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# Stratigraphy, Depositional Environments and Petroleum Potential of the Three Forks Formation (Upper Devonian), Williston Basin-North Dakota, United States

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**Abstract:** The petroleum potential of the three forks formation (upper devonian) in North Dakota is poorly known due to limited stratigraphic, geochemical and petrophysical data. This study is an analysis of the stratigraphy, lithofacies distribution, petroleum potential and paleo-environments of the three forks formation using log and core data. About 5 major lithofacies are identified and the detailed lithology of the formation is computed by employing a probabilistic interpretation approach calibrated with lab results. These facies correlate well with electrofacies predicted by employing principal component analysis and clustering techniques to selected lithology-sensitive logs. Petrophysical examination of clay volume, porosity and fluid saturations plus hydrocarbon source rock analysis including type, quantity and thermal maturity of kerogen on all 5 facies using Rock-Eval 6 pyrolysis and LECO TOC show that these units have poor to fair petroleum potential and contain immature type II and III kerogens. About 6 members of the Three forks are identified and a proposed depositional model for the formation is constructed based on detailed core examination and petrographic evidences. Sufficient evidence is provided to show that the three forks formation is of peritidal to sabkha-like origin.

**Key words:** Three forks formation, stratigraphy, depositional environments, petroleum potential, formation, rock-eval pyrolysis, principal component analysis

## INTRODUCTION

The three forks (Fig. 1) is an upper devonian formation present in the Williston Basin. The geologically define Williston Basin is a structural-sedimentary intracratonic oval-shaped depression that occupies the Western ramp shelf of the North American craton. A part of the Northern great plains of United States and Canada the Williston Basin consists of Paleozoic carbonate rocks interweaved with evaporates, detrital clastics and Mesozoic to Cenozoic clastic sediments with a total thickness of approximately 4880 m (16.000 ft.)

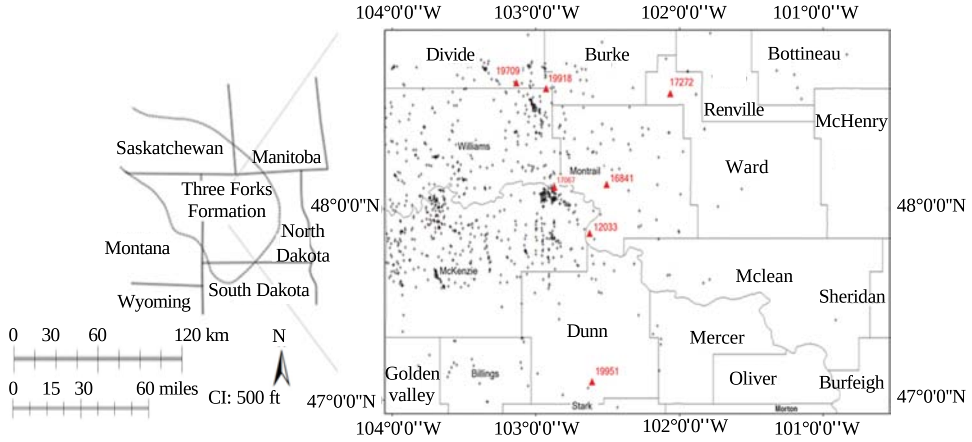


Fig. 1: Map showing the extent of the Three forks formation and the distribution of wells used in this study. Triangles indicate wells used for stratigraphic modeling and core description

(Borchert *et al*., 1990). The forks formation extends approximately 764 km (475 mi) North-South and 480 km (300 mi) East-West, covering about 75% of the State of North Dakota with a maximum thickness of 82 m (270 ft.). The composition of the three forks formation is mostly variations of greenish-gray, grayish-orange and grayish red silty to sandy dolomite, ferroan and non-ferroan dolo-mudstones, altering amounts of anhydrite and minor amounts of other detrital components. The well-defined depocenter covers Mountrail, Dunn and Eastern McKenzie counties and thins outwards from the basin center (LeFever and Nordeng, 2010).

In evaluating the petroleum potential or overall performance of the three forks, its sedimentary series, paleo-environments and a detailed well-to-well correlation of lithofacies is crucial in building a detailed 3-dimensional picture of the stratigraphy and reservoir quality of uncored wells. It is uncommon for wells that penetrate the three forks to have complete core sections across the reservoir. This creates a major challenge in detailed interpretation of the lithofacies within a specific area at the core-scale. The use of methods that apply artificial intelligence in predicting lithofacies from logs is necessary in such a situation. Therefore, establishing a sophisticated correlation between identified electrofacies and core data is a necessary step if geological information needs to be extracted from well-logs alone (Bucheb and Evans, 1994).

Little is known of the thermal maturity of the Upper Devonian Three forks formation even though such information is crucial for predicting the type of hydrocarbons that may have been generated or whether the hydrocarbon in the Three forks formation is indigenous or might have migrated from the bakken formation that lies above or from the birdbear formation underneath. In evaluating the petroleum potential of the Three forks, the amount and character of the Organic Matter (OM) that is or might have existed, given the proper conditions is examined. The porosity, permeability and fluid saturations are also highlight using examples from 5 wells. Understanding these aspects provides the basis for a more comprehensive evaluation of the resource potential of the Three forks in North Dakota.

**Study objectives:** This investigation is undertaken because of the need for a detailed study on the Upper Devonian rocks in the Williston Basin in North Dakota. Hence, the main objectives are to:

- Compute the lithology of the three forks, identified and describe its lithofacies through visual core description and to compare these lithofacies with predicted electrofacies
- Interpret the petroleum potential of the three forks by looking at the geochemical characteristics of these lithofacies
- Identify the sedimentary features of the different members and reconstruct their environments of depositional

## MATERIALS AND METHODS

The approach involves a series of steps outlined as follows: Wells are selected such that they have the same number and type of well logs. Cores from 7 wells that go through the Three Forks were described. Of the 7 wells, 5 are selected for petrophysical evaluation, creating a data base of 25 conventional logs with each log suite consisting of the Gamma ray (Gr), formation density (RHOB), neutron porosity (PHIN), sonic ($\Delta T$) and Resistivity (Rt) logs. A detailed description of the subsurface lithology is achieved by integrating data from visual core analysis with geophysical modeling using the Interactive Petrophysics software.

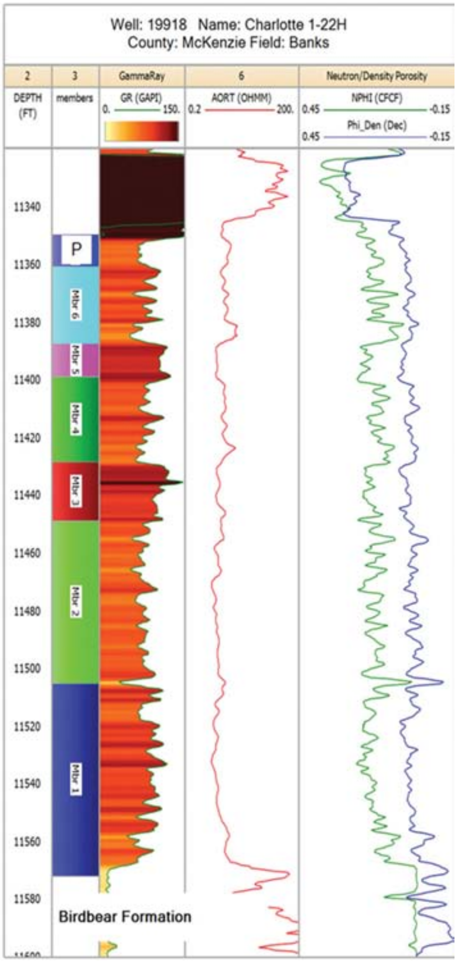
Electrofacies are predicted using a combination of Principal Component Analysis (PCA) plus clustering techniques and validated by comparing results with lithofacies identification at the core-scale. Logs had been environmentally corrected for borehole size, temperature, mud salinity and depth-matched to core depths. Also to reduce the error associated with tool calibration and malfunction, logs were normalized for each Principal Component (PC) before analysis by K-mean and hierarchical clustering techniques.

To determine the petroleum potential of the three forks, 2 samples from each lithofacies are analyzed to determine their TOC percent and kerogen characteristics using rock-eval 6 pyrolysis. The details of the analytical procedure, terminology and interpretive guidelines for rock-eval and TOC data have been thoroughly discussed (Espitalie *et al*., 1977; Snowdon *et al*., 1998).

## RESULTS AND DISCUSSION

The type section of the three forks formation is originally described from the outcrop north of the Gallatin river in Gallatin county, Montana (Sandberg and Hammond, 1958). Within the subsurface in North Dakota, the standard subsurface section of the three forks formation is placed between the depths of 10.076 and 10.310 ft., of the mobil birdbear well No. 1 in Dunn county. Lithologically, the Three forks consist of different colors of laminated to bedded carbonates, separated by dark gray to gray-brown, seams of shale and various forms of anhydrite. Within the studied wells, the distinction between the pronghorn and the overlying lower bakken is usually a sharp (erosive) unconformable contact while the contact between the pronghorn and the underlying three forks may be a sharp and disconformable surface or transitional which is difficult to identify. Where the pronghorn is absent the three forks makes a direct contact with the bakken formation. The lower contact with the birdbear formation is conformable and is taken at the base of the reddish brown dolomitic mudstones of the lower three forks. The three forks formation is divided into 6 members (from bottom to top) based on their gamma ray-resistivity log response. These members can be traced across most of the basin and are similar to those observed in South Eastern Saskatchewan (Christopher, 1961), all of which may or may not be present within a given well section in North Dakota. A reference log for the three forks is shown in Fig. 2.

**Three forks silt:** The three forks silt is defined to include member 5 and the rest of the upper three forks which consist of member 6 and the pronghorn member of the bakken formation where present. The reason for grouping these strata is the fact that these members are rare in cores and the strata between the lower bakken and member 4 of the three forks is quite thin compared to the rest of the three forks. Thus, grouping them together makes it easier for mapping purposes (Fig. 3a). The pronghorn includes rocks between a major unconformity at the top of member 5 and the lower bakken that constitute from bottom to top, a burrowed basal sandstone, a medium brown dolomitic mudstone with hummocky cross-stratification, a brachiopod bearing lime mudstone and dark gray limestone (LeFever and Nordeng, 2010). Member 6 consists of grayish-brown to tan colored silty dolomite, commonly interbedded with bluish-green shale and characterized by disseminated pyrite.



| Description | Interpretation |
|---|---|
| Limestone: dark gray, micrite; Dolomicrite: medium brown, burrowed sandstone/siltstones. | Subtidal. |
| Dolomite; light brown, grayish to tan; sucrosic, micro to cryptocrystalline, silty, disseminated pyrite. Shale: bluish green. | Intertidal to very shallow subtidal. Pyrite: reducing conditions e.g. mudflat. |
| Dolomite: Silty tan, highly deformed, brecciated; Shale?: light green. | Intertidal to mid-supratidal. |
| Dolomite; light gray to cream some tan; Shale: light blue/green; Laminated; minor bioturbation. | Supratidal to upper intertidal. |
| Dolomicrite: tan to brown; interbedded with: red calcareous mudstone, light gray-green shale. | Mud-rich coastal deposits (Intertidal) to sabkha. |
| Interbedded red or grayish orange mudstones and grey-green siltstones.<br>Occasional dolomitic, anhydritic. Massive, often brecciated. | Supratidal to sabkha. |
| Anhydrite: small-cystal noules, may be bedded; large-crystal nodules and bands.<br>Iinterbedded trace blue green to light gray, light brown to rust brown mudstones and sanstones. | Supratidal to sabkha.<br>Direct precipitation/replacement of gypsum nodules.<br>Enlargement of anhydrite crystals within supratidal sand. |

Fig. 2: Typical well log responses for the three forks, showing 6 members (from bottom to top) and the Pronghorn (P) with corresponding depositional environments

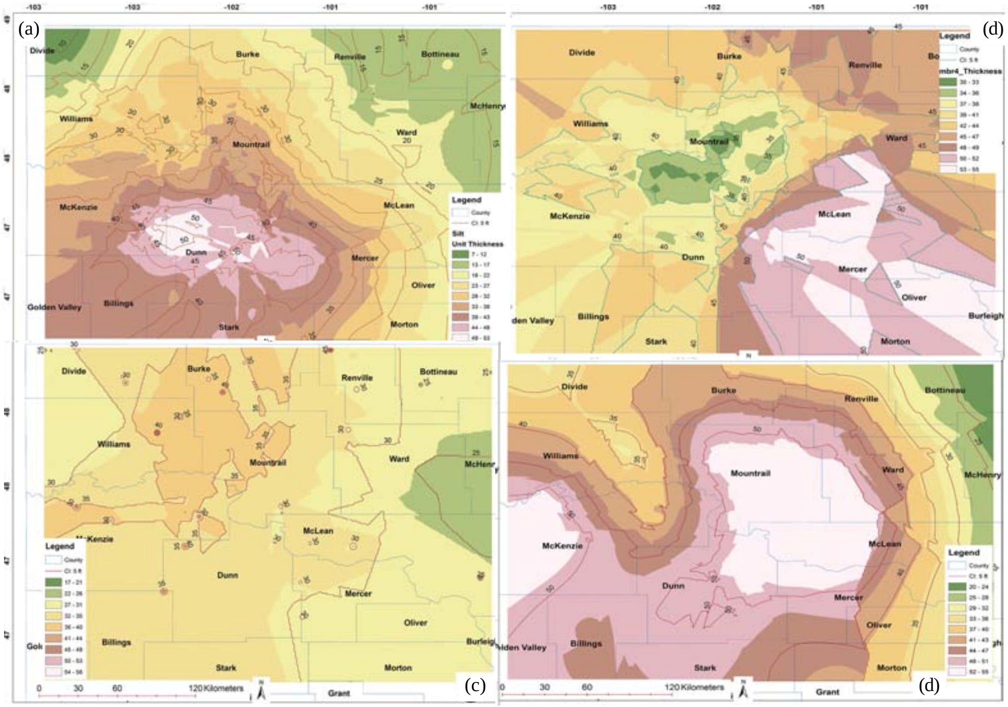


Fig. 3: Isopach maps of the Three forks formation: a) Three forks silt; b) Member 4; c) Member 3; d) Member 2

Member 5 forms the first bench of the Three forks, as observed on the gamma ray log and is the thinnest member with an average thickness between 4 m (13 ft.). About 3 lithologies commonly occur in cores of this member:

- A well sorted mixture of very fine to fine-grained tan and light to dark grey dolomitic siltstone
- A poorly sorted to brecciated, silty to sandy, greenish-gray to yellowish-gray dolomite
- Highly deformed gray-green shale and tan colored dolomitic mudstone from top to bottom (Fig. 4)

Together, these sediments represent a change in depositional environments from shallow intertidal to supratidal.

**Member 4:** Lithologically, member 4 is very similar to member 5, consisting of highly deformed, brecciated in parts, intercalated light to dark blue/green shales and light gray to cream dolo-mudstones at the top with periodic occurrence of parallel laminations with more or less planar contacts. This sequence terminates with moderately to highly deformed and brecciated sediments at its base (Fig. 4). Member 4 sits on the second marker bed of the Three forks and is present in all cores examined. Its thickness varies slightly throughout the studied sections ranging from about 6-18 m (20-60 ft.) (Fig. 3b). Recognizable sedimentary structures include cross-laminations, flaser, parallel lamination, climbing ripples, soft-sediment deformation and minor burrowing. The contact between member 4 and 3 is conformable throughout the study area.

**Member 3:** The thickness of this member ranges from 6-9 m (20-30 ft.) as shown in Fig. 2. Since, its contacts with member 4 above and member 2 below are both gradational, the lithology of member 3 may fall between dark grey-green slightly deformed and brecciated dolomite rich shales, interbedded with tan to brown, oxidized silty to sandy calcareous mudstones. These rocks are generally structureless or contain slight, wispy lamination and may become poorly sorted and anhydritic towards member 2. The isopach map of this member is shown in Fig. 3c.

**Member 2:** Member 2 is the third bench and is the most extensive member with an average thickness of over 15 m (50 ft.) (Fig. 3d). Member 2 consists predominantly of 2 lithologies, grey-green shales, occasionally dolomitic, interbedded with oxidized dolo-mudstones whose color varies from grayish orange to dark brown (or red) with sporadic appearances of various forms of anhydrite. Sedimentary structures are scarce but minor rootlet

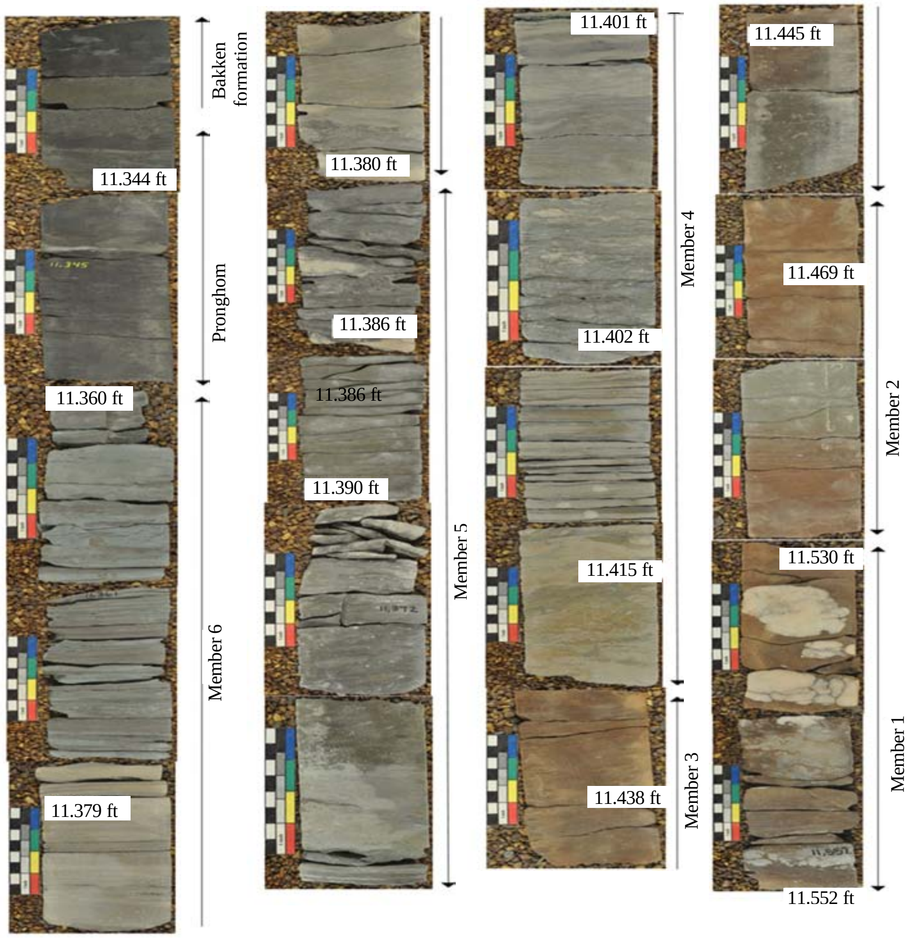


Fig. 4: Slabbed core of the three forks in the charlotte 1-22H well showing all members. Stratigraphic depth increases from left to right and from top to bottom

structures and soft sediment deformation are locally observed. Anhydrite may be nodular (chiken-wire) but mostly bedded.

**Member 1:** Member 1 (Fig. 5) is commonly represented by medium tan to rust brown or dark red sandstone beds intermixed with light gray to trace blue-green mudstones. Generally, the sediments are moderately dolomitic and ferroan, characterized by deformation and extremely diverse micro-breccias of both dolo-mudstones and anhydrite with poor intergranular porosity. The different forms of anhydrite identified include; bedded angular nodular, bedded nodular mosaic, distorted bedded nodular, distorted nodular, nodular mosaic (chicken-wire) and massive anhydrite. Primary sedimentary structures are less obvious as in member 2 probably due to the high degree of deformation. These breccias are interpreted as polygenetic, formed either by erosion and redeposition of irregular fragments of earlier formed dolomite during weak synsedimentary processes or a direct response to stress such as tectonic, physical deformation, neomorphism or dolomitization (Wanless, 1979).

The 5 main lithofacies from top to bottom are defined to be meaningful, predictable and mappable (Fig. 6). Representative samples of each lithofacies are selected for thin section, XRD, SEM and Rock-Eval analysis.

**Lithofacies 1:** The rocks belonging to this lithofacies consist mainly of very fine to fine-grained beds of dolo-mudstone and very thin, siltstone laminations. The color is a mixture of light to dark grey intermixed with very pale orange to grayish-yellow lime mud (Fig. 6a). Disseminated pyrite and interbedded fractures are quite common but stylolites occur less frequently. The typical bed thickness is between 1.5-6 cm (0.5-2 in). This facies may be massive or slightly cross-laminated and may display evidence of slight bioturbation.

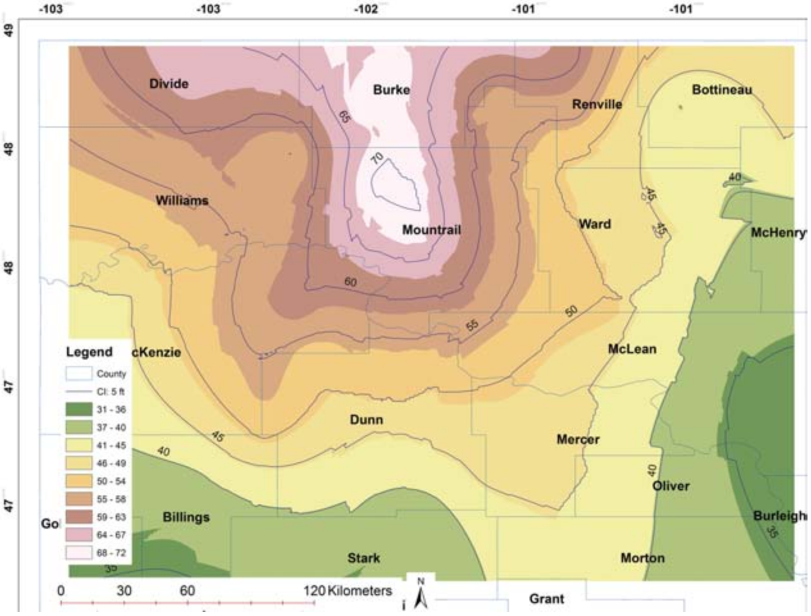
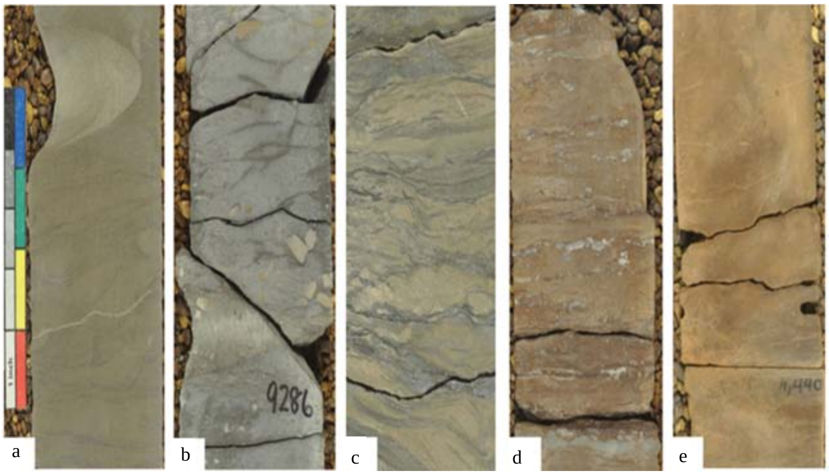


Fig. 5: Isopach map of member 1 of the three forks formation



Lithofacies 1
9.268 ft

Lithofacies 2
9.286 ft

Lithofacies 3
9.311 ft

Lithofacies 4
9.360 ft

Lithofacies 5
11.440 ft

Fig. 6: Identified lithofacies in the three forks formation. Samples from lithofacies 1-4 are selected from well 19951 while lithofacies 5 is from well 19918

**Lithofacies 2:** This lithofacies is recognized, as the grayish-blue green to pale yellowish gray colored silty to sandy dolomite of the Three forks formation (Fig. 6b). The main characteristics are the mottled, intraclastic to lightly brecciated textures. Locally, evidence of subaqueous shrinkage and minor desiccation cracks are present. Overall, this lithofacies appears blocky with less obvious sedimentary structures, such as cross-lamination and interbedding. Similar to lithofacies 1, pyrite crystals are disseminated locally.

**Lithofacies 3:** This lithofacies consists of interlaminated, interbedded dark grayish-green shale and light tan to olive-grey silty dolomite with a typical asymmetric boudinage structure (Fig. 6c). These cylinder-like structures of strongly deformed or disrupted layers develop as a response to bulk extension along the enveloping surfaces or layer-normal compression (Mandala *et al*., 2000). Similar to Berwick (2008)'s Facies C, brecciation and intense soft sediment deformation makes identification of primary and secondary structures very difficult. Breccias are subangular to irregular with sizes between 2 and 6 cm (0.79 and 2.36 in). This facies is the most extensive and is present in all studied cores and in all members.

**Lithofacies 4:** This lithofacies consists mainly of highly oxidized dark brown to medium tan silty to sandy dolomitic mudstone (Fig. 6d). This lithofacies mostly occurs in the lower members and often associated with bedded or nodular anhydrite. Overall, this lithofacies is less deformed with a massive appearance in hands specimens. Anhydrite nodules within this facies range from 0.2-10.0 cm (0.079-3.9 in) in diameter.

**Lithofacies 5:** This lithofacies consists of fine to very fine weakly oxidized moderate yellow to light brown siltstone, often interbedded with shales or claystones (Fig. 6e). Mostly massive although interbedding with green shales is common. This facies is quite similar to lithofacies 4 and was not observed in all cores.

**Electrofacies modeling:** Since, each selected log measures a different physical property when used in combination or in tandem they provide a much better understanding of both pore volume and mineral composition. By combining the litho-porosity crossplot (Burke *et al*., 1969) and a probabilistic interpretation technique, the mineralogy in the multiple reservoir zones of the three forks can be resolved. A mineral model is built to describe the main minerals and fluids at any particular zone of the formation and expressed in vertical profiles of variation. Calibrated with results from XRD and routine core analysis, the main elements included in the models for reservoir rocks of the three forks include porosity, resistivity and gamma ray logs, calcite, dolomite, anhydrite, clays, quartz, oil and water. Finally, the system of equations is solved to find the most probable result for each layer in the well and presented.

**Model validation:** The first step in the statistical application of litho-stratigraphic modeling is to separate the data into 2 sets. Set 1 consist of 3 wells (17067, 16841 and 12033) while set 2 consist of a reference well (15591) (Appendix). Results of the combined PCA for wells belonging to set 1 are given in Table 1. Results for the reference well are also provided. The first 2 PCs account for about 77% of the total variability in both cases. K-mean and hierarchical clustering techniques are applied to the first 2 PCs. A cluster randomness plot is then used to decide at which level adding another cluster provides more information or simply increases the level of noise. Finally, the three forksis subdivided into 4 major electrofacies with well-defined log characteristics (Fig. 7). To validate these results, electrofacies are derived for the reference well following the same approach and compared with results from core description. The result for the reference well as shown in Fig. 8, displays the zoned curve in track 4, the modeled lithology in track 5 and a perfect match between log-derived facies and core lithofacies in track 6 which strongly validates the procedure. Positions where the core was sampled for petrographic and geochemical analysis are also indicated.

Table 1: Summary of PCA for set 1 (wells 17067, 16841 and 12033) and the reference well (19951)

| Output | Names | Variability (%) | Variability (%) |
|---|---|---|---|
| 1st | PC1 | 50.18 | 57.37 |
| 2nd | PC2 | 26.09 | 19.37 |
| 3rd | PC3 | 15.16 | 9.99 |
| 4th | PC4 | 8.57 | 8.38 |
| 5th | PC5 | 0.00 | 4.89 |

Input curves: RT, GR, DT, NPHI and RHOZ

Table 2: Summary of fluid saturations (%) from core analysis

| | Member | | | | | |
|---|---|---|---|---|---|---|
| Units | 6 | 5 | 4 | 3 | 2 | 1 |
| Sw | 50 | 81 | 76 | 77 | 80 | 76 |
| So | 20 | 9 | 7 | 7 | 9 | 7 |
| Total | 70 | 90 | 83 | 84 | 89 | 83 |

**Petrophysical parameters:** Measurements of the Volume of clay (Vcl), porosity ($\phi$), Permeability (K), water Saturation (Sw) and oil Saturation (So) are derived from 4 wells (17271, 19709, 19918 and 19951) that penetrate the three forks formation and cored with Oil-Base Mud (OBM). The Vcl is calculated from wells logs and used to calculate log-porosities which are then compared with core-derived $\phi$, K, Sw and So obtained from 770 core plugs from all 4 wells. The average Vcl for the three forks, calculated as the minimum shale response of all single and double shale is 35% and routing core analysis at net effective overburden stresses of 4.000 psi revealed low porosities with a mean value of about 8%. Also, log-derived porosities, obtained from the density-neutron porosity crossplot (corrected for clay volume and hydrocarbon density) agree quite well with lab results. The average klinkenberg permeability is 0.016 mD and the average Sw and so are summarized in Table 2. The grain densities range from 2.73-2.95 g $cc^{-1}$ with a mean value of 2.79 g $cc^{-1}$. As an example, a summary of the petrophysical properties of the three forks formation in well 19709 is presented as Fig. 9.

**Organic richness, quality of organic matter and level of maturity:** TOC measurements represent the sum of kerogen and bitumen within the formation and provide both a quantitative assessment of organic richness and an

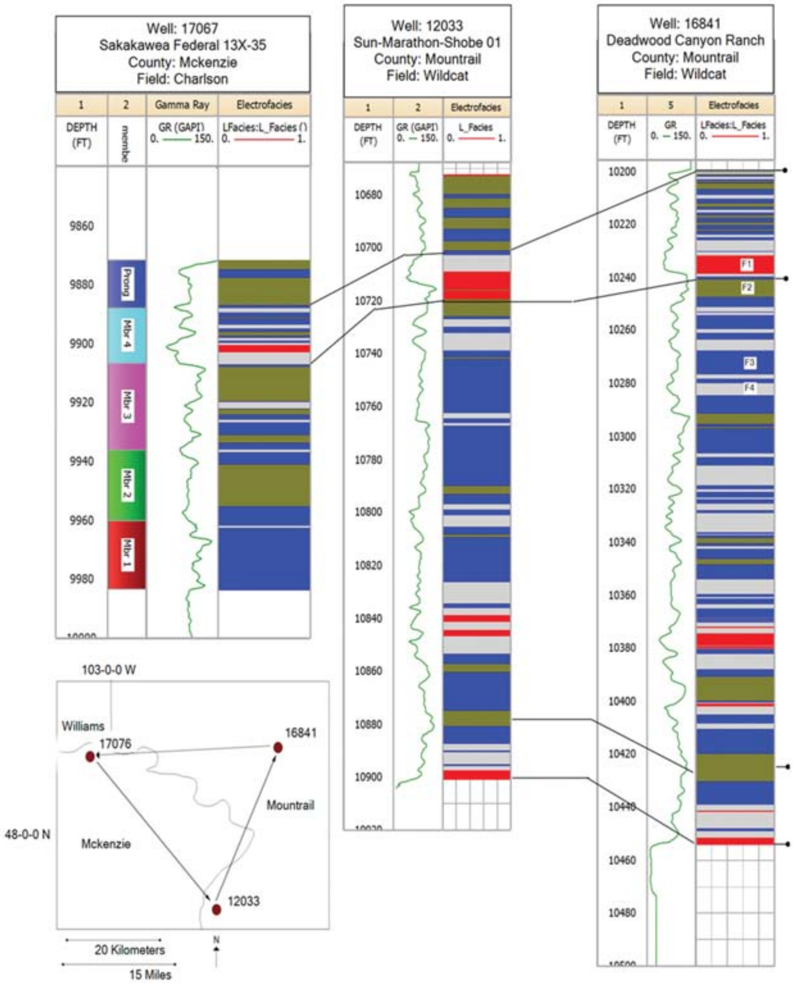


Fig. 7: Vertical stacking pattern and lateral correlation of electrofacies for wells in set 1. F1-F4 are hypothetical facies that can be traced across.

Table 3: Summary of rock-eval/Toc data from core samples

| Well # | ID | Depth (ft.) | TOC wt. (%) HC | (mg HC $g^{-1}$)<br>S1 | S2 | S3 (mg $CO_2$ $g^{-1}$) | Tmax (°C) | HI* | OI* | PI* |
|---|---|---|---|---|---|---|---|---|---|---|
| 19951 | Facies 1 | 9.264 | 0.13 | 0.21 | 0.17 | 0.45 | 357 | 130 | 344 | 0.55 |
| | | 9.268 | 0.15 | 0.23 | 0.19 | 0.45 | 355 | 131 | 310 | 0.55 |
| | Facies 2 | 9.279 | 0.13 | 0.47 | 0.21 | 0.40 | 420 | 165 | 315 | 0.69 |
| | | 9.286 | 0.14 | 0.46 | 0.22 | 0.41 | 418 | 159 | 297 | 0.68 |
| | Facies 3 | 9.311 | 0.10 | 0.44 | 0.16 | 0.38 | 418 | 166 | 393 | 0.73 |
| | | 9.321 | 0.12 | 0.44 | 0.17 | 0.38 | 417 | 139 | 311 | 0.72 |
| | Facies 4 | 9.350 | 0.10 | 0.24 | 0.30 | 0.28 | 348 | 306 | 286 | 0.44 |
| | | 9.360 | 0.10 | 0.24 | 0.29 | 0.28 | 349 | 293 | 283 | 0.55 |
| 19918 | Facies 5 | 11.440 | 0.24 | 1.58 | 0.50 | 0.17 | 430 | 207 | 70 | 0.76 |
| | | 11.469 | 0.24 | 1.59 | 0.51 | 0.16 | 430 | 211 | 66 | 0.76 |

*Hydrogen Index (HI) = (S2/TOC)*100; Oxygen Index (OI) = (S3/TOC)*100; Production Index (PI) = S1/(S1+S2)

indication of the generative potential of the formation (Jarvie, 1991). Table 3 shows that the results of TOC analyses from all 5 lithofacies range from 0.10-0.24 wt.% HC. Generally, sediments with <0.5 wt.% HC are consistent with rocks that have poor petroleum potential. Also, the S2 values <2.5 mg HC $g^{-1}$ of rock confirm this claim (Peters and Cassa, 1994). The plot of Tmax vs. HI suggests that all samples from the Three forks are immature although the degree of maturity of the OM generally increases with depth. However, Tmax values

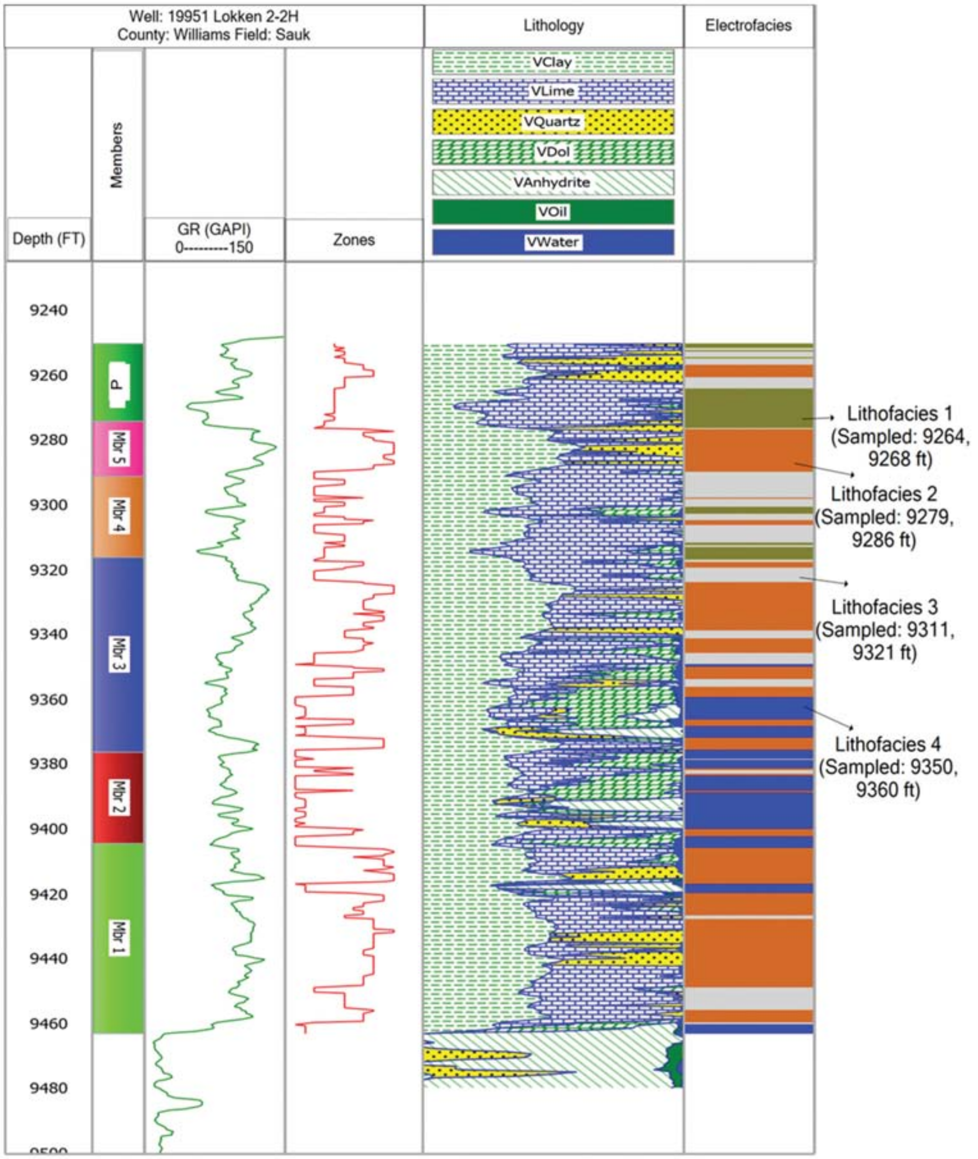


Fig. 8: Stratigraphic gamma-ray and facies interpretation of well 19951 (Sauk field). Sampled depths represent intervals where samples were collected

Table 4: Hydrocarbon indication and maturity parameters; calculated vitrinite reflectance, S2/S3 and normalized oil content for the three forks formation

| Well (#) | ID | Depth (ft.) | Calculated Ro (%) | S2/S3 conc. (mg HC $mg^{-1}$ $CO_2$) | Norm. oil content S1/TOC |
|---|---|---|---|---|---|
| 19951 | Facies 1 | 9.264 | | 0.38 | 160 |
| | | 9.268 | | 0.42 | 159 |
| | Facies 2 | 9.279 | 0.40 | 0.53 | 370 |
| | | 9.286 | 0.36 | 0.54 | 333 |
| | Facies 3 | 9.311 | 0.36 | 0.42 | 455 |
| | | 9.321 | 0.35 | 0.45 | 361 |
| | Facies 4 | 9.350 | | 1.07 | 245 |
| | | 9.360 | | 1.04 | 242 |
| 19918 | Facies 5 | 11.440 | 0.58 | 2.94 | 653 |
| | | 11.469 | 0.58 | 3.00 | 657 |

around 435°C and the calculated vitrinite reflectance of lithofacies 5 (Table 4) suggest that the formation may be in the immature to early mature stage with respect to oil generation. Also, the kerogen in these samples is a mixture of oil prone type II and gas prone type III material, indicating that the Three forks has some potential to generate hydrocarbon with lithofacies 4 and 5 having the greatest potentiality.

**Source of hydrocarbon:** The anomalously high normalized oil contents (Table 4) indicate productive oil or gas reservoir intervals that are probably the result of migrated

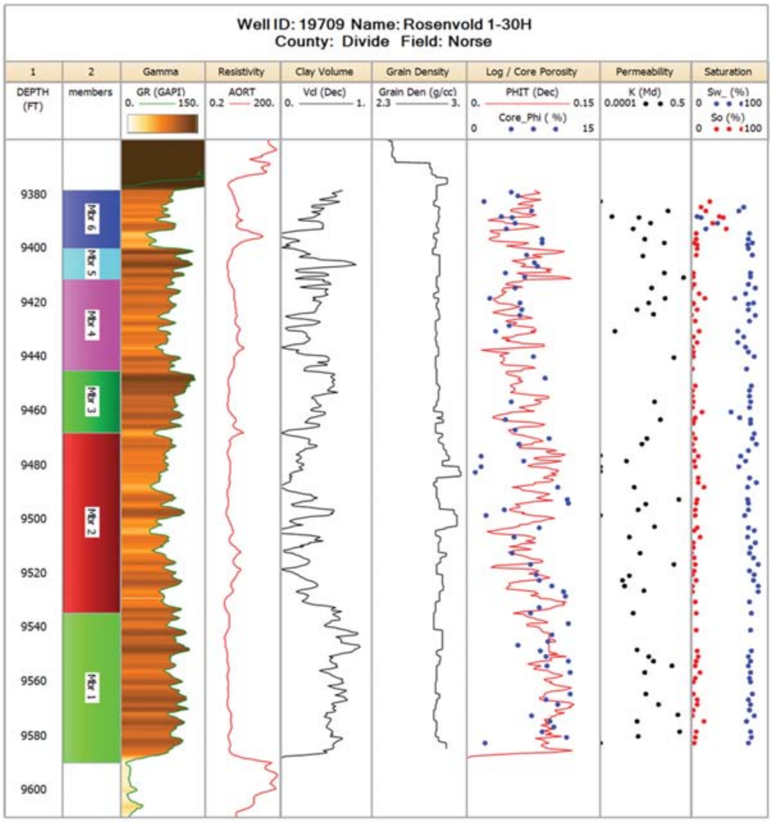


Fig. 9: Stratigraphic distribution of the volume of clay, grain density, log and core porosity, permeability, water saturation and oil saturation of the three forks

oil. Similarly, the PI values are anomalously high indicating possible contamination and are excluded from all evaluations. All samples from these lithofacies indicate some contribution from non-indigenous (expelled) hydrocarbons (Hunt, 1996), suggesting that the migrated hydrocarbon were not generated *in situ* but were generated by older, deeper source rocks, possibly the birdbear formation.

**Environments of deposition:** The lower members of the three forks contain abundant intrasediment anhydrite of bedded and non-bedded varieties which only forms in environments where evaporation losses exceed precipitation and can only accumulate in settings where concentrated brines are prevented from dilution by influx of less saline waters (Reading, 1996). Very often, the development of chicken-wire anhydrites is attributed to the replacement of an earlier gypsum crystal mush in a saline mudflat sabkha-like setting where additional nodules and nodule layers can develop within supratidal sediment above the main replacement zone, as in members 1 and 2.

Member 3 is interpreted as mud-rich coastal deposits that probably represent the transition from intertidal or lower supratidal to saline mudflat sabkha environments. Fossil evidence of the ordovician to late devonian stromatoporoid sponge was uncovered in member 4. This species seems to have been adapted to live in a range of environments extending from the distal subtidal to storm-dominated environments, i.e., from the storm wave base to above the fair-weather wave base (Tsien, 1980; Fernandez-Martinez *et al*., 2010). Coupled with sedimentary evidences, member 4 is thus a gradual change from supratidal to upper or mid-intertidal environments that underwent a very rapid sedimentation as indicated by its lack of burrowing.

The brecciated nature of member 5 reflects wave action that formed the breccias. This is probably a consequence of shoaling of the epicontinental sea because of a decrease in the rate of subsidence. Most of member 5 constitutes strata larking internal cross-stratification of any kind or cross-stratification makes up part of the layering but is typically, a subordinate component. In addition, the presence of disseminated pyrite within member 5 proves that chemically reducing conditions prevailed at some time during deposition. Such, anaerobic conditions occur in subtidal and intertidal sediments where oxygen is depleted just a few millimeters below the sediment surface. Given that the upper portion of member 6 is deformed by bioturbation, the interpretation is a progressive shift from the upper shoreface to subtidal environments from the top of member 5 to the start of the lower bakken member.

The anhydrite-dolomite relationship becomes less abundant or absent towards the outer ramp where silty/sandy lithologies become more prominent. Also, the thickness of the anhydrite-dolomitic cycles decreases upwards, towards the top of the formation. These anhydrite-dolomitic cycles are interpreted as deposits of restricted inner ramp environments with occasional seawater recharge. From results of petrographic analysis, such as very fine to fine, unimodal, anhedral crystals of dolomite and features like fenestral fabrics, anhydrite nodules and mud cracks, the origin of this dolomite is closely related to supratidal or arid upper intertidal environments in which the host limestone was being replaced. Based on these indicators the sabkha dolomitization model is suggested for the Three forks formation.

## CONCLUSION

The three forks formation is currently productive in the Sauk, Wildcat and Charlton fields with much existing rooms for research as a new exploration target. The lithology of the three forks is quite unusual and heterogeneous with different degrees of dolomitic mudstones with sandy textures, shales and various forms of anhydrite deformed in some places. Evidently, nodular and bedded anhydrites co-occur within the lower units, associated with oxidized dolo-mudtones with probable origin tied to a sabkha-like environment. About 5 lithofacies have been identified and correlated using multivariate analysis. Facies types and assemblages of this upper devonian succession represent a shallow-marine carbonate system of epeiric, ramp-like environment. From the absence of faunas, it is concluded that deposition was rather rapid. Large scale juxtaposition of these depositional facies indicates fluctuations in sea-level which resulted in substantial shifts in the position of the paleo-shoreline involving very shallow and subaqueous settings where more supratidal-dominated conditions prevail. Geophysical data from 4 wells is used provide an across-the-board assessment of the petrophysical characteristics of the three forks formation. Overall, the clay volume is high averaging 35%. Results from log and routine core analysis showed that the three forks in the studied wells has average porosities between 6.5 and 10% with a mean value of 8% and the mean permeability is about 0.016 mD. The grain density averages 2.79 g $cc^{-1}$. Oil saturation is low (~10%) while water saturation is very high (~80%). Geochemical data showed that the three forks has poor to fair petroleum potential, consisting of immature organic types II and III kerogens. The petroleum potential probably increases with depth as indicated by results from TOC and Rock-Eval pyrolysis.

## APPENDIX

Wells used in this study. (Obtained from the Wilson M. Laird Core and Sample Library of the North Dakota Geological Survey, 2013)

| Well | ID | API | Name | County | Field |
|---|---|---|---|---|---|
| 1 | 17067 | 33-053-02858 | Sakakawea federal 13X-35 | McKenzie | Charlson |
| 2 | 12033 | 33-061-00344 | Sun-Marathon-Shobe 01 | Mountrail | Wildcat |
| 3 | 16841 | 33-061-00581 | Deadwood canyon ranch | Mountrail | Wildcat |
| 4 | 17272 | 33-101-00473 | IM-Shorty 159-88 -0806H-1 | Ward | Wildcat |
| 5 | 19709 | 33-023-00658 | Rosenvold 1-30H | Divide | Norse |
| 6 | 19918 | 33-053-03358 | Charlotte 1-22H | McKenzie | Banks |
| 7 | 19951 | 33-105-02037 | Lokken 2-2H | Williams | Sauk |

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