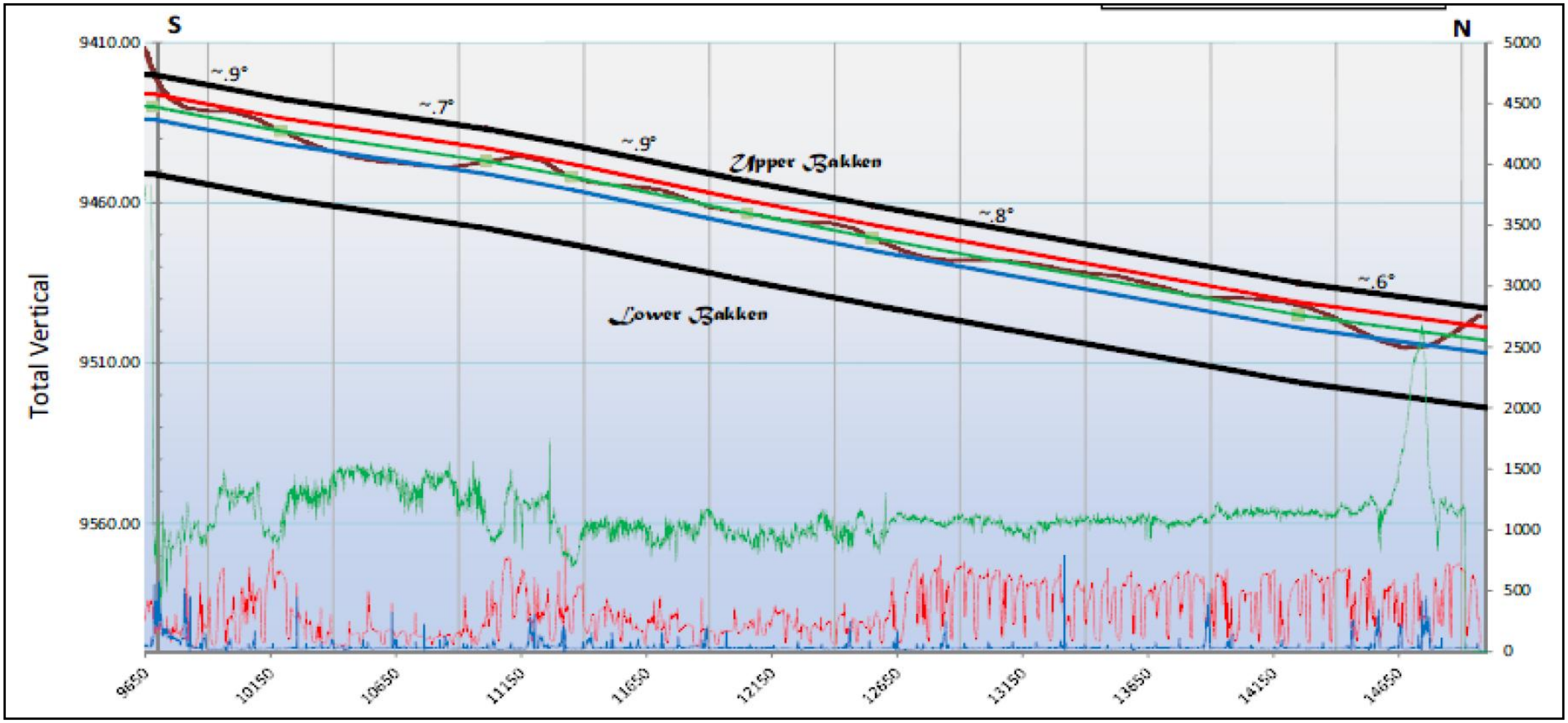

Figure 24. Log of Samson Australia II recorded significantly lower total gas while drilling the lateral through the Bakken middle member than the Samson Gretel II well. Pursuant to oral commumication with Conrad Woodland, geologist with Samson Oil and Gas, both wells were drilled slightly overbalanced. His interpretation of the lower readings was that there is poorer reservoir in the Australia II than in Gretel II (Samson, 2012, slide 20).

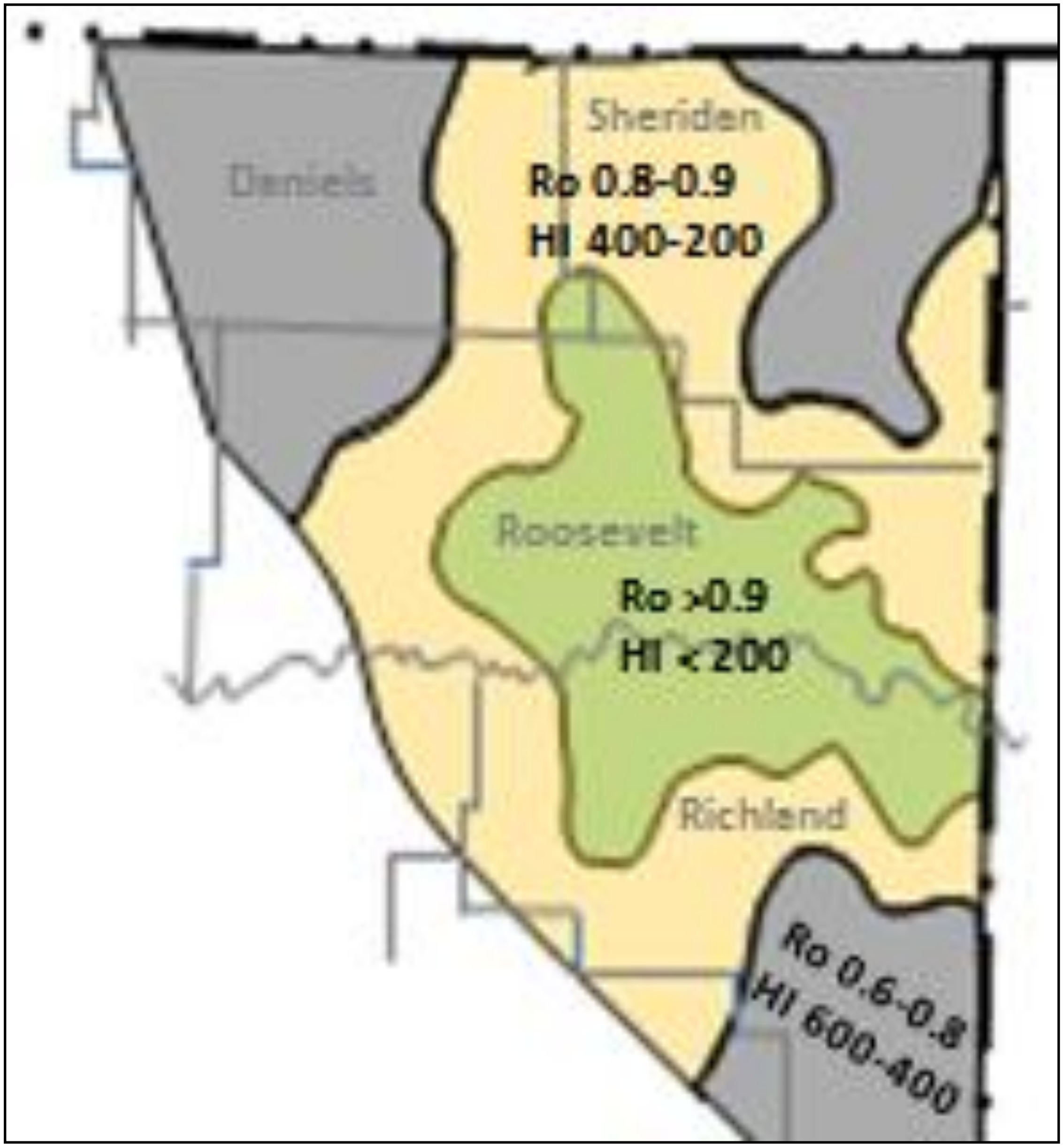

Figure 25. Bakken target map for northeastern Montana. Upper shale main target in gray area, Bakken middle member in green area; yellow area is transitional and dependent on BMM facies and thickness.

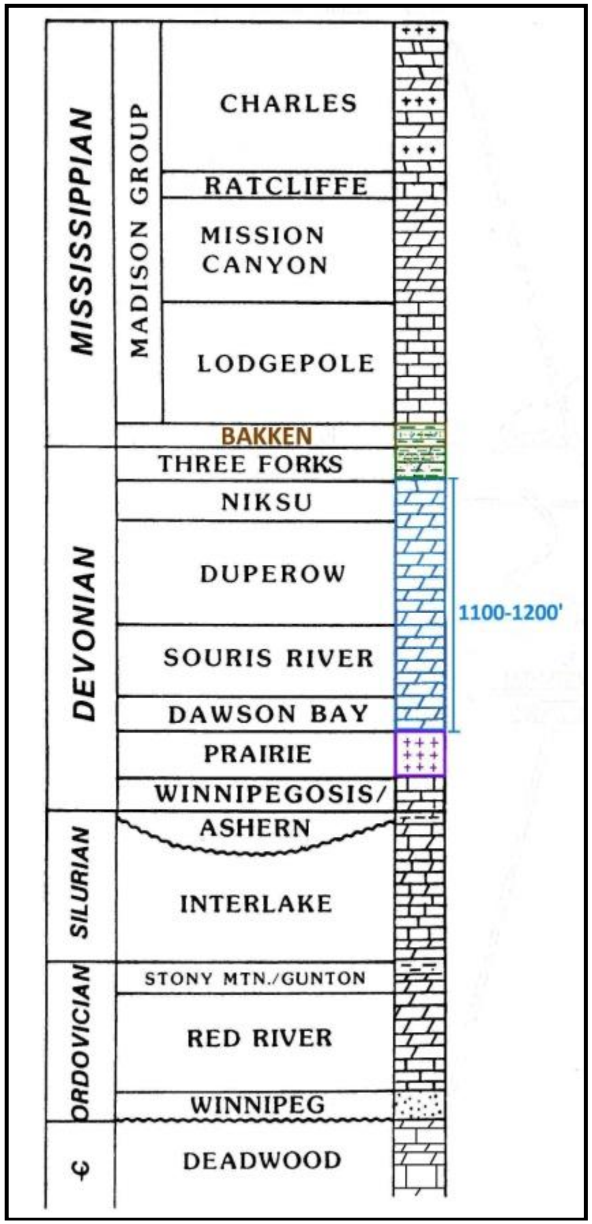

Figure 26. The Prairie Formation is separated from the Bakken by 1100 to 1200 feet of dolomite in most of the Williston Basin.

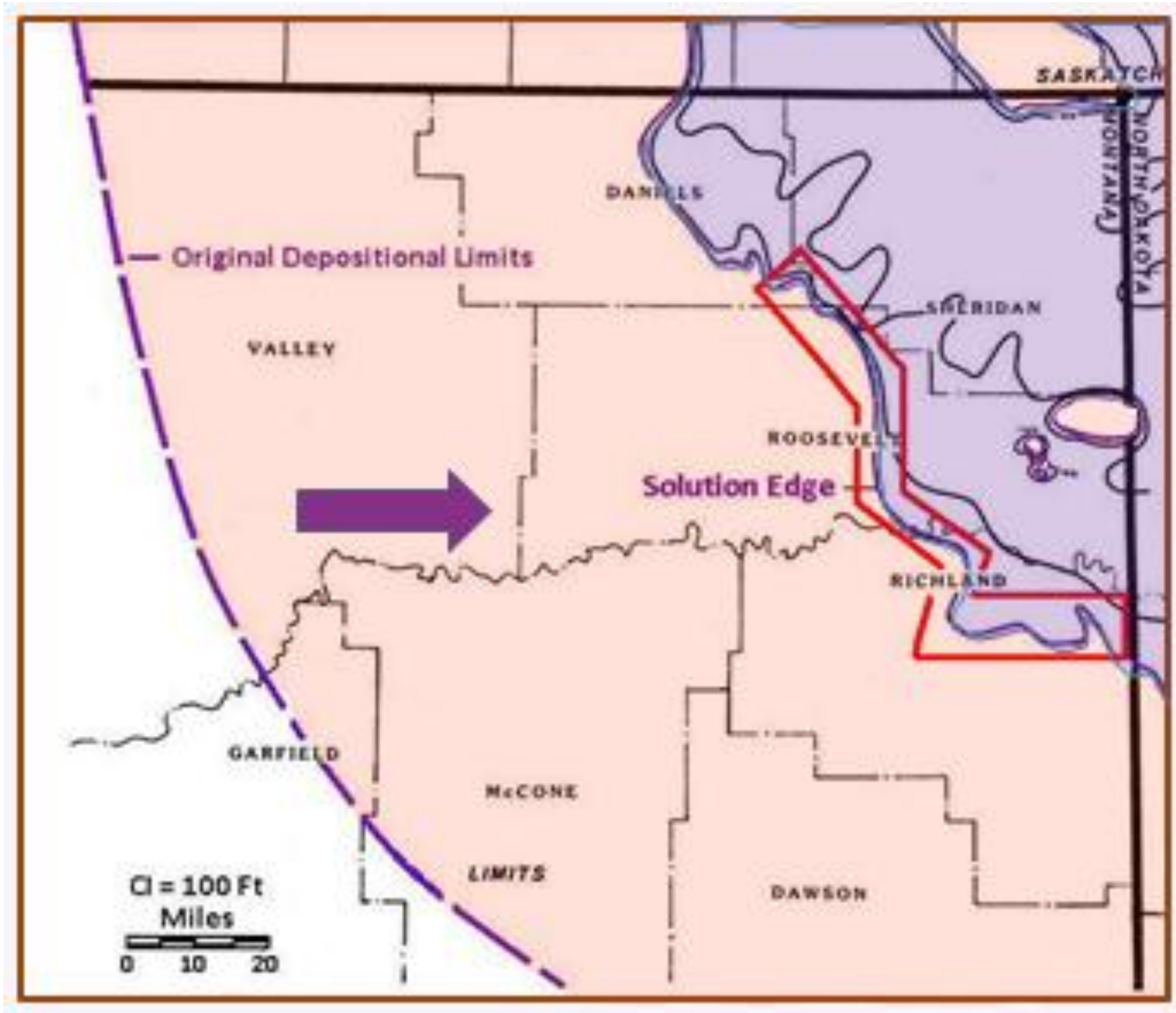

Figure 27. Isopach map of the Prairie salt in northeastern Montana, suggesting more than 60 miles of salt-edge retreat by solution. The dashed line represents the interpreted depositional limits of the Prairie and the solid purple lines are contours of Prairie thickness.

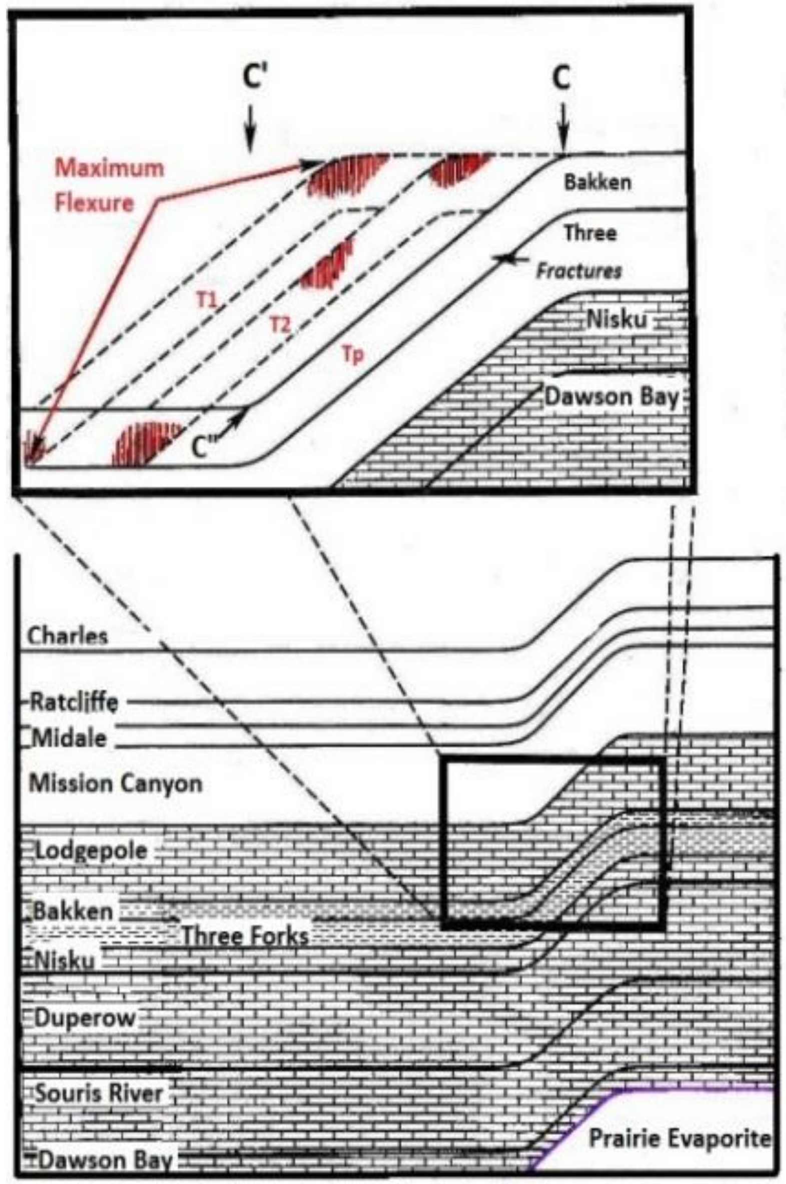

Figure 28. Schmatic diagram that depicts the process of fracture formation within the Bakken Oil System during solution of the Prairie salt. The fractures are formed by three processes: 1) maximum flexure at the top of the solution front, 2) maximum flexure at the base of the front and 3) physical collapse of the section into the void. Note the base of the migrating solution edge undergoes two stages of maximum flexure.

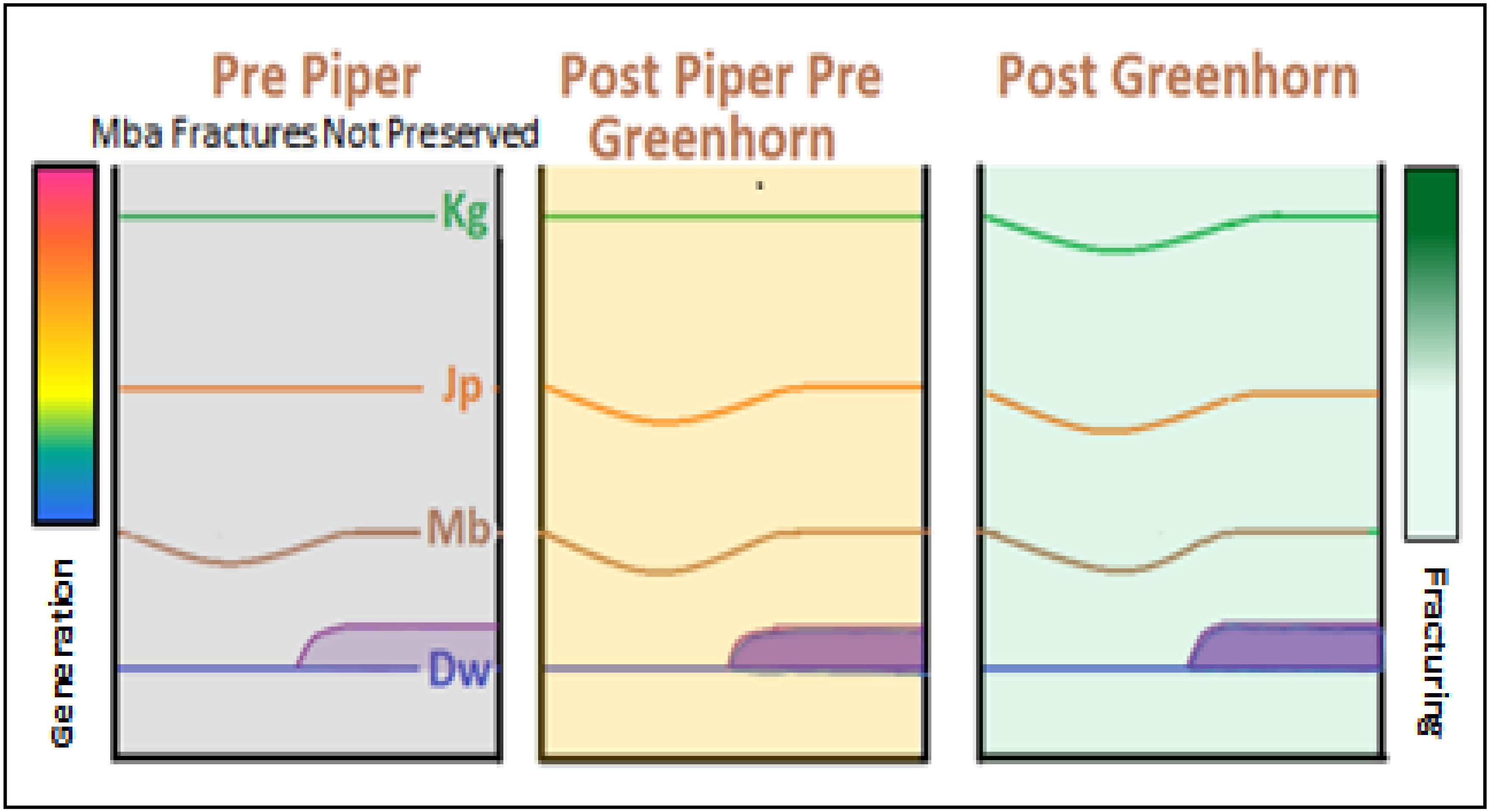

Figure 29. Dating of the solution of the Prairie is determined by isochron thicks and consequent sags produced by differential substance during collapse into a salt void. Optimum conditions for formation of a BOS sweet spot occurred where solution was Late Cretaceous or younger.

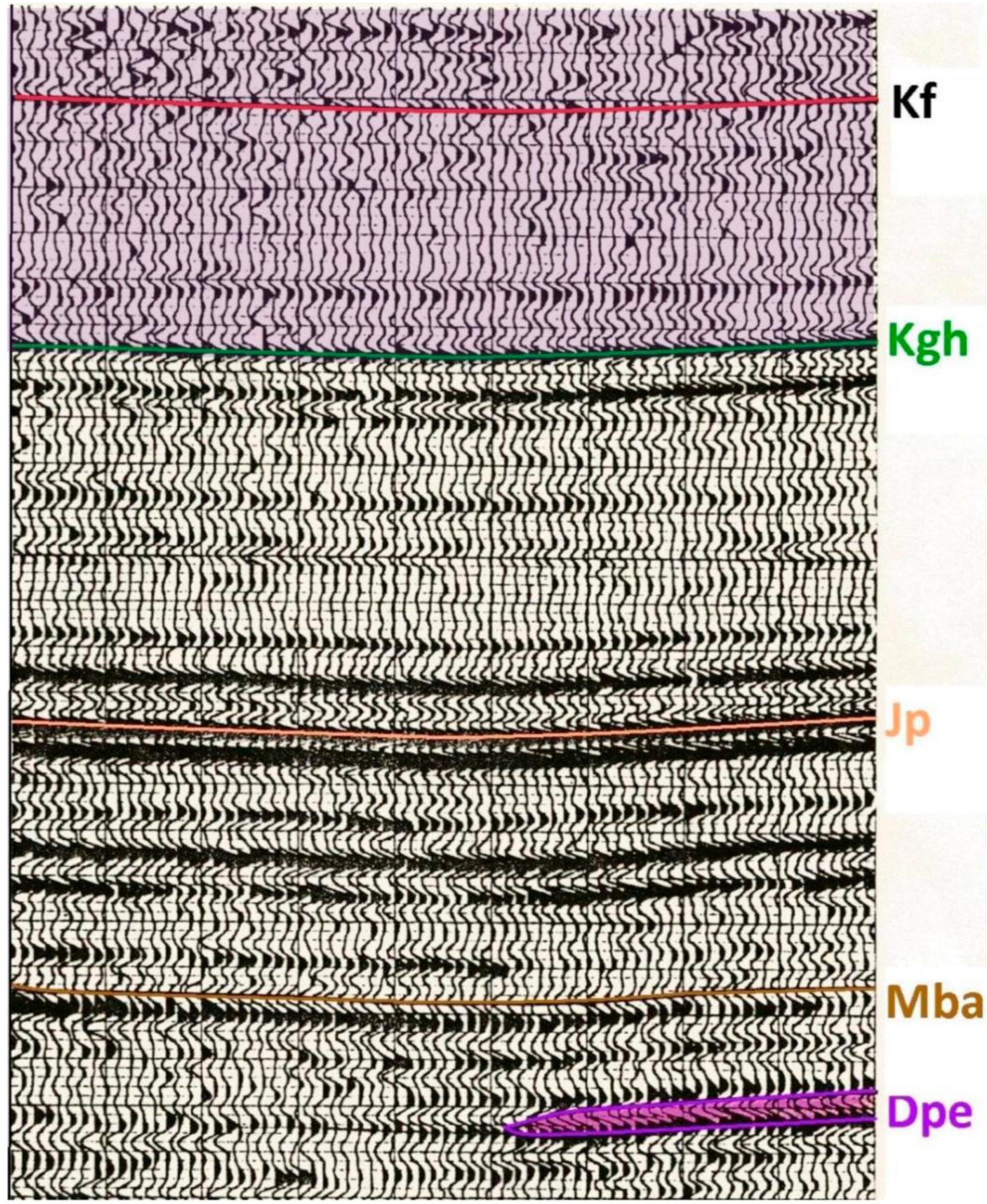

Figure 30. A west-to-east 12-fold, CDP, dynamite line clearly depicts the present edge of the Praire salt (purple). The youngest definite reflector that demarks collapse into the salt void represents the Greenhorn (mid- to Late Cretaceous), although the less definitive reflector representing the Frontier Formation suggests continuation of solution. All solution post-dates Greenhorn deposition.